PREDICTING AND MITIGATING THE EFFECTS OF AIR BLASTS IN MINES

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Abstract

Falling rock from the roof of a mine cavity can cause shock waves to propagate in tunnels connected to the cavity. Two models for the formation and propagation of a shock wave in an adjoining tunnel are presented, namely the Piston model and the Laval nozzle model. A simple model is used to estimate an effective piston speed at the entrance to the tunnel. In the Laval nozzle model an equation for the critical sectional area of the tunnel for the formation of a shock is derived. An equation for the shock strength is also obtained. Suggestions to mitigate the damaging effects of the air blast in the tunnel are made.

1 Introduction

Air blasts in mines are the result of falling rock from the roof of a mine cavity into a large air space. The falling rock has a piston-like effect on the air in the cavity. It compresses the air, forcing it to move through the adjoining tunnels,

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shafts, ore-passes, underground roadways and also through the gaps between the falling rocks.

The effects of air blasts in mines may be disastrous. The force of the air blast has been known to damage mining equipment and block access to the shafts and passageways. Air blasts also pose a serious safety hazard to mine workers.

The aim of this report is to determine the strengths and speeds of the shocks that occur in adjoining tunnels of the mining cavity where the roof collapse occurs.

This report considers two models; a piston model in Section 2 and a Laval Nozzle model in Section 3. Possible procedures for reducing the shock strength are described in Section 4 and conclusions are drawn in Section 5.

2 The Piston model

2.1 Shocks

Shocks, shock fronts or shock waves are "discontinuous" changes (jumps) in physical properties, such as pressure, density and velocity, which are propagated at speeds in excess of the "communication speed" of the medium; the "speed of sound" in the case of gases, the "shallow water speed" in the case of hydraulic jumps, or the "signal speed" in the case of continuous models of traffic flow. Shocks arise for a number of different reasons. Perhaps the most familiar shock is the bow shock wave generated by the supersonic "motion" of an aircraft. The "cause" is the supersonic motion of the aircraft and the "effect" is a shock wave which heats, compresses and turns the flow round the aircraft.

There is also the infamous shock wave associated with the explosion of a "bomb". In this case the "cause" is the sudden release of large amounts of energy in a small space. The "effect" is a blast wave which propagates out from the explosion region at highly supersonic speeds. Supernova blast waves are also of this type and it is possible to find a similarity solution, which is spherically symmetric, (the well known Sedov solution) which describes the shock speed ($\dot{R}(t) \propto t^{\frac{2}{5}}$) and the flow of the shocked material behind the blast. Also in astrophysics there is the phenomena of stellar winds. Our own sun generates such a supersonic "solar wind" outflow which eventually must adjust to the ambient interstellar medium. This it does through a "termination shock". The Voyager spacecraft have recently reported crossing this heliospheric termination shock at a distance of about 80 A.U. (1 A.U. is the distance between the sun and the earth $\sim 220\ R_0 \sim 1.5 \text{ x } 10^8$ km). It is interesting to note that such "termination" shocks associated with supersonic stellar wind flows find an analogy with the flow of the water over a sink from the discharge from an open tap above. It will be observed when the water from the tap strikes the sink there is a fast, smooth, flowing inner region followed by a "hydraulic" jump (shock) which raises the water height and slows down the flow into a sub-critical, turbulent flow. In fact from a formal viewpoint this shallow water flow is entirely analogous to a gas dynamic one in which γ (the ratio of specific heats) = 2 since the force per unit width of the water (integral of the pressure) varies as the square of the height which assumes the role of the density.

Since the "flow equation" for stellar winds applies equally well to inflows (negative flow speeds) there is also a critical solution which takes the gas at "rest" far from the gravitating star through a smooth subsonic-supersonic flow. This accretion flow may also be "terminated" by an accretion shock situated above the star which slows and compresses the in-falling material.

In some sense stellar wind flows are similar to those in a de Laval nozzle, in which the presence of a throat together with the property that the gas mass flux per unit area maximises at the speed of sound conspire to yield subsonic-supersonic flows, provided that the exit pressure is sufficiently larger than the reservoir pressure. At the exit of the nozzle a shock can be formed.

Perhaps the greatest shock ever generated on earth was the one caused by a meteor which crashed into the earth about 65 million years ago, near Chicxulub in the Yucatan Peninsula, and lead to the extinction of the Dinosaurs.

