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Ventilation network modelling for acceleration from air blasts from caving events

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ABSTRACT

With mining methods involving large underground voids, a significant risk to be managed is the air blast resulting from intentional or accidental caving events. There are difficult to determine factors influencing the extent of a caving air blast, such as, the amount of airflow pushed from the void drawpoints and through the porous falling rock, as well as the ability of seals on the void and throughout the mine to resist overpressure. Another factor is the airflow resistance of the entire mine, which will mitigate the blast to some extent; but this is a difficult factor to model in a mine ventilation network solver typically steady state in nature. The overpressure from a large air blast event will introduce a strong acceleration of the airflow, which will in turn increase the frictional pressure loss. This is problematic for a ventilation network solver that models airflows as if the overpressure from the air blast event is steady state, leading in general to an overestimation of the airflow velocities attained. This study presents a method for better simulating the airflow acceleration and deceleration, using the steady state solver to attain a temporary steady state airflow, towards which the actual airflows are relaxed over a certain timestep. This dynamic airflow is used to recalculate pressure losses through the mine, which are then accounted for in the diminishing overpressure in the caved void, leading to a better representation of airflow velocities during an air blast event, which can be used to inform risk management.

1 INTRODUCTION

Managing the risk of air blasts from the sudden collapse of underground voids is of critical importance for underground mines. This is the case particularly for block cave mines which require some form of airgap to induce caving. It also is relevant to other mining methods at different scales; risk of air blasts resulting from shaft, goaf or stope collapse must be managed.

One of the tools being used to predict the extent of potential blasts is mine network ventilation simulation (Vejrazka, 2016). It is now common for mines to have a detailed and up to date ventilation model, which is used to manage the ventilation system, plan extensions to the mine and select fans to use. These models can also be used to model the effect of an air blast. Modelling the collapsing cave back as a piston, a pressure can be calculated as a function of the collapsed void volume and then added as a ventilating pressure to the mine ventilation network. In this way, the added pressure from the cave is modelled in the same way as the added pressure from a fan. Doing this allows the effect of the pressure from the cave to be modelled. Such models can output the peak pressures across seals and the peak velocities throughout the mine resulting from the blast. The failure of seals can be modelled.

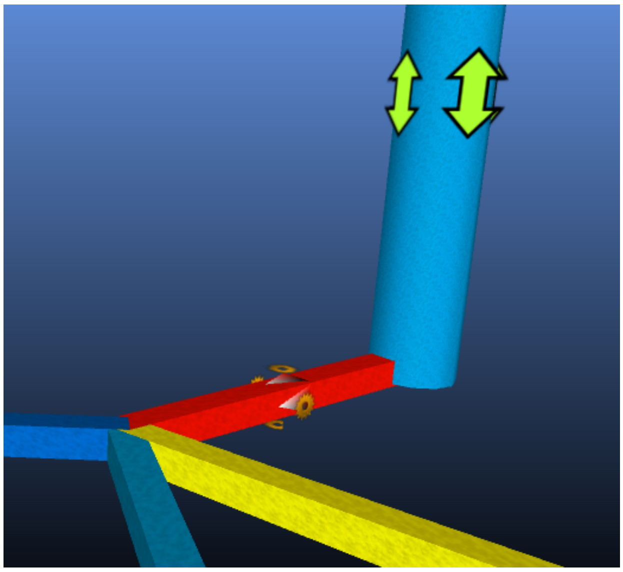
A widely-used mine ventilation software is Ventsim DESIGN, which currently features a tool to model the air blast. The tool is described below, however it is primarily a distillation of the work of Vejrazka (2016). Useful descriptions and discussion of the topic can be found there and the reader is recommended to seek them out. The tool takes as inputs:

- The cave height and footprint diameter
- The muckpile height, representing the height of existing caved rock
- The existing mine ventilation model
- The locations of connections between the collapsing cave and the mine ventilation network

It models the falling rock over time, ramping up the pressure as the rock falls, reaching a maximum once the cave back has fallen to the bottom of the cave. The pressure can be calculated either using Boyle's Law or the isentropic compression to relate the pressure to the compressed volume of air. This varying pressure is then added to the standard air simulation at each timestep, modelling the resulting flow over time. The flow rate out of the cave is monitored to reduce the amount of air remaining to exhaust in the cave, bringing the pressure down over time, as well as the resultant flows out of the cave. Once the pressure in the cave is equalized the air blast simulation finishes.

