ROCKBURST AND MUD

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Abstract

It has been observed that the presence of water or mud on the floor of a mining tunnel seems to reduce tunnel failure associated with remote seismic events. We examine two mechanisms that could explain this phenomenon. The investigations suggest that lubrication effects due to the presence of water within cracks could well affect the occurrence of spalling, and the results obtained suggest that coating the tunnel walls with moisture containing semi-liquid pastes may be effective for tunnel wall stabilization.

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1 Introduction

Rockbursts are explosive events caused by the build up of stress in the walls of mining tunnels. Either directly because of this buildup or because of impulses of seismic or mining origin, rocks are ejected from the tunnel walls, or concrete is broken and heaved. It has been observed that such events do not seem to occur in the presence of water or mud on the tunnel floor. The objective was to investigate various mechanisms that could explain this. It is not clear if the mud on the floor is responsible for the apparent changed

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behaviour or if the presence of the mud simply indicates wet conditions which may significantly effect behaviour (so mud is simply a symptom not the cause). Certainly wave speeds will be altered and reflection and transmission coefficients at interfaces (air to rock, saturated to unsaturated rock etc.) will be significantly changed by the presence of water so that the impact on tunnel walls will be altered. Waves might also be trapped within saturated rock zones and thus may be directed away from tunnel walls, and also there will be exchanges of energy between P and S waves which could strongly effect conditions at the tunnel face. Additionally rock failure is often associated with crack extension which may be effected by the presence of water. In short there are many possible mechanisms and insufficient available evidence at this stage to favor one over another, if indeed the observations are confirmed. After discussing possible mechanisms the group decided to investigate just two in any detail; elastic wave 'cushioning' due to presence of a mud layer, and lubricative suction within cracks.

2 Wave cushioning or trapping

A longitudinal elastic (P) wave propagates with greater speed from a source than a shear (S) wave and thus normally arrives first at a rock face. Furthermore the P wave subjects rock elements to more vigorous distortion than S waves or other combination waves, so that P waves are generally thought to be more destructive in the deep tunnel context of interest here. The situation is however complex in that P waves rarely occur in isolation, and if the wave source is remote and/or the tunnel relatively close to the surface then much of the received energy will be in surface (Rayleigh or Love) modes. However in view of the above comments it seems appropriate to first examine a simple P wave impact model.

A positive pressure pulse propagating through rock is reflected at a free surface as a tensile pulse, and because rock is weak under tension[1], the surface may rupture causing a rockburst. If, however, the rock surface is lined with a rigid material then such a positive pressure pulse will be reflected as a positive pulse so that the rock surface will not be subjected to tension; in this way the liner acts to protect the surface from such an impact. A layer of water or mud can be considered to act as a liner; the question is whether such

[1]The fracture strength of rock under tension is typically a factor of 10 less than that under compression

a liner could cushion the rock face sufficiently to avoid a rockburst. In fact the effect of liners of various types (thin spray-on liners (TSL's), concrete or steel) on dynamic stress levels at the rock face is also of interest in the mining context.

2.1 An impacting longitudinal wave

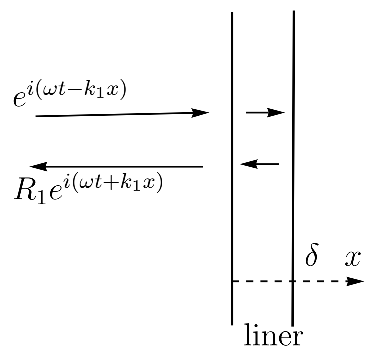

Figure 1: Elastic wave impact on a lined tunnel wall

If a longitudinal elastic wave travelling through rock impacts normally on an interface, see Figure 1, then both the transmitted and reflected waves will also be of longitudinal type, and the particle displacement satisfies the wave equation with wave speed

$$c = \sqrt{E(1-\nu)/(\rho(1+\nu)(1-2\nu))}\ ,$$

where E, ρ, ν are the Young's modulus, density and Poisson's ratio in the propagating materials [2]. If the impact is not normal then a shear wave will be generated at the interface, a much more complicated situation, see later.

