Coal Bumps and Odd Dynamic Phenomena - A Numerical Investigation

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ABSTRACT

The Crandall Canyon accident investigation included an interesting and unexplained observation by rescuers that the "barrier rib had shifted northward as a unit, as much as 10 feet." This is not the first mention of such a movement, although such reports are rare. Historical accounts describe unusual movement and displacement of intact coal, cribs and timbers. Two movements of particular interest are the creation of gaps above coal pillars and falling of standing support elements without apparent damage. A dynamic boundary element program was used to explore movements induced by slip on geologic features removed from the affected panel. While the resulting models are much too simple to fully replicate these observations, they do show that the types of phenomena observed are possible. They can also provide insight into the types of motions that ground support elements are subjected to during large bump events. This was demonstrated for the case of a large bump in a Book Cliffs coal mine. Seismic information suggested the source mechanism to be normal slip on a fault. A model of that source showed initial dilation of the panel followed by dynamic compression and rebound – consistent with underground observations. The initial dilation is important as it may allow slender standing support to shift or fall.

INTRODUCTION

Dynamic motion of mine roof and floor during a major dynamic failure event, often called a bump or bounce, is of considerable interest to mine safety research at the National Institute for Occupational Safety and Health. This is for two reasons. First, these motions may provide insight into location and mechanism of the event. While recent investigations have benefited from impressive advances in satellite subsidence and seismic monitoring (e.g. Gates et al., 2008), there is still a paucity of information available during both rescue and investigation.   Second, the physical hazard of many events is posed by the interaction of these motions with the coal seam and support elements. Some motions may degrade support protection or even exacerbate the hazard, a concern raised in a recent Department of Labor investigation (Teaster and Pavlovich, 2008). Thus, a fuller understanding of these motions may provide important clues for improving the selection and design of support subject to dynamic loading.

This work builds on an observation from a deep South African reef gold mine – that energy-absorbing props were found laying on the floor, intact, after a rockburst (Napier, 2009). Loken (1992) used a dynamic boundary element program to follow the complex dynamic response to a sudden extension of an idealized stope or panel. This response includes both body and surface waves. In an idealized model of this case, Loken showed that a net dilation (vertical expansion) precedes closure at certain locations in the panel. Such a motion unloads props, allowing them to fall over – especially if installed at an angle in a dipping panel or stope.

This study extends this method of dynamic analysis to events driven by slip on geologic features. The paper starts with a review of dynamic phenomena that have been observed in coal mines. An attempt is made to infer surface movements, and the sequence of movements, that might cause the observed phenomena. A simple dynamic boundary element program is then described. The program simulates production of body waves by simple ground motions including slip, the travel of these waves through the ground and the conversion of body waves to surface waves at the surface of mine openings. Finally, a simple case study is analyzed to demonstrate use of the model.

ODD OBSERVATIONS AND INFERRED MOTIONS

A small number of observations of odd dynamic phenomena have been reported in association with dynamic failure events in a few mines. The rarity of these observations suggests that the phenomena are also rare, or at least observers rarely report them. Another interpretation is that observers may have been confused by events. However, recent reporting of such an observation in the Crandall Canyon investigation (Gates et al., 2008) suggests that, even if rare, these phenomena are real and important. Observations from throughout North America were collected and are summarized here in a roughly chronological order.

Johnson Colliery

Ashmead (1924) reports observations from the Johnson Colliery, an Anthracite mine.   Generally, he states that "men who have been at work in a section where a bump or shock took place state that anything and everything in the direct line of the bump is destroyed.

The direction of the force is marked. One man was walking along his room and had one foot in the air in the act of taking a step forward when a bump occurred. The only blow that he felt was one administered to the foot that was raised in taking the forward step. His leg was broken but no other part of his body was injured."

Ashmead also provides detailed descriptions, including sketches, from three specific incidents. These are:

1. Two men were mining a pillar when a bump occurred. The rescue party found the "roof, floor and ribs, so far as visual indications were concerned, in their normal conditions, but the cogs, instead of being 10 ft. apart were only 3 ½ ft apart yet were intact." (Figure 1) Track running between the cogs (packs) was nearly on edge. Further mining revealed a "channel or crevice 5 ft wide at the top and about 2 ft wide at the bottom" within the pillar.
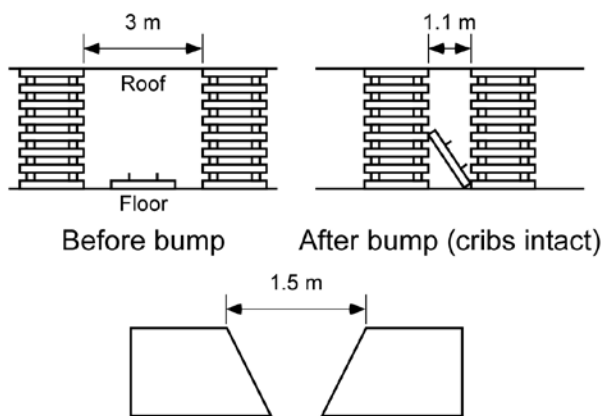

Figure 1. Displacement of packs and track attributed to a bump event that also appeared to have created a 1.5 m split in a pillar (after Ashmead, 1924).