Figure 1 shows an example for a 15 meter diameter, 100 meter height collapsing void connected to a mine ventilation network at a single connection with zero muckpile height. The top image shows the vertical cave connected to the existing mine ventilation network. The double-sided green arrow icon represents where the added pressure from the collapsing cave is added. The graph shows the resulting variation of the cave pressure and the air velocity of the one connection at the bottom of the void.

The void ceiling in freefall takes 4.5 seconds to fall 100 meters and the resulting pressure due to the compression of the air in the cave can be seen in Figure 1 to ramp up, according to Boyle's Law. The failing cave back behaves as a perfect piston, not allowing any air to travel through it. It stops at an arbitrary height of 5 meters above the cave floor to avoid infinite pressures from compression appearing and the solver failing. Physically this can be thought to represent some space left after the fragmented, falling rock has fallen, or instead a highly pressurized zone immediately downstream of the obliterated cave void. This parameter is difficult to calibrate while also having a strong effect on the peak pressure eventually reached.



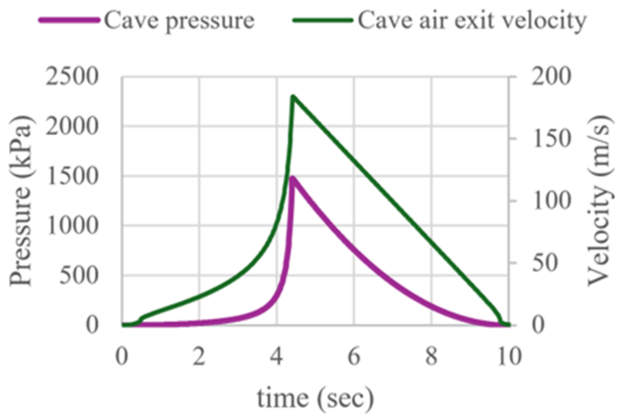


Figure 1 **Results from the existing blast simulation tool, showing pressure and velocity of air from the cave.**

In this example all the air leaves the cave via a single opening or single connection at the bottom of the cave and then flows out to the surface via the mine workings. In this way, the effect of the air blast can be seen in the model by examining peak pressures and velocities in each airway throughout the mine, not just at the cave. This allows critical areas of the mine to be identified where velocities may reach unacceptable levels. Similarly, peak pressures on seals and other ventilation controls can be examined and checked as to whether they will withstand the blast.

Further features exist to improve the model. Multiple connections can be made between the cave and the existing ventilation network. These connections could be drawpoints on a large block cave, or on a smaller scale, connections to a stope traversing multiple development levels. Once the falling rock falls past a connection, the connection is assumed blocked and flow out of it stops.

Also, a height of the falling rock can be specified, whereby rather than the falling piston/cave ceiling obliterating the void, a space opens up above it. The falling rock still permits no air through it, but if connections exist through the mine workings between different cave connections, once the top of the falling rock has fallen past a connection, the connection reopens to a space of negative pressure above the falling rock, drawing flow back in. If the cave connections are closely connected through the mine workings, this can induce high flow rates between the 2 voids but lessen the effect further afield. All this depends on the idiosyncrasies of the mine ventilation network the caving void is connected to.

Lastly, strength ratings can be assigned to seals and then be tested throughout the simulation. The user has the option to make seals fail when the pressure they experience exceeds their strength, and the resultant flow through the broken seal is modelled. Alternatively, only a warning can be reported at the end of the simulation, indicating that the strength was exceeded, but leaving the control in place. It is generally advised to run the solver in both modes, given the unreliability inherent in predicting the pressure a seal would fail at. Firstly to see where the flow goes after broken seals fail, but also to see where it goes and what pressures it induces elsewhere should the seal not fail.

