Effect of Dynamic Loading on Stability of Longwall Gate Roads

E. Westman, C. Haycocks, and M. Karmis
Department of Mining and Minerals Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061 USA

Abstract: In underground coal mines sudden failure of either the seam or a stiff member in the roof or floor (termed a coal bump) can result in a dynamic load propagating outward and causing extended failure of the pillars and supports. Wu (1995) showed that, based on elastic beam theory, the strain energy produced in a coal bump could be determined analytically. This paper presents a simplified method, based on Wu's analytical solution, for estimating potential bump magnitudes when mining in bump prone areas. Given a potential bump magnitude, two approaches are outlined for determining the effect of the dynamic load on the pillars and supports. The first method incorporates a maximum peak particle velocity causing damage and quantifies the radius to which this extends. The second approach considers the normal force generated by the dynamic load. This normal force is superimposed on the existing static loads borne by the pillars and supports. The effectiveness of the methods is shown with three case studies from U.S. longwall mines.

Key Words: coal bumps, magnitude, dynamic loading, pillar performance

Introduction

Kusznir and Farmer (1983) defined a coal bump as a brittle failure associated with high stresses, low confinement, and strong rocks. Coal bumps have resulted in numerous fatalities historically, and continue to cause fatal accidents. In addition to the health and safety concerns, economic losses due to lost production are typically tens of thousands of dollars per day that a longwall face is inactive.

Numerous factors have been stated to influence the occurrence of bumps, including properties of the coal, geology (joints, folds, faults, etc.), mining induced stresses, strong sandstone beds in the roof, pillar size and shape, mining technique, and mining rate (Holland, 1958, Whittaker, 1983, Iannacchione et al., 1987, Arabasz et al., 1997). Haramy and McDonnell (1988) emphasized that the energy released in a bump is from accumulated strain energy in the coal, roof, or floor. Strain energy accumulates in the strata as a result of deflection under abutment stresses. The roof strata deflect either by bridging or cantilevering. Failure of the coal is termed a "pressure" bump, while failure of the roof is termed a "shock" bump (Ricc, 1936).

The energy associated with a bump can be quantified in terms of magnitude. Several different magnitude scales exist, with the most common being the local, or Richter, magnitude and the moment magnitude (Richter, 1935, Kanamori, 1977). The advantage of the moment magnitude is that it is directly related to the failure mechanics as it is a function of the modulus of rigidity of the rock and the size of the failure. The local magnitude is more commonly used, however becomes inaccurate at magnitudes greater than 6.5 (Nuttli and Herrmann, 1982). Because mining-induced
seismicity rarely exceeds magnitudes of 4.5, the local magnitude will be used in this paper.

Wu (1994) showed that, based on elastic beam theory, the strain energy per unit width stored in the roof and foundation (coal and floor) could be calculated for either bridging or cantilevering beds, given the following parameters:

- roof thickness, elastic modulus (tensile and compressive), and effective tensile strength,
- coal thickness, compressive strength, elastic modulus, and Poisson’s ratio,
- overburden depth and specific gravity
- face width,
- abutment stress concentration factor,
- stress concentration length, and
- seismic efficiency.

The equations developed by Wu, while shown to be reasonably accurate in several case studies, were so complicated that a computer program was developed to allow their implementation (Karfakis et al., 1996).

While many of the parameters in the analysis are easily understood, several are not, such as the stress concentration factor. This is the ratio of the maximum forward abutment stress to the virgin stress. This has been shown to vary from 2 to 7.5 when the sandstone layer is directly on the coal seam, but approaches 1 if the sandstone layer is more than 30 m above the coal seam (Song et al., 1982). The stress concentration length is the horizontal distance in which the forward abutment stresses are concentrated. This value is typically between 0.1 to 0.4 times the overburden thickness (Haramy and Kneisley, 1989). The seismic efficiency is the amount of strain energy that is released as seismic energy rather than heat. For South African gold mines, this value has been found to be as low as 0.0024 (McGarr, 1976) with an average value of 0.06 from laboratory experiments (Mendecki, 1997).

The goal of this paper is to present simplified methods for estimating potential bump magnitudes when mining in a bump prone area and the effect of the dynamic load on the pillars and support.