In this report we will first consider the simplest case of all, namely the shock produced in a shock tube by a piston moving uniformly into it. In this case a shock is "immediately" formed and propagated into the undisturbed gas with a supersonic speed determined by the piston speed as well as the speed of sound of the undisturbed gas. We shall adopt this picture as providing a crude and zeroth order approximation to air blasts in mines caused by a rockfall from a great height in an adjoining wide shaft.

2.2 Piston generated shock in a shock tube and jump relations

The shock generated by the uniform motion of a piston in a tube is, perhaps, the simplest of all shock problems. It is assumed that a shock is "immediately" generated and moves forward into the undisturbed gas with speed v_s. The shock speed is readily calculated in terms of the piston speed v_p and the speed of sound c_0 of the undisturbed gas by using Prandtl's relation for plane shocks, namely:

$$v_0 v_1 = c_*^2 = \mu^2 v_0^2 + (1-\mu^2)c_0^2 \equiv \mu^2 v_1^2 + (1-\mu^2)c_1^2, \tag{1}$$

where

$$\mu^2 = \frac{(\gamma - 1)}{(\gamma + 1)} = \frac{1}{6}$$

and $\gamma = \frac{7}{5}$ for air. Here v_i are the relative velocities given by

$$v_i = u_i - v_s, \tag{2}$$

where $i = 0$ (ahead of the shock) and $i = 1$ (behind the shock). The speeds u_i are the gas speeds in region i. In region 0, the gas is at rest ($u_0 = 0$) whilst in region 1 the gas moves with the piston ($u_1 = v_p$). Equation (1) is a quadratic equation for v_s yielding the shock speed,

$$v_s = \frac{v_p}{2(1-\mu^2)} + \sqrt{c_0^2 + \frac{v_p^2}{4(1-\mu^2)^2}}. \tag{3}$$

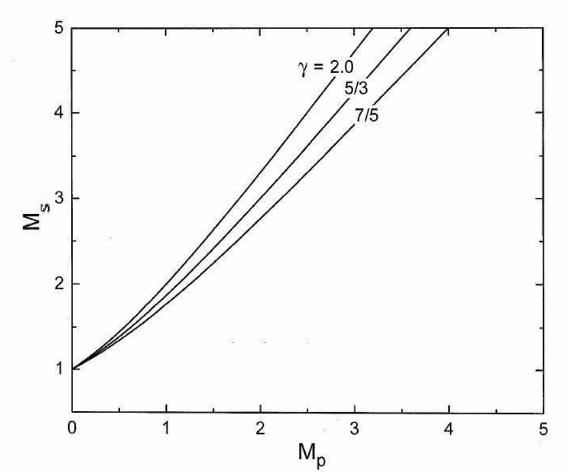

Figure 1: The shock Mach number (M_s) as a function of the piston Mach number (M_p), for different values of γ ($\gamma = 1.4$ in air).

Figure 1 depicts equation (3) expressed in terms of the shock Mach number $M_s \left(= \frac{v_s}{c_0}\right)$ as a function of the piston Mach number $M_p \left(= \frac{v_p}{c_0}\right)$ for various γ. Note that M_s is always > 1 and that in the case $M_p \gg 1$ the shock speed is 20 % greater than the piston speed. The question here is how do we determine the effective piston speed for the situation of an air blast generated by a roof collapse.

However before doing so we note the well known relations for the pressure $\left(\frac{p_1}{p_0}\right)$, density $\left(\frac{\rho_1}{\rho_0}\right)$ ratios which follow from the Rankine-Hugoniot conditions across the shock which conserve mass, momentum and energy. In the shock frame (that is, one in which it appears stationary) these are:

$$\frac{p_1}{p_0} = \left(1 + \mu^2\right) M_0^2 - \mu^2 \,, \tag{4}$$

$$\frac{\rho_1}{\rho_0} = \frac{M_0^2}{1 - \mu^2 + \mu^2 M_0^2} \,, \tag{5}$$

$$\frac{T_1}{T_0} = \frac{p_1/p_0}{\rho_1/\rho_0} \,, \tag{6}$$

$$M_1^2 = \frac{(1 - \mu^2) + \mu^2 M_0^2}{(1 + \mu^2) M_0^2 - \mu^2} \,, \tag{7}$$

$$\frac{S_1}{S_0} = \ln \left[\frac{(p_1/p_0)}{(\rho_1/\rho_0\ ,)^\gamma} \right] \,, \tag{8}$$

in which $\frac{T_1}{T_0}$ is the temperature ratio, M_1 is the Mach number behind the shock and $\frac{S_1}{S_0}$ is the ratio of the entropies/unit volume. These relations are shown in Figure 2 as functions of the Mach number M_0 ahead. As we have already indicated, this will be given by equation (3) once we have determined a model for the piston speed (or Mach number). Note for moderate to strong shocks, $M_0 \gg 1$, the pressure, density and temperature ratios approximate to