All the features are efforts to move the model closer to what the reality would be for what is not only a highly dynamic and unpredictable event, but also a critical, while infrequent, one. For this reason, the tool is built in such a way to err on the side of caution when creating assumptions about the model. Assumptions like the perfect piston tend the solution towards being of a worst-case scenario type. For this reason, the modeler using this tool will often generate results with very high pressures and velocities during the caving event, which in turn invites questions about the assumptions and simplifications, such as: what is an appropriate airflow resistance to set for the muckpile resistance? and, what effect would a permeable piston have?

Another frequent question regards the nature of the airflow solver. The airflow solver is steady-state in nature. It is the same airflow solver that the mine ventilation modeler will use for all the other simulations they run in the course of their work, such as choosing fans, or optimizing shaft sizes. While the air blast simulation tool is a dynamic time-varying simulation, it is essentially a series of steady-state simulations. At each step in time of the simulation, the airflow is simulated as if the existing pressures at that timestep are constant and unchanging and that the flow resulting from those pressures has fully developed. This invites questions about the effect of the inertia of the air during the blast. Once a pressure is applied to a mass of air, it will not achieve its steady-state velocities immediately but take some finite amount of time to accelerate to it. So for the air blast simulation tool, it is most likely over-predicting the peak air velocities achieved as it does not allow for flow acceleration. Again, this is an assumption in the tool that has been chosen to err on the side of caution. Nonetheless, it would improve the simulation tool to have a better idea of what that error is. If sufficient confidence can be found in the error's extent, then it would be possible to correct the results of the tool in such a way to improve their accuracy, while also maintaining a level of caution in the predictions it makes for blast pressures and peak velocities.

The aim of the paper is to investigate this question of inertia in the mine air mass and its attenuating effect on large air blasts. A better understanding of this effect will improve the accuracy of the air blast prediction, and user's confidence in its use. There are potentially other fields involving impulse pressures in ventilation networks, such as piston effects from vehicles and trains in tunnels to which this would also be applicable.

2 METHOD

To investigate the effect of air inertia on a caving air blast, first considered is the case of an accelerating flow. Imagine a 1 kilometer tunnel of 25 m^2 area, open at both ends with a fan adding 1,000 kW of ventilation power. We use Atkinson's resistance equation of:

$$P = rQ^2 \quad (1)$$

Where P is the frictional pressure drop along the tunnel in pascals, Q is the volumetric flow rate in m^3/s, and r is the Atkinson's resistance (McPherson, 1993). Assuming incompressibility and setting wall roughness such that resistance is $r = 0.01536$ Ns^2/m^8 for the whole tunnel, a flow rate of 402 m^3/s and an added pressure from the fan of 2,486 Pa is obtained, with the power of the fan equal to the multiple of its added pressure and flow quantity (*power* = *PQ*). This is the result obtained from the steady-state air solver.

Now considered is the acceleration case, where 1,000 kW of ventilation power is applied to the same tunnel but with the flow starting at rest. The fan will be assumed to instantaneously switch between 0 and full power.

A highly simplified model based on an energy balance between the fan power, the frictional power loss and the mass of the air to be ventilated is developed. Starting with the flow at rest, the air in the tunnel has zero kinetic energy. For the purposes of this study, a base kinetic energy is defined as:

$$BKE = 0.5mV^2 \quad (2)$$

Where m is the mass of air in kilograms and V is the mean cross-sectional velocity of air in the tunnel in m/s. We will call it the base kinetic energy, as there are several problems with this definition of kinetic energy which will be addressed later in this section.

When the fan is switched on it immediately adds 1,000 kW of power. The accelerating flow is numerically solved by first stepping forward some small amount of time, dt, then calculating the amount of energy in kilojoules introduced by the fan over that time, which will be equal to $dt \times 1,000$ kW. Then a flow rate in the tunnel is determined using a root-finding method such that the base kinetic energy of the air in the tunnel is equal to the amount of energy introduced over that timestep. At the next timestep, the process is repeated, but this time with the available power to accelerate limited to the fan power minus the power now required to overcome the friction from the previously calculated flow rate. Therefore, as the time advances and the flow accelerates, more power is used to overcome the friction and less is available to accelerate.