**Development Of Equation For Local Magnitude**

To develop a simplified equation relating expected bump magnitude to the various parameters used by Wu, a simple parametric analysis was performed. The parameters used and their values are shown in Table 1. Many of the values used came from a statistical summary of physical properties of bump prone coals by Maleki et al. (1997). Although Wu’s solution allowed multiple roof layers, analyses were only conducted for a strong roof immediately overlying the coal seam. Analyses were run for both bridging and cantilevering; only bridging required the horizontal stress as input.

Multiple linear regression was performed on the results of the parametric analysis to develop an equation for magnitude. The regression results showed that local
Table 1: Parameters and values used in parametric analysis to develop simplified equation for calculating expected bump magnitude.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof elastic modulus (GPa)</td>
<td>13, 27</td>
<td>Overburden depth (m)</td>
<td>365, 635</td>
</tr>
<tr>
<td>Roof thickness (m)</td>
<td>5, 15</td>
<td>Stress concentration factor</td>
<td>2, 6</td>
</tr>
<tr>
<td>Roof tensile strength (MPa)</td>
<td>13, 21</td>
<td>Horizontal stress (MPa)</td>
<td>6.5, 20.5</td>
</tr>
<tr>
<td>Coal elastic modulus (GPa)</td>
<td>3.3</td>
<td>Width of working face (m)</td>
<td>170</td>
</tr>
<tr>
<td>Coal compressive strength (MPa)</td>
<td>17, 27</td>
<td>Specific weight of overburden (N/m²)</td>
<td>25000</td>
</tr>
<tr>
<td>Coal Poisson’s ratio</td>
<td>0.25</td>
<td>Stress concentration length (m)</td>
<td>Depth/10</td>
</tr>
<tr>
<td>Coal thickness (m)</td>
<td>2</td>
<td>Seismic efficiency</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Magnitude expected for various conditions can be calculated for bridging beds as:

\[
M_L = 1.65 - 0.00989E + 0.0518t + 0.0197T_o + 0.000110d + 0.0802c + 0.0195\sigma_h \\
\text{Eqn. 1}
\]

and for cantilevering beds as:

\[
M_L = 0.956 + 0.00151E + 0.0131t + 0.00601T_o + 0.00142d + 0.0867c \\
\text{Eqn. 2}
\]

where $E$ is the elastic modulus of the sandstone (GPa),
$t$ is the thickness of the sandstone (m),
$T_o$ is the tensile strength of the sandstone (MPa),
d is the overburden depth (m),
c is the stress concentration factor, and
$\sigma_h$ is the horizontal stress (MPa).

To determine the relevance of various parameters to the equation a best subsets regression was conducted. Table 2 shows the coefficient of determination ($R^2$) for both bridging and cantilevering, using various parameters. For cantilevering, a coefficient of determination of 96.7 was achieved by including the sandstone thickness, overburden depth, and stress concentration factor; if only sandstone thickness and overburden depth are used the coefficient of determination is 56.1. For bridging, a coefficient of determination of 92.8 is achieved using sandstone thickness and tensile strength, stress concentration factor, and horizontal stress. A very approximate result ($R^2$ of 52.9) can be obtained by using only the sandstone thickness.

Simplified expressions for estimating expected local magnitude when mining in bump prone conditions have been developed. Very good agreement can be achieve between the relationships (Eqns. 1 & 2) and Wu’s analytical solutions. When all parameters required by the equations are not known, or cannot be accurately judged, it is recommended that average values, as defined by Maleki et al. (1997) be used.
Table 2: Results of Best Subsets Regression, showing relevance of parameters and associated coefficient of determination ($R^2$).

<table>
<thead>
<tr>
<th>Cantilevering</th>
<th>Coefficient of Determination ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden depth</td>
<td>X</td>
</tr>
<tr>
<td>Stress concentration factor</td>
<td>X</td>
</tr>
<tr>
<td>Roof thickness</td>
<td>X</td>
</tr>
<tr>
<td>Roof tensile strength</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>50.2</td>
</tr>
<tr>
<td></td>
<td>56.1</td>
</tr>
<tr>
<td></td>
<td>90.9</td>
</tr>
<tr>
<td></td>
<td>91.7</td>
</tr>
<tr>
<td></td>
<td>96.7</td>
</tr>
<tr>
<td></td>
<td>97.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bridging</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof thickness</td>
<td>X</td>
</tr>
<tr>
<td>Stress concentration factor</td>
<td>X</td>
</tr>
<tr>
<td>Horizontal stress</td>
<td>X</td>
</tr>
<tr>
<td>Roof tensile strength</td>
<td>X</td>
</tr>
<tr>
<td>Roof elastic modulus</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>52.9</td>
</tr>
<tr>
<td></td>
<td>73.2</td>
</tr>
<tr>
<td></td>
<td>78.1</td>
</tr>
<tr>
<td></td>
<td>87.9</td>
</tr>
<tr>
<td></td>
<td>92.8</td>
</tr>
<tr>
<td></td>
<td>96.6</td>
</tr>
</tbody>
</table>