$$\frac{p_1}{p_0} \sim \frac{7}{6} M_0^2, \qquad \frac{\rho_1}{\rho_0} \to 6 \,, \tag{9}$$

$$\frac{T_1}{T_0} \sim \frac{7}{36} M_0^2, \qquad M_1 \to 0.38 \,. \tag{10}$$

The entropy is a secondary variable and plays no dynamical role whatsoever. That it increases through the shock is automatically guaranteed if $M_0 > 1$. It is also worth noting that the amount of dissipation (entropy generation) across the shock is completely independent of the dissipation mechanism(s), but is in fact determined by the boundary conditions through the upstream Mach number M_0.

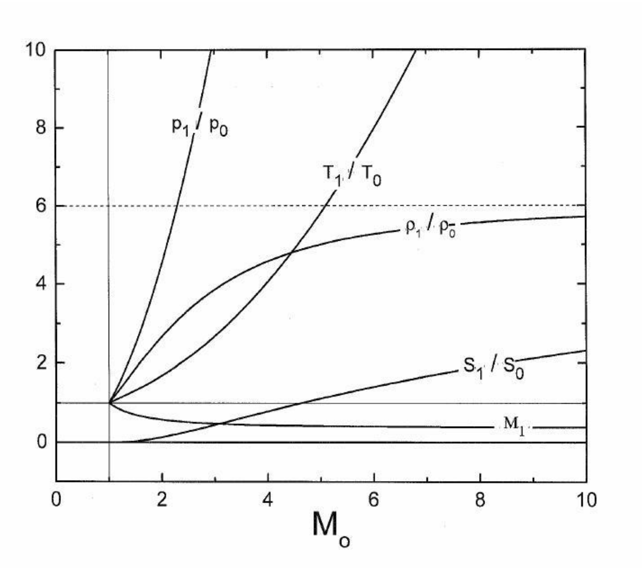

Figure 2: The pressure(p), density(ρ), temperature(T), entropy(S) and the Mach number(M_1) behind a shock as a function of the Mach number(M_0) ahead.

2.3 Estimation of piston speeds

Crude, zeroth order estimate of piston speed

In the absence of a full numerical gas-dynamic model of the roof collapse and the subsequent air blast in the tunnel, we will assume that the air under the collapsing roof is compressed adiabatically. This is used to estimate an effective piston speed v_p at the entrance of the tunnel of height h and depth D between the uncollapsed roof and the tunnel.

Hence an effective piston speed v_p at the entrance to the tunnel will be of order

$$v_p \approx \sqrt{\frac{p_e - p_0}{\rho_e - \rho_0}}, \tag{11}$$

in which p_e and ρ_e are the adiabatically compressed pressures and densities at the tunnel height, respectively. In a simple free fall model

$$\frac{\rho_e}{\rho_0} = \frac{D}{h}. \tag{12}$$

Therefore (12) gives the piston Mach number as

$$M_p = \frac{v_p}{c_0} = \frac{1}{\sqrt{\gamma}} \left[\frac{\left(\frac{D}{h}\right)^{\gamma} - 1}{\left(\frac{D}{h}\right) - 1} \right]^{\frac{1}{2}}. \tag{13}$$

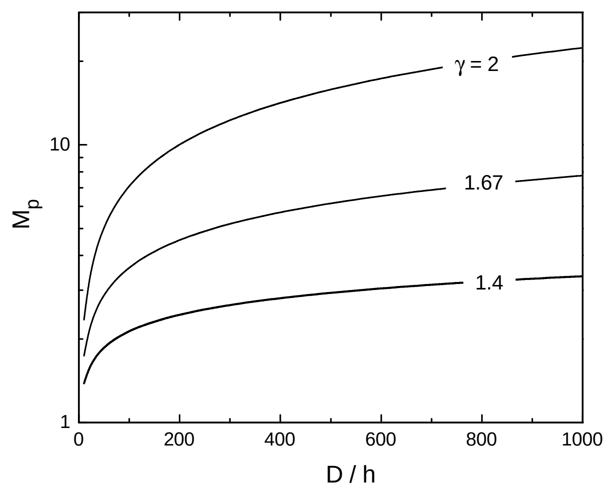

Figure 3: The piston Mach number (M_p) as a function of $\dfrac{D}{h}$.