Figure 2 shows in orange the obtained flowrate over time for the accelerating case described, using the method described in the above paragraph. The same process can be used to calculate the deceleration when the fan is turned off, and this is plotted in blue in the same figure.

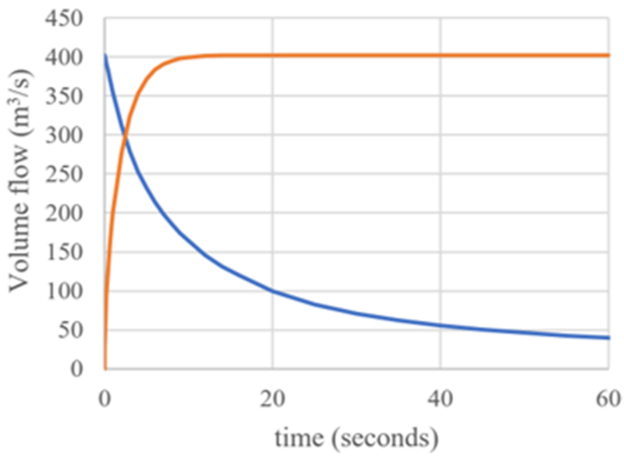


Figure 2 Theoretical acceleration (in orange) of flow from rest to 402 m^3/s, and deceleration (in blue) from the same.

In the decelerating case, the power to slow the flow is the frictional loss from the previous timestep. As the flow slows down, this decelerating power reduces with the cube of the quantity (*power* = rQ^3), so little power exists to decelerate once the flow has slowed so it takes longer to reach the steady state. In each case, and at each timestep, a corresponding pseudo-pressure can be found, which will be some factor of the true pressure of 2,486 Pa, for which a steady-state air simulation at that pseudo-pressure will yield the flowrate at that time. This concept of a pseudo-pressure will be applied to the air blast and the series of steady-state simulations that constitute the current caving air blast simulation tool.

So there is a model for acceleration and deceleration, but it has some significant weaknesses that should be borne in mind and are listed below:

1. Firstly, equation 2 is not a proper definition of kinetic energy; due to viscosity, the velocity of the fluid near the wall must be zero, meaning the flow in the center of the tunnel will be greater than the mean velocity. This means that the definition of base kinetic energy in equation 2 will underpredict the true kinetic energy, given the squared term. However, since it is generally highly turbulent flows that are being considered, the velocities will rise quickly as we move away from the wall, so for now we will leave this error in, but bear it in mind later.

2. The turbulent kinetic energy is neglected in the definition of base kinetic energy in equation 2. This is the energy associated with the turbulent fluctuations in the flow that act in all directions and is averaged out when considering only the mean axial velocity in the tunnel. This is acceptable when considering the axial bulk acceleration of the flow, however, the turbulent kinetic energy must be fed from the accelerating portion of the fan power, as the flow in the tunnel accelerates and moves to higher Reynolds numbers and a more energetic turbulent state. Therefore in Figure 2, the acceleration is being overpredicted, as some portion of the input energy will go into establishing the required turbulent kinetic energy of the new flow.

3. Everything so far is based on the Atkinson resistance equation and a constant resistance. However, this equation assumes that there is a fully-developed turbulent flow in the tunnel. Inherent therefore in the equation is the turbulent dissipation of energy; the pressure loss seen over the length of the tunnel results mostly from the production and dissipation of turbulent energy, but in the accelerating case the flow is still developing, so the energy loss from friction as the flow accelerates is likely to be overpredicted. In a fully developed flow, the generation of turbulent kinetic energy will equalize with the dissipation rate, but not while accelerating. The flow at any moment during the acceleration will be less turbulent than the fully developed flow, and therefore not losing as much energy to turbulent dissipation; this would mean the flow would to some extent accelerate faster than Figure 2 suggests. But this amplifying effect is likely to be less than the attenuating effect described above in point 2, as the dissipation rate will be smaller relative to the fully developed flow, due to the lag in generation of the turbulent kinetic energy, on which the dissipation rate depends. Similarly, in the decelerating case, the flow at any moment during the deceleration would exhibit a greater turbulent kinetic energy given its deceleration than a fully-developed flow for the same flow rate, so it would dissipate energy faster than the Atkinson resistance equation suggests. Therefore it would decelerate somewhat faster.