2. Men were loading a car during pillar mining. After the accident the "roof, floor and ribs appeared to be in normal condition." However, one miner was found lying on top of the car "where he had evidently been thrown," and died as a result.

3. A miner was driving a gangway through a pillar when a bump occurred. Reportedly, "the roof, the floor and the ribs were apparently normal, but the end of the mine track was sticking up in the air and the miner lying under it."

Coronado Mine, 1924

Rice (1924) also recounts observations from the Coronado Mine in Washington State. These include what he called "two remarkable manifestations of wave motion." These are:

1. "the roof was not broken yet a timber crib had been moved from the upper side of the entry to the lower side and was intact and tight to the roof"

2. "at the lower side rib, over the coal which had been crushed down 4 or 5 inches, there was a space between it and the solid roof which extended in 3 or 4 ft."

Springhill No. 2 Mine

Rice (1924), in a detailed history of bumps at the Springhill No. 2 Mine, includes an account from a bord "where a pack or crib 7 feet high made of 4 foot sticks had been built on the high side [of an entry driven on strike]. After the bump, this crib was found tight against the low side with not a stick displaced."

Herd (1930) described district bumps that "caused large-scale destruction of the levels ahead of the longwall face but no damage to the face itself." In each case, the "lower part of the coal seam was extruded bodily up-dip into the upper level."

McCall (1934) updated Herd's descriptions of Springhill Mine observations, including particular instances. In the first (Figure 2), "all east side chocks in this place have been moved about two feet westward." Also, with few exceptions, "individual sticks have not been displaced." Finally, "the booms and the collar boom which supports the booms between chocks have not moved but the lower portion has moved as a unit." In the second location, this same event displaced empty and full mine cars without other damage (Figure 3).
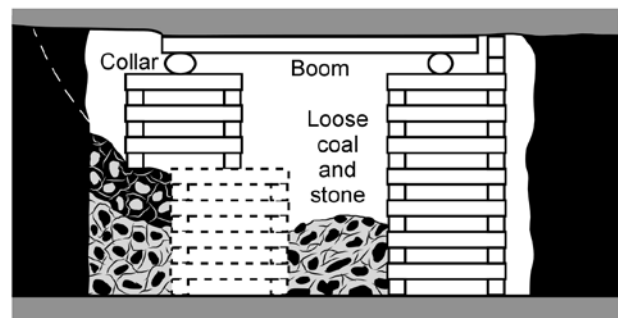

Figure 2. Section of a timber pack displaced as a unit during a coal bump (after McCall, 1934).

Notley (1980) describes two unusual phenomena observed during the long history of bumping at Springhill (with reference to some of the observations described above). Both occurred with minimal roof disturbance. These are:

1. "a sudden extrusion into the mine openings of solid sections of the coal seam"

2. "bodily movement of timber packs without disturbing their structure"

In the case of movement of intact blocks of coal, Notley elaborated further, describing how the top 14 inches of coal usually remained attached to the roof and that separation occurred along a well-defined parting in the coal seam. In addition, the "displaced coal often retained its structure, requiring as much cutting force in recovery operations as in original mining."

Greene (2003) provides a historical account of the 1958 bump disaster. This account includes description of a miner's arm becoming entrapped in a timber pack during the event. According to Greene (p. 50), the pack "bounced apart and then came together
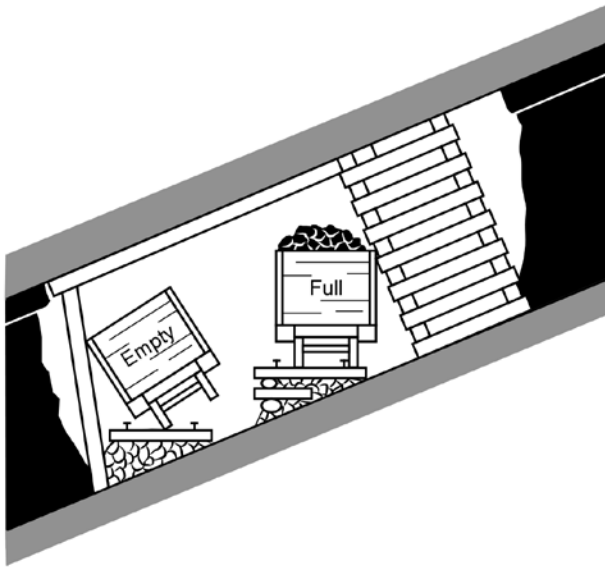
Figure 3. Displacement of mine cars by a coal bump (after McCall, 1934).

with Rector's elbow area flattened between two beams" of the recompressed pack.