A plot of M_p versus $\dfrac{D}{h}$ is shown in Figure 3 which displays the rather weak increase of M_p with $\dfrac{D}{h}$ varying from about 2, for $\dfrac{D}{h} = 100$, to 4, for $\dfrac{D}{h} = 1000$, as a result of the $\dfrac{1}{5}$ power dependence. The corresponding shock Mach number M_s (Figure 1) then varies between 2.5 and 5, thus indicating a moderate to strong shock. The shock is associated with pressure and density ratios ranging from 10 to 28 and 4 to 5 respectively, with corresponding temperature ratios ranging from 4 to 5.

3 Laval nozzle model

3.1 Previous work and the problem at hand

A collapsing roof in a mining cavern can cause shock waves to propagate in tunnels leading away from the cavern. Such shock waves can be of sufficient

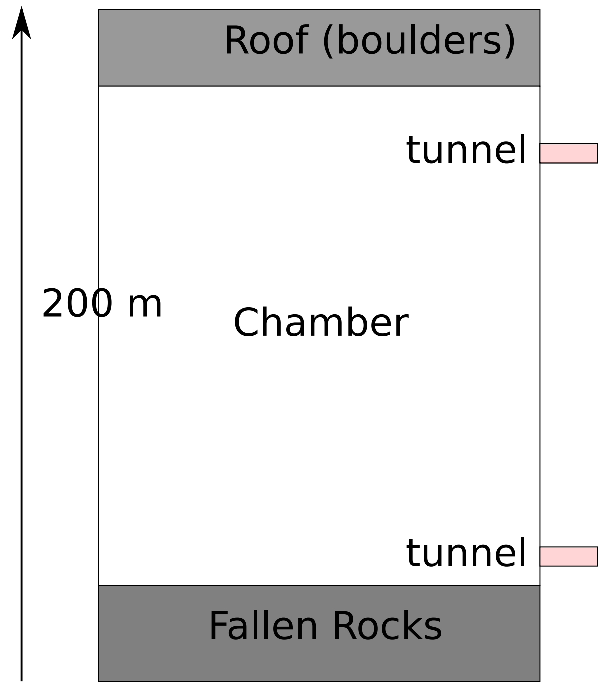

Figure 4: Roof collapse in a cavern. The cavern lies under an open pit with the roof of the cavern consisting of compacted boulders (30 m deep). The floor is covered with fallen rocks (20 m deep). One tunnel is at floor level the other close to the roof.

magnitude to overturn vehicles and cause loss of life as well as massive damage within the tunnels. This air blast problem has been addressed in two earlier MISG's and was prescribed in terms of a particular event that occurred in November 1999 in an Australian mine. The calculations made in the two previous MISGs were based on this specific situation and this report will also focus on this event. The cavern geometry was as shown in Figure 4. The cavern was about 30 m square and about 200 m total depth. The 'roof' consisted of about a 30 m layer of solid rock boulders temporarily stored in the upper portion of the cavern of height 100 m with rubble of depth 60 m on the floor of the cavern. The boulders in the roof were being removed gradually, but evidently key rock support components were accidentally dislodged leading to a complete roof collapse and consequent shock propagation in tunnels leading out of the cavern.

In the first MISG report (2005) [1] a number of models were produced that aimed at prescribing the pressure development within the cavern due to the roof collapse (impervious piston models, a rock rain model, and a porous flow model). The simplest model results are relevant here and will be briefly described. Now understandably there was no detailed information about the collapse sequence and the pressure development within the cavern would strongly depend on this sequence. If for example the roof fell 'boulder by boulder' then there would be little net air displacement caused by such individual events and no resultant shock. In the other extreme the roof could have collapsed 'as a unit', in which case the air below the roof would be trapped and high pressures would have developed. Given the damage caused this second scenario seems closer to what happened, see later. The simplest model assumed uniform conditions within the 'sealed' collapsing cavern and in this case if the air volume in the cavern under the roof at time t is $V_c(t)$ and $p_c(t), T_c(t)$ the associated gas pressure and temperature then, assuming no venting, and adiabatic perfect gas law conditions, we obtain

$$\frac{\rho_c(t)}{\rho_0} = \frac{V_0}{V_c(t)}, \text{ with } \frac{p_c(t)}{P_0} = (\frac{V_0}{V_c(t)})^\gamma \text{ and } \frac{T_c(t)}{T_0} = \frac{p_c(t)}{P_0}\frac{\rho_0}{\rho_c(t)}\ , \tag{14}$$

where V_0 is the initial volume occupied by the air in the cavern (including voids in the floor rubble), and where P_0 is atmospheric pressure and $\gamma \approx 1.4$. The above model gives cavern pressures of the order of 1.3 P_0 when the rock fall passes by a tunnel 20 m from the roof of the cavern and 16.8 P_0 for a tunnel near the floor of the cavern, assuming the roof collapses onto the solid rubble floor with void fraction 1/3. These are of course overestimates for the cavern pressures generated since air escapes through tunnels and more importantly through gaps between the falling rocks[1], but the model indicates that the air blasts generated in tunnels high up in the cavern will be weak, but major blasts may occur in tunnels close to the cavern floor if the falling rock remains relatively consolidated. Other relevant features of the problem are:

- Rocks take a time of order of 6 secs to reach the floor.
- Typical maximum gas velocities of the order of 60 m/sec (the rock speed at floor impact) may be expected within the cavern; we have subsonic flow within the cavern.
- In the tunnels one might expect maximum flow velocities of the order of (60 × 25) m/sec where the factor 25 corresponds to the tunnel area to cavern area ratio. This give approximately $5a_0$ where a_0 is the sonic speed; supersonic flow can occur within the tunnels.

[1]The models developed in MISGSA (2005) indicate much lower cavern pressures may occur.

It is a simple matter to take into account the loss of air through the tunnel (by adjusting V_0), but determining the break up of the falling rock is probably a practical impossibility so the best one can do is to work with a worst case scenario; the above represents such a scenario. In the following we will assume the cavern conditions $(\rho_c(t), p_c(t), T_c(t))$ are prescribed by any suitable model, see MISG report (2005) [1].

In the second MISG report (2006) [2] a Fanno model was developed to describe the boundary layer dissipation of mechanical energy from the shock as it passes down a straight tunnel. It should be noted that there is little mechanical energy loss across the shock so that the primary losses occur as a result of viscous dissipation in the tunnel boundary layers.

The task for this MISG was to explore methods for either reducing the strength of the shock wave generated from roof collapse or increase its dissipation within a tunnel or the tunnel complex. A suggestion was made that the introduction of tunnel loops may be useful in this regard. In Section 3.2.2 we estimate the shock strength and speed and in Section 4 we will describe possible attenuation procedures.

3.2 Shock generation in the tunnel

The work to follow is slightly adapted standard knowledge as presented in Liepmann and Roskho [6], (see especially Chapters 2 and 5), Courant and Friedrichs [4], and Whitham [5]).

The falling rock in the cavern produces a rapid rise in pressure in the cavern, followed by an abrupt recovery to normal. This abrupt rise in pressure at the tunnel entrance will drive flow into the tunnel until the rock 'curtain' passes by the entrance. The assumption/assertion made here is that cavern plus tunnel acts as a Laval nozzle (Liepmann and Roshko [6]) of rather unusual shape, with the cavern identified with the reservoir and with the throat being identified with the tunnel entrance, see later.

Of major importance for Laval nozzle flows is whether reservoir pressures and temperatures are sufficiently large to cause sonic flow conditions at the throat, thus 'choking' the flow. In context, choked flow conditions will occur if cavern pressures are high enough. If cavern pressure levels are too small to cause choking then we have subcritical (subsonic) flow, the resultant pressure rise in the tunnel will be relatively 'local', and the pressure variations with distance along the tunnel will also be relatively mild. In such circumstances one would expect just local damage. Under supercritical conditions, there will be a transition from subsonic to supersonic flow 'across' the entrance, with a return to subsonic flow across an 'impulsive' shock which will propagate down the tunnel with little reduction in strength as it travels. Under such circumstances the damage will be more major and spread well beyond the cavern.

It would appear therefore that the best way to limit air blast damage is to ensure (if possible) that the maximum cavern pressure $p_c(t)$ and the tunnel area A_t conditions are such that the flow remains subsonic; equivalently subcritical at the tunnel entrance. We have seen that the cavern pressure $p_c(t)$ is strongly dependent on the permeability of the falling rock 'slab', which in turn depends on the compactness of the collapsing roof before (and more importantly after) collapse; perhaps this can be managed. Also by increasing the tunnel sectional area one might avoid criticality.

3.2.1 The critical tunnel area

We consider a flow tube running from the top of the cavern of sectional area A_c to the (single) tunnel entrance of area A_t, which we identify as the throat of our Laval nozzle. Under (steady state) isentropic conditions the conservation and state conditions yield explicit results for flow variables as a function of flow tube area A, and if one chooses sonic conditions as a datum then one obtains

$$(\frac{A}{A_t^\star})^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{(\gamma+1)/(\gamma-1)} \quad \text{where} \quad M = \frac{u}{a}$$

is the Mach number of the flow at the location corresponding area A, see Liepmann and Roshko [6] p126 (eqn (5.2)). Here, following Liepmann and Roshko, we have used the superscript * to denote critical (sonic) conditions, so criticality is obtained when $A = A^\star$, as yet unidentified.