4. Another factor is the establishment of the pressure gradient. The accelerating and decelerating cases of Figure 2 imply an instantaneous establishment of the pressure gradient. In reality this would take some time to establish and we are not considering any dynamics around potential shock waves.

How far off the result in Figure 2 is something that can be worked on in the future and is treated as beyond the scope of this paper. For now it serves as a useful first order approximation of the acceleration-deceleration process that can be applied to the air blast, and a first step in investigating the effect of air inertia on impulsive effects in complex ventilation networks.

Applying this to a caving air blast, we can treat the cave as a pressure source, in much the same way we imagine a fan. However, the connected mine workings constitute a more complex and not so easily analyzed network than that presented for the 1 km tunnel above. Instead, the root-finding method which determines the flow rate in the tunnel must incorporate the network airflow simulation tool (Pilati, 1987) that is run at each timestep of the caving air blast simulation.

Calculating the base kinetic energy of all the air in the mine is straightforward using equation 2, given the dimensions of all the tunnels and their air velocities are known. However, we are interested in the difference of base kinetic energy from one steady-state simulation at a given pressure to another steady-state simulation at a different pressure. If we imagine a cave in a mine, at the start of the event there is no flow from the cave, therefore the standard ventilation flow will be passing by the cave. Once the event begins and the cave becomes a pressure source, it will initially accelerate the flow out of the mine (increasing the base kinetic energy in those existing airways) but slow the flow in airways connected to the intakes. Therefore, as pressure increases in the cave, its effect will be to increase energy in some airways, and decrease it in others, leading in some cases to a decrease in total base kinetic energy with the added pressure. But in those airways where it decreases, for the purposes of this tool, we need to consider it as energy gain. With this, a function is written which returns the base kinetic energy difference between two air simulations.

With this function, the caving air blast simulation is run as normal, however, as the cave pressure increases from one timestep to the next, a pseudo-pressure is calculated using the root-finding method such that when that pseudo-pressure is applied to the cave and run at a steady state, the base kinetic energy difference with the state at the previous step is equal to the amount of ventilating energy that the cave put out, minus the amount of energy needed to ventilate the previous step. In this way we have a model of air inertia, which will attenuate the air blast.

3 RESULTS

The new method is applied to the same case as shown in Figure 1, the results of which are shown in Figure 3. In red, we see the pseudo-pressure, which – when accelerating – at any given timestep represents a pressure that when run at steady-state achieves a model-wide base kinetic energy difference from the base kinetic energy at the previous timestep equal to the portion of the ventilating pressure from the cave available to accelerate the flow. When decelerating, the frictional loss of energy from the previous step is used as the negative input in determining the base kinetic energy of the next step.

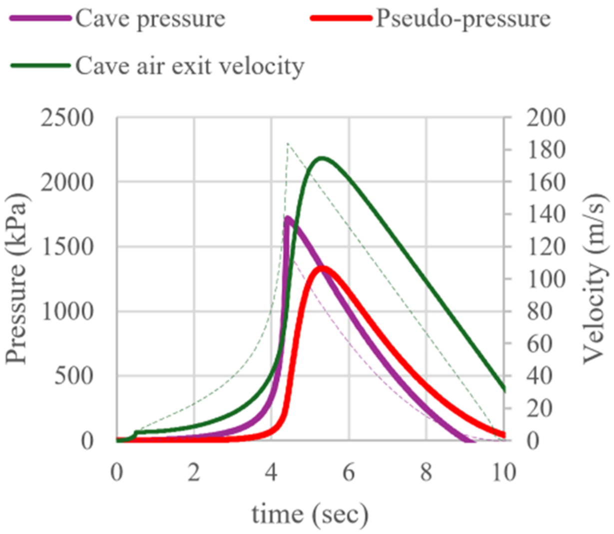


Figure 3 Results for the same case as Figure 1, but with the new method of attenuating the development of the blast.