We consider a longitudinal plane harmonic wave of unit amplitude and frequency ω impacting on liner of thickness δ. The 'liner', occupying the region $0 < x < \delta$, may be either a layer of water or mud, or in fact an elastic material. The liner is assumed to be 'welded' to the rock face and the external face of the liner forms the tunnel face. The wave is partially reflected at the rock/liner interface and partially transmitted. The transmitted wave is subsequently reflected at the liner/air interface and this wave is then reflected and transmitted at the liner/rock interface, etc. The effect of these successive reflections and transmissions is to produce a net reflected wave propagating back into the rock material, whose amplitude and phase will be determined by the relative material properties of the liner and rock. The particle displacement $u = u_1$ in the rock $x < 0$ and $u = u_2$ in the liner $0 < x < \delta$ is given by

$$u(x,t) = \begin{cases} u_1 = e^{i(\omega t - k_1 x)} + R_1 e^{i(\omega t + k_1 x)} & \text{for } x < 0 \\ u_2 = T_1(e^{i(\omega t - k_2 x)} + R_2 e^{i(\omega t + k_2 x)}) & \text{for } 0 < x < \delta \end{cases}, \tag{2.1}$$

where $k_1,\ k_2$ are the wave numbers in the rock and liner respectively corresponding to wave speeds of $c_1 = \omega/k_1$ and $c_2 = \omega/k_2$. The reflection and transmission coefficients R_1, R_2, T_1 need to be determined so that the normal stress on the air/liner interface $x = \delta$ is zero and displacement and stress continuity is assured across the rock/liner interface $x = 0$; explicitly we require

$$\frac{\partial u_2}{\partial x}(\delta, t) = 0, \quad u_1(0,t) = u_2(0,t)\ , \quad \mathcal{E}_1 \frac{\partial u_1}{\partial x}(0,t) = \mathcal{E}_2 \frac{\partial u_2}{\partial x}(0,t), \tag{2.2}$$

where $\mathcal{E}_1$, $\mathcal{E}_2$ are the effective Young's moduli for the rock and liner materials respectively:

$$\mathcal{E}_i = \frac{E_i(1-\nu_i)}{(1-2\nu_i)(1+\nu_i)}\ , \quad i = 1, 2.$$

The equations give

$$\frac{1 - R_1}{1 + R_1} = \imath \kappa_r \tan \delta_2\ , \qquad R_2 = \exp(-2\imath \delta_2), \tag{2.3}$$

where the dimensionless groups are

$$\kappa_r = \frac{k_2 \mathcal{E}_2}{k_1 \mathcal{E}_1} \equiv \frac{c_2 \rho_2}{c_1 \rho_1}, \qquad \delta_2 = k_2 \delta \equiv \omega \delta / c_2; \tag{2.4}$$

a *propagation parameter* and a liner *effective thickness parameter* determine the effect of the liner on the reflection characteristics.

Solving for the reflection coefficient we obtain

$$R_1 = \exp(\imath \alpha),\ \text{where}\ \tan \alpha = \frac{-2\kappa_r \tan \delta_2}{1 - \kappa_r^2 \tan^2(\delta_2)}. \tag{2.5}$$

Thus the amplitude of the reflected wave in the rock is the same as that of the incident wave and the effect of the liner is simply to cause a phase shift α. Our model assumes loss-less media so that this result may have been anticipated. Note that the effective thickness of the liner tends to zero as $\alpha \to 0$ and $R_1 \to +1$, so that we recover the rock/air interface result and the liner offers no protection to the rock face.