Now if we assume conditions are such that criticality is obtained at the tunnel entrance, so $A_t = A^\star \equiv A_t^\star$, we can determine the associated conditions within the cavern by choosing $A = A_c$ (with associated flow variables $u = u_c, a = a_c$), which gives

$$(\frac{A_c}{A^\star})^2 = \frac{1}{M_c^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M_c^2\right)\right]^{(\gamma+1)/(\gamma-1)} \quad \text{where} \quad M_c = \frac{u_c(t)}{a_c(t)};$$

this determines the cavity conditions required for criticality (i.e. sonic conditions at the throat).

Now both the Mach number of flow in the cavern M_c, and the area ratio $A_t^\star/A_c$ are small, so that the above result can be approximated by

$$\frac{A_t^*}{A_c} = M_c\left[\frac{\gamma+1}{2}\right]^{(\gamma+1)/2(\gamma-1)} \approx \xi 1.73 M_c, \tag{15}$$

using $\gamma = 1.4$, and where ξ is a correction factor.

Aside: The correction factor ξ is introduced to account for the necking of streamlines near the sharp tunnel entrance corner; Laval nozzle theory assumes a rounded throat. This engineering correction factor needs to be obtained experimentally and although the correction is significant ($\xi \approx 0.6$ for the corresponding weir problem) the factor is primarily geometric so the results obtained are found to be robust.

For later purposes note that the associated (critical) flow variables at the tunnel entrance are given by

$$\frac{p_t^\star}{p_c} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} \approx 0.528, \text{ and } \frac{T_t^\star}{T_c} = \frac{a_t^{\star 2}}{a_c^2} = \frac{2}{\gamma+1} \approx 0.833, \text{ so } \frac{a_t^\star}{a_c} \approx 0.91 \tag{16}$$

(Liepmann and Roshko, equations (2.34-5) p 54), after again using $\gamma = 1.4$.

As indicated earlier the blast damage will likely be much less if the tunnel area exceeds the critical value A_t^* determined by (15), so the tunnel system may be designed to do this.

Assume we have the roof collapse situation described in Figure 4 with a 5 m by 5 m tunnel and a cavern of dimensions 20 m by 20 m, so $A_t/A_c \approx 0.06$. The rock speed is given by $\sqrt{2gL}$ where L is the drop. This gives (with $L = 10$m) approximately $u_c = 10$ m/sec past the higher tunnel and 60 m/sec past the lower one. Taking $a_c = 343$ m/sec (a slight underestimate) we obtain a critical area ratio given by $A_t^\star/A_c = 0.05\xi$ for the upper tunnel and 0.3ξ for the lower tunnel. Thus A_t/A_c is greater than the critical value for the upper tunnel and so shocks would not be expected. For the lower tunnel A_t/A_c is much less than the critical value so shocks are to be expected. Again one should recall that $\xi \approx 0.6$ and the flow velocities in the cavern are over estimates.

3.2.2 The shock strength

We will now confine our attention to circumstances in which the tunnel entrance (or throat) area is less than critical for the cavern conditions at time t. Now, providing the cavern pressure continues to increase, sonic conditions will be maintained at the throat and the results above (16) will track the changing flow state at the throat ($p_t^\star = 0.528 p_c(t)$ etc.). Thus, for example, the pressure at the throat will continue to increase in proportion to the changing cavern pressure. The through-flux will also increase.

The flow beyond the throat is supersonic so that (a) conditions within the cavern cannot be affected by flow conditions occurring within the tunnel and (b) the only input required for tunnel flow calculations are the flow conditions at the tunnel entrance, see (16), together with initial conditions. Given these initial conditions the solution can be determined numerically for any prescribed