For comparison, Figure 3 also reproduces in faint lines the results from the standard method shown in Figure 1. The pseudo-pressure can be seen to lag the actual cave pressure, representing the acceleration of the air mass contained in the mine. As the cave pressure rises with the falling ceiling, the pseudo-pressure trails it, as the air mass takes time to accelerate; then as the cave pressure drops after the ceiling has hit the bottom of the cave, the pseudo-pressure catches up with the true pressure and then exceeds it. This represents the existing momentum of the air mass maintaining a higher flow rate for some time.

Next, the peak velocity using the new method can be seen to occur sometime later than the peak in the previous method, and at a lower magnitude, resulting from the lower pressure applied by the pseudo-pressure. In the second half of the event, the pseudo-pressure exceeds the cave pressure, drawing more flow out of the cave than the true pressure would. This has the interesting effect of there being an air velocity of approximately 50 m/s at the time where the true cave pressure has equalized and there is no more air left to exit the cave. Here the momentum of the flow continues to draw air from the void, creating a negative pressure in the cave which will eventually draw air back into it. The tool has not yet been developed to simulate this negative pressure, but if it did, we would most likely see some small oscillation around zero pressure until stabilized. This makes sense when considering the energies involved in such an event. If the air blast event is of sufficient magnitude, then the existing momentum of the air in the mine at the moment that all of the pressure has left the cave would create negative relative pressure in the cave which would create suction back into it. But this would happen at the tail end of the event and the dynamics of it is not critical.

The new peak velocities obtained from the new method can be analyzed both at the cave and throughout the model. But some caution should be used in examining peak pressures. The pseudo-pressure is a simulation parameter and does not have any straightforward physical nature. Therefore, within the cave, and on seals directly connected to the cave, the pressure is still best represented by the true cave pressure. It is just a pressure whose corresponding steady-state velocities are never realized. At some distance further from the cave, the peak pressures obtained from the pseudo-pressures perhaps become more relevant, but there is still some thinking and work to be done on what pressures seals further from the cave would truly experience.

Another point of difference of Figure 3 is that the new method creates a higher true cave pressure inside the cave, in this case higher by 240 kPa, or 16 %. This results from the fact that simply less air exits the cave during the ramp up of the pressure, and once the ceiling has fallen in there is more air in the collapsed cave and therefore a higher pressure. Therefore attenuation of the blast from air inertia would likely increase the pressure directly inside the cave.

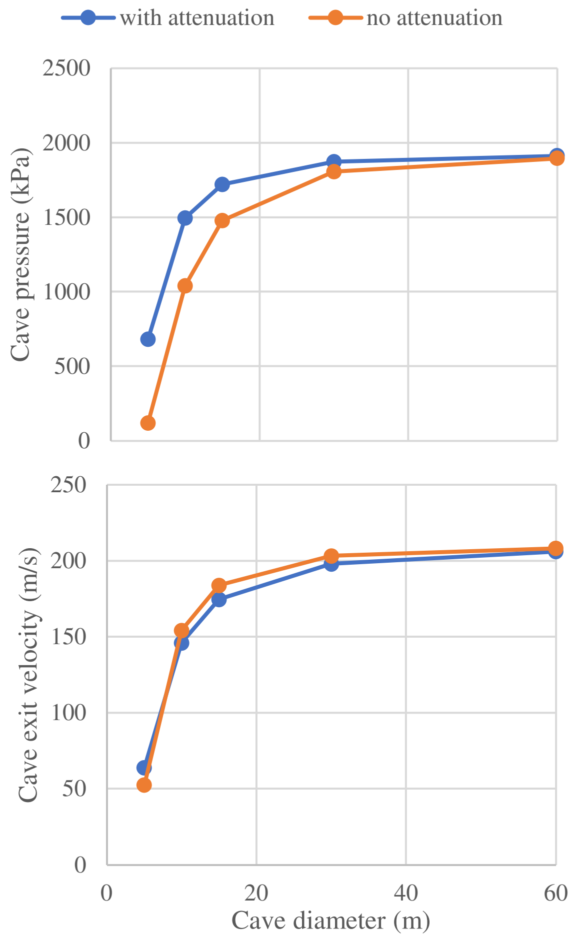


Figure 4 Cave pressure and air velocity comparison between the standard (no attenuation) and new method (attenuation).