2.2 Parameter values

The effective thickness parameter δ_r is the ratio of the liner thickness to the wavelength in the liner material. Seismic waves are of typical periods 20 sec and waves speeds in water are 320 m/sec so that wave lengths of the order of 1000 m are typical giving $\delta_2 \approx 10^{-4}$ (very small) even for liner thicknesses of order 1 m, see [4]. Vibrations in the auditory range are produced by equipment or explosives on the mining site. For a frequency of 100 cycles/sec (lower end of the audible range) the wave length is about 3 m; so $\delta_2 \approx 0.1$. Typically $\rho_2/\rho_1 \approx 0.3$ and $c_2/c_1 \approx 0.1$ for water/rock ratio so that $k_r \approx 0.03$. Thus, from (2.5), for 'mud liners' the induced phase shift is given approximately by

$$\alpha \approx -2k_r\delta_2,$$

and is very small, if not negligible, even for vibrations in the auditory range. The solution corresponding to an impacting pulse can be generated by the superposition of waves of the above type. The phase shift is frequency dependent so that the reflected pulse will be slightly different in shape to the incoming pulse, but again one can only conclude that a mud liner will not cushion the rock face against an impacting pulse.

impacts at any other angle then reflected S and P waves will be generated at the liner/rock interface and the transmitted wave will be of P type. This transmitted wave will subsequently be reflected at the air interface and

If the incident P wave is non-normally incident on an interface then reflected P and S waves will be generated at the interface and a P wave will be transmitted. If the angle of incidence is greater than a critical value then a Rayleigh wave will be produced traveling along the rock/liner interface. Evidently such directional effects will reduce the amplitudes of the transmitted and eflected waves at the liner/rock interface, however at most the liner could only cushion the rock face against impacts within small angle ranges, so are unlikely to be generally effective. For more details see Tolstoy [3] and

Segel [2].

The propagation parameter will only be of unit order for relatively rigid liners; such liners may be effective for high frequency events of mining origin.

2.3 Conclusions

It was found that a normally incident P wave experienced a phase change as a result of impact on a water liner, the size of which depends on two dimensionless combination of parameters, one related to the liner thickness and frequency of incoming wave and the other related to the relative propagation and mechanical characteristics of the liner and the rock. For mud liners such effects were negligible so that wave cushioning can be ruled out as a possible mechanism for reduced rock burst observations. A more likely mechanism is wave trapping or channeling associated with saturated zones close to the tunnel walls.

3 A suction model

Naturally occurring rock is heavily fractured as a result of past crustal movements. The effect of an impulse can be to rupture remaining connections between an individual block of rock and the surrounding rock wall so that this block of rock is ejected from the wall, floor or ceiling. Furthermore the structural integrity of the tunnel can be compromised as a result of the dislodgment, so that the tunnel may collapse. Water present in the tunnel may penetrate into the thin fractures (gravitationally and/or surface tension driven) and the resultant thin lubricating layer may provide strong resistance (suction) to separation between the rock and the surrounding wall, a lubrication effect. In this way the rock burst may be avoided. A model is developed to assess this effect, see Figure 2. In this model we have a mass M supported by (weak) elastic springs on a table. Under equilibrium conditions the gap between the table and the mass is h_0 (so $Mg = kh_0$). The table oscillates with frequency ω and amplitude H_0, so that

$$H(t) = \bar{H} + H_0 \sin \omega t, \tag{3.1}$$

where $H(t)$ is the height above a prescribed datum. If the oscillation is sufficiently vigorous the supporting 'springs' will break and the weight will not return to its resting position. If however there is a thin lubricating layer of water (thickness $h(t)$) and length $2L$ and *fixed* depth Z (into the page))