$p_c(t)$, however simpler approximate results are more appropriate in context. Under the increasing cavern pressure conditions the shock strength and speed will increase. Stronger shocks travel faster than (and thus catch up to) slower shocks so that the eventual outcome will be a single (strong) shock travelling at the higher speed. In our situation the tunnel entry pressure reaches a maximum when the rocks pass the entrance so that the eventual strength and speed of the generated shock will be determined by this maximum pressure $p_t^* = 0.528 p_{cmax}$. After that the cavern pressure drops to zero so it makes sense to model the pressure input as a pulse of fixed strength $p_t^* = 0.528 p_{cmax}$ over a time interval of τ (the fall time). If one additionally assumes the initial state is quiescent, then the classical impulsive piston solution applies over the time interval τ (the piston speed is u_t). Over this time interval we simply have uniform conditions both behind and in front of a fixed speed shock. The shock strength is evidently given by

$$z = \frac{p_t^\star(t) - P_0}{P_0} \equiv \frac{0.0.528 p_{cmax}(t) - P_0}{P_0}, \tag{17}$$

see (16), and other results follow, see Whitham p174. The shock speed is given by a_t^* for a uniform tunnel, which is somewhat greater than the normal sound speed in air because of the higher temperatures in the chamber. Using the upper estimates for cavern pressure obtained earlier this gives shock strengths of order $z = (0.528 \times 16.8) - 1 = 7.8$ for the lower tunnel under impermeable falling slab conditions; this is certainly large enough to overturn vehicles in a tunnel.

After the time interval τ an expansion fan serves to reduce the shock strength to zero, so criticality is lost and there will be a subsonic flow recovery to normal. The details can be worked out but are of little interest in context. The important results are (15), which can be used to determine if shocks will be generated under particular scenarios, and (17), which can be used to determine the resulting shock strengths.

4 Shock abatement

As far as mitigating effects are concerned, the aim would be to absorb a sufficient amount of energy from the air blast to minimise damage to life and property.

There is very little mechanical energy loss across a shock wave (due to viscous dissipation), and even the entropy change across a shock is small for the moderate strength shocks of interest, see [5], p174. Also (turbulent) boundary layer losses for normal tunnels are small, so that long propagation distances are required to dissipate the shock energy, see MISG report (2006) [2].

The shock negotiates directional changes in the tunnel by shock/expansion fan combinations, with a small increase in mechanical energy loss due to boundary layer interaction with the shock, see Liepmann and Roshko [6] p 54, 342, Courant and Friedricks [4] p 176, and Whitham [5] p204. There is an associated change in the pressure profile along the tunnel (which would effect the destructiveness of the shock), however stronger shocks travel with greater speed than weaker ones so that after negotiating a corner or wedge the shocks that are formed later coalesce, so that the pressure profile recovers; however see below. Head on collisions (as can occur with a loop in the tunnel) do produce a complex arrangement of shocks and expansion fans (with associated local changes in the pressure profile) but do not result in significant energy reduction and again the profile regenerates, see Courant and Fredrichs [4]. Eddies can however be generated in corners resulting in mechanical energy dissipation; these effects are however reportedly small.

It can be seen from the above discussion that shock strength reduction is not easily achieved. Crude devices such as venting the tunnel to the surface or dropping a barrier are evidently prohibitively expensive. If there is a convenient tunnel to the surface then fine, but of course the location of the event causing the burst cannot be normally anticipated. There will be a reduction in energy due to the tunnel network partly because of a energy splitting but also because of the increased boundary layer dissipation and wedge effects. There has been effective modelling in this area, see Skews [8].

There are, however, a variety of practical methods that have been suggested for abatement in a military context but also a train tunnel context [12], and some of these are known to be effective. These include:

- Multiple shock interactions can be produced by introducing tight U or W shaped bends in the tunnel or by sudden tunnel area reductions. Oblique shocks are produced by the geometry and the accumulated effect of the many interactions is significant. Some numerical work has been done.

- A suggestion was made to construct an adjoining tunnel. It was later thought to be of limited value, essentially because the return air flow into the air blasted tunnel could be introduced after the main blast has already passed through the tunnel.

- Boundary layer interactions are increased by introducing closely spaced wall spikes. This procedure has been used for train tunnels. The effect of the spikes is to generate eddies and thus increase the effective boundary layer thickness.

- The introduction of particles or water droplets. The viscosity of the resulting mixture is changed so that dissipation across the shock increases. Evaporating water droplets also extract energy from the shock, see Schwer and Kailasanath[11]; likely a more effective procedure.

- A suggestion from the meeting was the use of an impermeable liner around and some distance (say $d = 1$m) from the tunnel walls. The liner may be either air filled of water filled. As the shock progresses the high pressure of the shock will press the liner against the wall thus generating flow between the wall and the liner in the process.