With the current model working, the rest of the results describe the effect of the blast attenuation on caves of different sizes, and on mines of different total air mass. Figure 4 shows comparison of the two methods for a 100 m height collapsing cave at the midpoint of a mine network of 225,000 m^3 volume, with no muckpile height, and therefore an unsealed blast.

Figure 5 shows a comparison for a cave of 100 meters diameter and a 5 meter muckpile height at the bottom of the cave, on the same mine. The 5 meter muckpile features a resistance of 0.0203

$(Ns^2/m^8)/m/10000m^2$, so therefore the cave is well-sealed. Figure 5 plots the variation of the cave pressure and exit velocities for the two methods at different air gap heights between the ceiling and top of the muckpile. For the large, well-sealed cave there is very little attenuation from the new method. This makes sense given the generally lower air speeds from the sealed cave (so less acceleration required). However this will change if the cave becomes suddenly unsealed.

As discussed earlier, the failure of seals can be included in the simulation. Figure 6 plots the results from the two methods, where the cave failure with 80 meter airgap includes a second cave connection, above the muckpile with a seal that fails at a given differential pressure. This broken seal vents the blast directly to the mine workings.

For this figure there are two velocity readings, one in green for the lower connection through the muckpile, and another for the upper connection with the failed seal, in orange. As in Figure 3, the velocity results for the standard method are shown in dashed lines. For this case, with the higher exit velocities, the attenuation can be seen to have an effect, but only really in the timings of the peak velocities and not in their magnitudes, nor for the peak pressures. However, although not presented here, simulating the cave at smaller diameters or smaller muckpile heights could produce larger differences in magnitude.

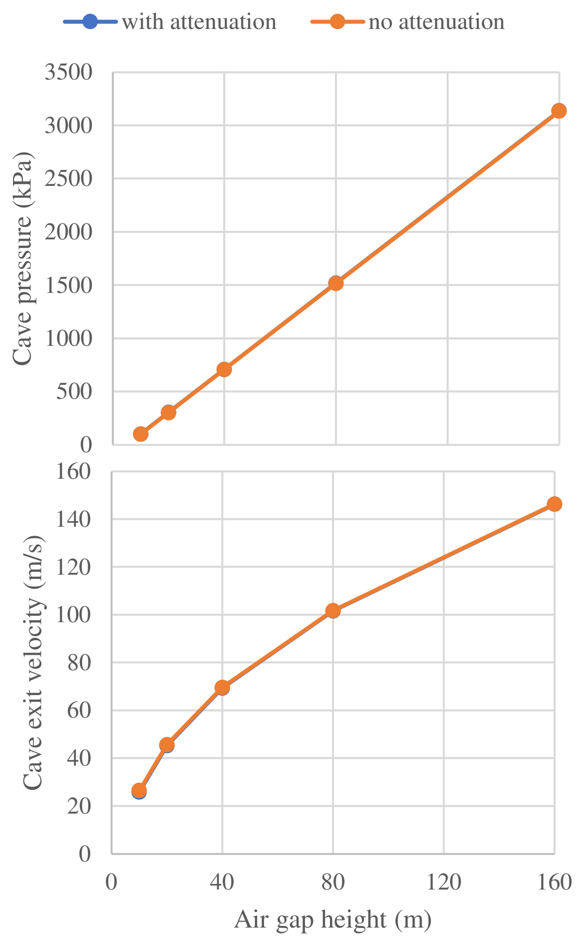


Figure 5 Cave pressures and exit velocities for the two methods for a well-sealed cave, varying the air gap height.