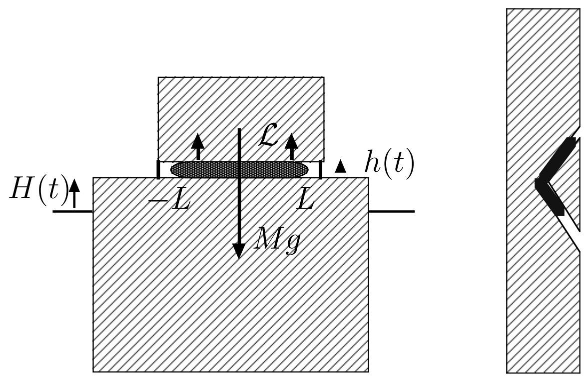

Figure 2: Left: the oscillating table model. Right: a wall rock burst.

separating the mass from the table, then the suction generated within this layer may reduce the motion sufficiently to prevent separation. The mass represents a rock lump which is tenouusly attached to the rock floor (the weak elastic springs). The gap (or crack) between the rock (mass) and the wall is filled with water. The surface area of contact S between the water layer and the two rock faces corresponds to a contact of length $2L$ and fixed width in the table model. Since the width Z is fixed in the table case the water layer will only expand and contract in the x direction; the flow will be unidirectional. In practice the rock will be 'wedge shaped' and the gap will not be uniform and the flow will be more cylindrical. Full contact between the rock faces will occur at isolated resting points or points of attachment (the elastic springs); we assume the flow will not be greatly hindered by such obstructions. The length scale of impacting waves is generally much larger than the dimensions of the tunnel, let alone the rocks that break away from the tunnel walls or floor, so that the impinging wave is accurately modeled by a wall (or table) oscillation.

The equation of motion of the mass (rock) is:

$$M(\ddot{H} + \ddot{h}) = \mathcal{L} - F_0 \,, \tag{3.2}$$

where the elastic restoring force F_0 is given by

$$F_0 = kh(t) - Mg = k(h_0 - h), \tag{3.3}$$

$h_0 = Mg/k$ is the equilibrium gap size, and the quasi-steady total upward force due to the lubricating layer is given by

$$\mathcal{L} = \int_S p(x, y, t)dxdy \tag{3.4}$$

and in the one-dimensional flow case by

$$\mathcal{L} = Z \int_{-L}^{L} p(x, t)dx \ :$$

p is the pressure exerted by the water layer on the mass. These equations model the movement of a rock attached to either the floor, the walls or the roof of the tunnel (as in Figure 2 Right). For structural reasons detachment from the supporting walls is likely to be more critical.

3.1 The lubricating layer force

The effect of the oscillation is to cause the water layer to be sucked backwards and forwards between the rock faces generating the lubrication force on the rock mass as it does so. The total volume V_0 of the lubricating layer remains fixed. For simplicity we will consider the situation in which the gap under the rock is uniform and horizontal.

The (quasi-static) pressure distribution within the lubricating squeeze layer in the general case is governed by Poisson's equation

$$p_{xx} + p_{yy} = \left[\frac{12\mu}{h^3}\frac{dh}{dt}\right] \text{ in } \mathcal{S}, \tag{3.5}$$

with

$$p = 0 \text{ around the boundary } \partial\mathcal{S},$$

where $\mathcal{S}$ is the 'surface' of water/rock contact, see [1]. In the fixed depth lubricating layer table case of Figure 2 Left (the parallel flow case)

$$p(x, t) = -\frac{(x^2 - L^2)}{2}\left[\frac{12\mu}{h^3}\frac{dh}{dt}\right], \tag{3.6}$$

so that

$$\mathcal{L} = -\frac{2}{3} Z L^3 \left[\frac{12\mu}{h^3} \frac{dh}{dt} \right], \tag{3.7}$$

and since the volume of water $V_0 = Z(2L(t))h(t)$ remains fixed (with Z also fixed) we see that

$$\mathcal{L} = -\frac{\mu \dot{h}(t) V_0^3}{Z^2 h^6(t)} = -K_1 \frac{\dot{h}(t)}{h^6(t)} \text{ (say)}; \tag{3.8}$$