- A related method is the use of a foam lining, as reported by Fondaw [7]. Experiments were performed using a 20 cm layer of foam of 90% void (0.126 g/cm^3 in a 100 m, 1 m radius tunnel. A 70% reduction in the pressure pulse over a distance of 50 m was reported; lower density foams performed better. Pressures of roughly 2.4 atmospheres were produced using explosives. The liner may either temporarily absorb elastic energy, or may be sacrificial. Perforated liners have also been suggested.

- Drop down perforated barriers have been suggested. A gravity motion detector could be placed in the roof of the stopes which would give an early trigger and activate a slab, hinged to the roof of the tunnel, which would be pushed down and jammed on the tunnel floor and hence absorb a significant fraction of the blast. An adjoining cavity would suck and contain the air blast gases. It was suggested that the slab should be made of a strong, light-weight material which would be useful in the case of accidental triggering.

There was insufficient time to examine such abatement procedures, the most promising of which is the use of liners.

4.1 The effect of liners on shock strength

One would expect the primary effect of the liner would be to simply extract a known amount of energy (the elastically stored energy) from the travelling shock wave, but there may be more subtle effects (shock speed, strength etc), so a detailed analysis is appropriate:

As indicated above the pressure distribution behind the travelling shock due to the pressure pulse is uniform so one would expect the liner to be uniformly 'flattened' against the tunnel wall behind the travelling shock; the sectional area of the tunnel plus liner would change from A_2 ahead of the shock, to A_1 behind the shock due to compression of the liner described by

$$(p_1 - p_2) = k(A_2 - A_1),$$

where a passive (volumetric) elastic liner response is assumed. The conservation conditions across the shock become (see Liepmann and Roshko p56):

$$A_1(\rho_1 u_1) = A_2(\rho_2 u_2)$$

$$A_1(p_1 + \rho_1 u_1^2) = A_2(p_2 + \rho_2 u_2^2)$$

$$A_1(h_1 + u_1^2/2) + (k/2)(A_2 - A_1)^2 = A_2(h_2 + u_2^2/2),$$

The stored elastic energy in the liner will be a small to moderate proportion of the shock energy,and $A_1 - A_2 \ll A_1$, so approximations are possible. If we write $A_2 = A_1(1+\epsilon)$ then to first order the above equations can be approximated by

$$\rho_1 u_1 = \rho_2 u_2,$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2,$$

$$(h_1 + u_1^2/2) + \epsilon\,(k\,A_1) = (h_2 + u_2^2/2),$$

Thus the 'normal' mass and momentum equations are essentially unaltered so the Prandtl Meyer relation is unchanged, and the shock speed is only marginally modified. The pressure in the tunnel will be only marginally modified so the shock strength will be (only) marginally changed. The energy equation is of course where the interest lies; the absorbed energy per unit length along the tunnel will be small but is likely to be larger than (and additional to) the absorption due to normal boundary layer effects. An investigation is under way.

5 Conclusions

The models of the falling rock in the cavern indicate that the air blasts generated in tunnels high up in the cavern will be weak but major air blasts may occur in tunnels close to the cavern floor if the falling rock mass remains relatively consolidated.

In the absence of a full numerical gas-dynamic model of the roof collapse and the subsequent air blast into the working tunnel, the crude piston model predicts that it is very likely the air blast is preceded by a moderate to strong shock. For example, for piston Mach numbers of the order of 3 the shock Mach number is of order 4 with concomitant pressure, density and temperature ratios of 28, 5 and 4 respectively. See Figures 1, 2, and 3

In the Laval nozzle model an important role is played by the tunnel entrance in the physics. Equation (15) was derived for the critical tunnel area which can be used to determine if shocks will be generated. Equation (17) can be used to estimate the shock strength. Using upper estimates for cavern pressure, calculated assuming impermeable falling slab conditions, shock strengths of order 7.8 for the lower tunnel near the cavern floor were obtained which is large enough to cause considerable damage such as overturning vehicles in a tunnel.

Several suggestions were made to mitigate the effects of the blast wave. Attempts could be made to ensure that the roof of the cavern does not collapse as an impermeable falling slab but that there are gaps between the falling rocks. The effective tunnel area could be increased.

In the Laval nozzle model the blast wave damage will be much less if the tunnel area exceeds the critical value determined by equation (15). The energy of the shock could be dissipated by introducing tight U or W shaped bends in the tunnel. Boundary layer interactions with the shock could be increased by putting closely spaced spikes in the tunnel wall. The eddies generated by the spikes increase the effective thickness of the boundary layer. Impermeable liners some distance from the tunnel wall and filled with air or water could be used to dissipate energy. Light weight but strong drop down perforated barriers, triggered by a gravity motion detector, could be used to mitigate the effects of the blast wave.

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