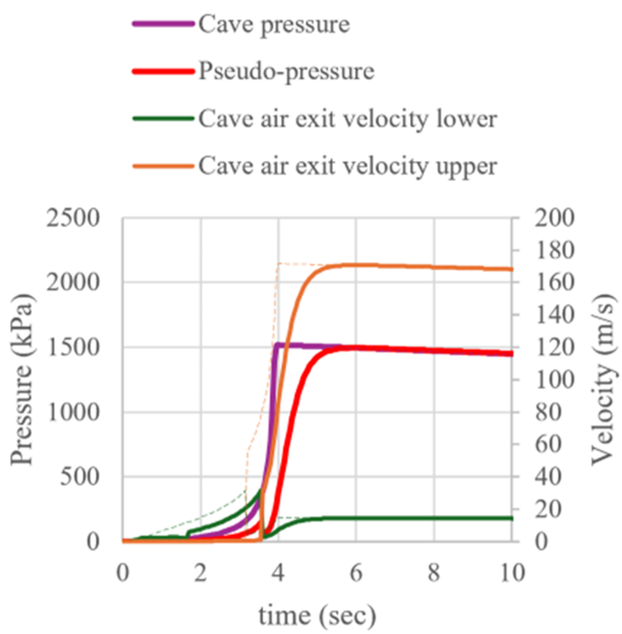


Figure 6 Results for a sealed cave collapse subject to a seal rupture.

DISCUSSION

The attenuation of the blast due to flow acceleration, using the method described, has a greater effect on unsealed blasts at the smaller scale of air blasts usually considered in underground mines. If the blast is unsealed the pressure created is applied directly to the ventilation system of the mine, with no extra resistance from the cave. This creates the most acceleration and therefore the greater effect from the model of air inertia. If a sealed cave is modelled with a large resistance from a muckpile, the extra resistance reduces the acceleration, giving more time for the flow to accelerate and therefore resulting in a smaller difference between the old steady-state series method and the present attenuated method.

The results are encouraging in that they qualitatively show attenuation of the blast effects as would be expected, particularly in the case of unsealed blasts from smaller caves, such as stopes. However, there are still significant caveats around this that need to be investigated further. The most important is how to treat the rate of turbulent kinetic energy production in the accelerating flow. This effect – not modelled in the current method – will attenuate the blast further. However, modelling it will require first a robust method for approximating the amount of turbulent kinetic energy present in a fully-developed flow, as a function of Reynolds number and wall roughness. Such a method may already be available in the literature, but at this moment the authors are unaware of it. With this, an approximation of the rate of turbulent kinetic production in the accelerating flow could be included in the energy balance which forms the basis of the new method. Further consideration also needs to be given to the dynamics of the inital blast wave from the event and how or if it can be considered as part of the current method.

CONCLUSIONS

A method of attenuating the modelled air blast from a caving event in a 1D ventilation network has been presented, which seeks to include the effect of inertia of the mine air mass on the progression of the resulting air velocities. The model uses a highly simplified notion of base kinetic energy to model the acceleration of the flow, using the concept of a steady-state pseudo-pressure for the time-varying air blast pressure. The effect of the model was most pronounced in air blasts from unsealed stopes. The method shows promise, but further research and work is required to properly model the effect of turbulent kinetic energy production and dissipation during the flow acceleration as well as the effect of initial blast waves, for the method to be more widely used. Nonetheless, the results and attenuation presented are appropriately cautious, with a degree of confidence that the effects yet to be modelled would in general increase the effect of attenuation and therfore not underpredict the extent or danger of the blast.

REFERENCES

McPherson, M. (1993). Subsurface Ventilation Engineering. Chapman & Hall.

Pilati, E. T. (1987). A Gradient Method for the Analysis of Pipe Networks. International Conference on Computer Applications for Water Supply and Distribution. Leicester.

Vejrazka, C. (2016). Northparkes Mines' Current Air Blast. Proceedings of the 7th International Conference & Exhibition on Mass Mining, (pp. 257-263). Sydney.