it is this very strong dependence of the lubrication force on the layer thickness (for small thicknesses) that underlies the physics of lubrication. In the purely cylindrically flow case $p(x, y, t) = p(r, t)$ and (3.5) integrates to give

$$p(r,t) = -(r^2 - R_0^2) \left[\frac{12\mu}{h^3} \frac{dh}{dt} \right], \tag{3.9}$$

so that

$$\mathcal{L} = -\frac{\pi}{8} R_0^4 \left[\frac{12\mu}{h^3} \frac{dh}{dt} \right], \tag{3.10}$$

where R_0 is the radius of the water layer. In this case $V_0 = \pi R_0^2 h(t)$, so that

$$\mathcal{L} = -\frac{3\mu \dot{h}(t) V_0^2}{2h^5(t)\pi} = -K_2 \frac{\dot{h}(t)}{h^5(t)} \text{ (say)}; \tag{3.11}$$

significantly the dependence of the strength of the lubrication force for small layer thicknesses is reduced from that obtained in the unidirectional flow case because the flow is now less constrained. Both situations are likely to occur in practice. We will work with the unidirectional flow case here; the cylindrical flow case results are very similar.

3.2 Parameter values

For present estimates we will consider a cylinder of granite of radius 20 cm and thickness 15 cm. Such a rock would weigh 52 kg (the density of granite is 2.75 gm/cm^3) and its dislodgment from a tunnel wall could well cause a significant rock burst. If the induced suction force to weight ratio

$$\| \frac{\mathcal{L}}{(Mg)} \| = \frac{3\mu \dot{h}(t) V_0^2}{2h^5(t)\pi M g}$$

for this rock is of unit order then one would expect lubricative forces to significantly effect dislodgment (dynamic details later). The strength of the lubricative force increases linearly with rock speed and dramatically with gap thickness h. If we take rock speed as 1m/sec as being typical of mining induced rock wall speeds and a gap of 1mm, then this ratio is 14.8; that is, lubrication forces *much* larger than gravitational forces are possible! Seismic induced rock particle velocities are likely to be more of the order of 10 cm/sec; for such speeds the ratio is of unit order. Cracks smaller than 1mm are perhaps more usual, so that lubricative forces can be much larger, although the attachment force (modelled by the spring) is also likely to be greater for thin cracks. The conclusion is that if water is present within the cracks then lubricative forces will certainly be significant.

Returning to the dynamics of the semi-detached block's motion as contained in (3.2) it is convenient to introduce the scales

$$t = t'/\omega, \qquad H = H_0 H'(t'), \qquad h = H_0 h'(t').$$

It should be appreciated that the amplitude of the vibration would be normally much greater than the water layer thickness, so this choice is something of a geometric/physics compromise; the lubrication force is very strongly gap size dependent and so the size of the above coefficient underestimates $\mathcal{L}$. Working with the 1D flow case this leads to the dimensionless description

$$\ddot{h} + \eta(h - h_0) + \xi \frac{\dot{h}}{h^6} = \sin t \ , \quad t > 0, \tag{3.12}$$

where primes have been dropped and where the dimensionless groups are

$$\eta = \frac{k}{M\omega^2} \ , \qquad \xi = \frac{K_1}{M H_0^6 \omega}.$$

The parameter η is the ratio of the natural frequency of vibration associated with the rock wall/rock (spring) attachment to the frequency of vibration of the table. We will assume the rock is weakly attached so that $\eta \ll 1$. The parameter ξ measures the ratio of the lubricative force on the mass to the force exerted by the table movement; as indicated earlier this is strongly dependent on the initial gap size. For purpose of illustration we will use $\eta = 0.01$, and $\xi = 0.1$. We examine the situation in which