Support Performance Under Dynamic Loading

Underground coal mines depend not only on the pillars to support the roof, but also incorporate several types of support, which can fall into internal and external classifications. Internal supports include roof bolts and cable bolts. External supports include cribs, timbers, and other various secondary supports. The effect of the dynamic load from a bump will be briefly discussed for pillars and supports.

Pillar Performance

Several factors affect the relationship between bump magnitude and pillar performance. As seismic energy is radiated from the focal point it is attenuated both with distance and by the material through which it is traveling. A special condition exists at a free surface, such as a mine opening underground. Persson et al. (1994 p. 247) assume that the peak particle velocity of a point near a free surface is double that of a point within a rockmass. The effect of a the high stress rate of a dynamic load must also be considered. Goodman (1989 p. 215) reports the work of several researchers who show that the ultimate strength of a rock mass may be nearly doubled by increasing the stress rate by four orders of magnitude.

Pillar failure caused by a bump can be related most accurately to peak particle velocity (Naismith, 1984). Ortlepp’s review (1993) showed that damage occurred when peak particle velocity exceeded anywhere from 0.075 to 4 m/sec. The local magnitude has been empirically related to peak particle velocity at a distance for South African gold mines by McGarr et al. (1981) (McGarr p 208) as:

$$\log Rv = -0.05 + 0.57 M_l$$

Eqn. 3

where $R$ is the distance from the bump (m), $v$ is the peak particle velocity (m/sec), and $M_l$ is the local magnitude.
As this relationship was developed empirically it includes the effects of the free surface and the higher stress rate. The drawback to this method is that an accurate definition of peak particle velocity required for failure has not been developed for longwall mines.

**Support Performance**

Wagner (1984) provided an evaluation of support performance under dynamic loading in South African gold mines. He developed relationships between support stiffness, hump magnitude, and distance from source for several different types of supports by analyzing the amount of work done by the support for increasing displacements. He emphasized four factors for an effective support under dynamic loads:

1) it must be able to yield at closure rates of 2 to 3 m/sec,
2) it must be able to handle convergences of 60 mm,
3) it must have a minimum support resistance of 100 kN/m²,
4) it must be able to maintain the integrity of the opening during yield.

Support performance can also be evaluated by converting the peak particle velocity to a load, and considering the effect of the load on the support structure. Persson et al. (1994 p. 247) state that a plane sinusoidal stress wave exerts a stress equal to:

\[ \sigma = (\nu E) v_m^{-1} \]

Eqn. 4

where \( \sigma \) is the stress level (MPa),
\( \nu \) is peak particle velocity (m/sec),
\( E \) is the elastic modulus of the rockmass (MPa), and
\( v_m \) is the velocity of the seismic wave through the rockmass (m/sec).

As the greatest damage is likely associated with the shear wave, a velocity (\( v_m \)) of 3,000 m/sec is typical for coal measure sandstones or shales.

The dynamic loads applied to the supports are superimposed on the previously existing static loads. Several evaluations of support performance have been published. Barczak and Molinda (1996) published force vs. displacement charts for various of wood cribs and also evaluated alternative secondary supports including cables, confined core cribs, propsetters, wood posts, and others. The disadvantage of the approach is that it may be difficult to accurately determine the existing static loads on the supports.

**Case Studies**

Three case studies are examined to compare the damage measured at the site from a coal bump to the damage estimated using the equation from Wu's analytical solution. All three mines are located in the United States and are retreating longwalls. The peak particle velocity technique (Equation 3) was used to estimate damage radius rather than the support load technique (Equation 4). Input parameters for the three case studies are given in Table 3. In each of the three cases very little description of support performance is given, so pillar performance will be examined.
Case Study One

Campoli et al. (1990) describe a longwall in southwest Virginia which had bump problems. The seam height averaged 1.7 m, and the over varied between 360 and 670 m. In the area that the bumps occurred, the immediate roof was a siltstone between 10 and 15 m thick. Overlying the siltstone, the main roof was a very competent sandstone between 60 and 70 m thick. The mine floor was a competent siltstone and sandstone. Horizontal stresses were found to be 23.4 MPa at N 76° E and 11.0 MPa at N 16° W. The mine used a four-entry yield-abutment-yield pillar configuration. The bumps occurred well beyond the first break, so that the cantilevering equation is more appropriate than the bridging equation.