$$h(0) = h_0, \qquad h'(0) = 1,$$

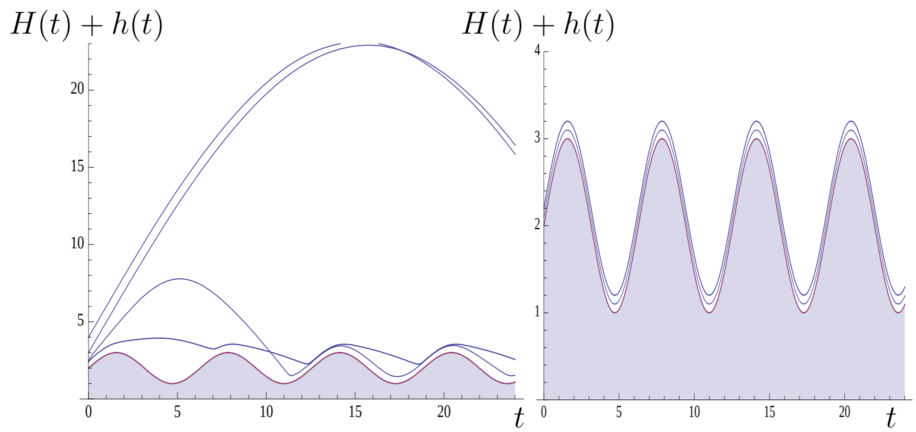

Figure 3: Lubrication effects: the displacement $h(t) + H(t)$ of the rock under the action of different thickness water layers. Left: $h_0 = 0.3, 0.4, 0.5, 1, 2$. Right: $h = 0.1, 0.2, 0.3$ (with expanded vertical scale). The rock face (or table) position $H(t)$ is shaded. The parameter values are $\eta = 0.01$ and $\xi = 0.1$.

so that the mass (rock) is initially moving with the table (wall). Given the above parameters we expect lubricative forces to be relatively small for h_0 of unit order and becoming larger as h_0 reduces; the initial layer thickness h_0 thus provides a useful parameter for displaying the effect of gap thickness on the dynamics. In the absence of the lubricating layer the mass will immediately separate from the table moving with the initial table (or wall) speed, however eventually (with this spring model) the restoring force will return the mass to its equilibrium position. In practice the connection may be broken and the rock will dislodge. This can be seen in Figure 3 (Left) for $h_0 = 1$ and $h_0 = 2$ where the table (wall) position and rock trajectory are plotted; evidently the lubricating layer has very little effect for such gap sizes. For small values of h_0 ($h_0 < 0.3$) the rock will remain 'attached' to the wall, see Figure 3 (Right). For values of $0.5 > h_0 > 0.3$ one sees an evolving behaviour in which the lubrication layer partially prevents separation. The detailed behaviour in this range depends on the relative size of the restoring force as expressed in η. Evidently detachment may not occur within this gap range if the oscillation is not sustained; a detailed analysis will not be undertaken here.

3.3 Conclusions

It was found that suction forces due to the presence of a water layer in rock cracks can be very large for thin cracks and this will act to inhibit rockburst damage. This could well provide an explanation for the observed effect of moisture on rock bursts. Of course rock bursts are spasmodic so checking out this explanation in the field is not a trivial matter, however, it is a simple matter to experimentally check out the mechanism described; our experience with lubrication engineering suggests that the mechanism will work if indeed water fills the cracks. Under such circumstances the main issue is whether water will penetrate into cracks and will remain there.

4 Final remarks

Two possible explanations for the observations of reduced rock burst activity were examined. Wave propagation cushioning associated with a mud 'liner' was rejected, but wave trapping associated with water layers within the rock face could direct waves away from tunnels. Lubrication suction due to the presence of water in cracks is however a real possibility; in fact certainly such effects are of sufficient magnitude and they will act to help prevent rock burst damage. This work raises the possibility of using a semi-liquid paste to stabilize tunnel walls. It should be noted that for different reasons (solid) TSL's have also been shown to be effective for stabilization, so a semi-liquid paste may combine both beneficial features.

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