Table 3: Parameters used in case studies and results obtained.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case Study 1</th>
<th>Case Study 2</th>
<th>Case Study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden depth (m)</td>
<td>410</td>
<td>800</td>
<td>360</td>
</tr>
<tr>
<td>Roof thickness (m)</td>
<td>60</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>Roof elastic modulus (GPa)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Roof tensile strength (MPa)</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Stress concentration factor</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Observed damage radius (m)</td>
<td>80</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>Calculated damage radius (m)</td>
<td>71</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>Calculated local magnitude</td>
<td>2.8</td>
<td>3.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Using Equation 2 with a 410 m overburden depth, 60 m thick sandstone layer, and average values for the other parameters (from Table 1), a local magnitude of 2.8 is calculated for a likely bump at the mine. Using this value in Equation 3, it is calculated that a damage-inducing peak particle velocity of 0.5 m/s, which is reasonable for a highly stressed tailgate, extends for a radius of 71 meters.

At the site, it was determined that the bump was centered at the abutment pillar nearest the face. Coal was expelled from the two yield pillars and two abutment pillars outby the face. Inby the face, damage could be observed to the first abutment pillar, but because of access limitations, no other observations could be made. A radius of damage of approximately 80 m observed at the site agrees well with the value calculated using equations 2 and 3.

Case Study Two

The second case study was a western longwall in the Book Cliffs coalfield of central Utah (DeMarco et al., 1995). The mine used a two-entry system with a yield pillar. The seam was under 800 m of cover and a 55 m thick sandstone layer formed the main roof. The bump occurred in the headgate while the pillar was in the process of
yielding. DeMarco et al. document excessive to severe bumping in the pillars near the site as the face approached. The main bump ejected coal from two pillars into the gateroads and damaged several cribs. As with the first case study, the face had advanced well beyond the first break of the main roof, so that the main roof was cantilevering.

By incorporating the cover depth and sandstone thickness into Equation 2, along with average values as given in Table 1, a local magnitude of 3.3 was calculated for the bump. As the bump was in the headgate, where the pillars were more competent than in the tailgate, a peak particle velocity of 3 m/sec was estimated to cause pillar damage. Using this value in Equation 3 it was calculated that the radius of damage is 22 m. The pillars at this site were 17 m wide by 32 m long. As two pillars were damaged, the radius of damage agrees reasonably well with that calculated from Equation 3.

Case Study Three

Zelanko and Heasley (1995) describe a bump event at a southeastern Kentucky longwall. The bump occurred in the tailgate. The mine used a three-entry yield abutment design, with the yield pillar adjacent to the active panel in the tailgate. At the site, the seam was under 360 m of cover and the main roof was a 10 m thick sandstone channel which the face had recently come under. As with the initial two case studies, the main roof was cantilevering into the gob.

Using Equation 2 with the described cover depth and sandstone thickness, and average values from Table 1 for the other parameters, a local magnitude of 2.1 is calculated. As the bump occurred in the tailgate, a peak particle velocity of 0.5 m/s is used in Equation 3, as with the first case study, resulting in a damage radius of 27 m. At the site at least two pillars outby the face were damaged. As the pillars were 30 m long, if the bump were centered between the two pillars, the calculated damage radius agrees with the observed damage.

Conclusions

When mining in bump prone conditions, an equation has been developed based on Wu's (1995) analytical solution which estimates the local (Richter) magnitude which can be expected at the site, for either bridging or cantilevering conditions. Results of the equation closely match Wu's analytical results. An equation relating local magnitude to damage radius caused by a maximum peak particle velocity is also presented. A brief description is given of the stress caused by a dynamic load, and its effect on support structure. Three case studies show the usefulness of the relationships for estimating damage radius.

Although the results of the case studies agree well with those calculated from the equations, future research should verify the relationship expressed in Equation 3 for longwall coal mines, as the constants were generated using data from South African gold mines. Additionally, appropriate peak particle velocities should be established for causing damage under various conditions. Finally, a better understanding of the
performance of primary and secondary support under dynamic loading should be investigated for longwall mines.

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