Book Cliffs, 1993

Boler et al., (1997) investigated a 1993 failure event in the Book Cliffs Coal Mining District of Utah that produced a 3.6 magnitude seismic event. Underground, the bump destroyed several pillars. Coal expelled from pillars filled entries and partially buried miners. After the bump, "pillars were crushed and became piles of broken coal, such that over the entire damaged pillar array there was no longer any contact between roof and crushed pillars. The roof remained substantially intact and suspended above the pillar array with negligible closure (p. 21)." Timber support was also observed to be affected as follows:

"Support timbers were broken in compression, maintaining roof-to-floor contact and indicating roof-to-floor convergence of a few centimeters (estimated from photographs of support timbers that were broken in compression). Support timbers were displaced relative to wedges that hold them in place indicative of roof-to-floor shearing motion or roof-to-floor vertical opening that allowed timbers to partially fall and retrap. With roof-to-floor shearing, neighboring timbers might be expected to show consistent orientation of horizontal offset. Because neighboring timbers were observed to show random directions of horizontal (if any) motion, the vertical opening with retrap scenario is more likely."

Crandall Canyon, 2007

Gates et al., (2008) reported observations made during efforts to re-establish the No. 1 Entry. The first of these was that "as loading advanced inby crosscut 123, rescuers observed that part of the barrier south of the No. 1 entry had moved northward as a result of the August 6 ground failure. The barrier rib had shifted northward as a unit, as much as 10 feet. In some areas, the displaced barrier slid along the immediate roof and tore loose the original roof mesh"

(see Figure 4). "In other areas, the immediate roof was carried northward and damaged the original installed roof bolts" (Figures 4 and 5).

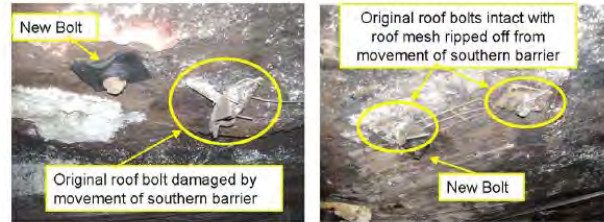**Figure 4. Damaged roof bolts and torn mesh after August 6 accident resulting from northward movement of southern barrier (after Gates et al., 2008).**

Figure 5. Damaged roof bolts in No. 1 entry after August 6 accident resulting from northern movement of southern barrier. Mesh shown was installed during rescueoperations, over damaged original bolts. Camera view is indicated by arrow in index map insert (after Gates et al., 2008).

One crosscut further inby (#124), the condition of displaced coal is described as follows (p. 23 of Gates et al., 2008). "The No. 1 entry was packed with rubble the full width and height of the original mined opening. The continuous mining machine was loading from a rubble pile that resembled an unmined coal face."

Movements may have continued during the rescue operation. An observation in one inspector's notebook "following a bounce that occurred on August 15th, that it appeared that the tops and bottoms of the Rocprops had moved" was reported by Teaster and Pavlovich (2008).

Gate et al., (p. 27) described a "void up to 20 feet deep into pillar at the roof line" (see Figures 6 and 7) created by the bump that ended rescue efforts. Gates et al., also mention that "coal was thrown violently across the No. 1 entry." And finally, that this "dislodged coal threw eight RocProps, steel cables, chain-link fence, and a steel channel toward the left side of the entry, striking rescue workers and filling the entry with about four feet of debris." One injured miner was found "entangled in chain-link fencing."
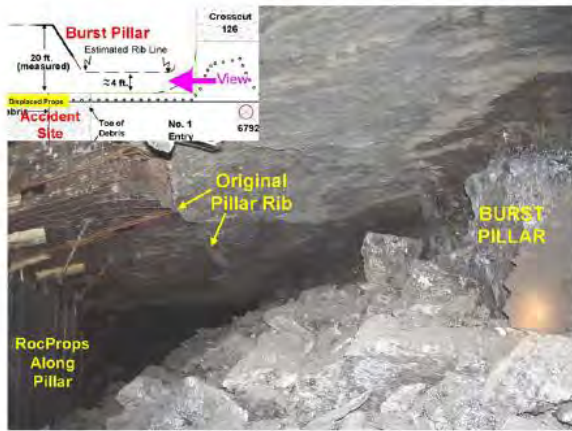
Figure 6. Damage to outby portion of pillar on right side of No. 1 entry, outby August 16 accident site (After Gates et al., 2008).

Figure 7. 20-ft deep void over pillar on right side of No. 1 entry following August 16 accident (After Gates et al., 2008).

Interpretation

These observations are difficult to fully interpret and many appear to have confounded observers. However, a few key characteristics of ground response to dynamic failure are evident. These characteristics are "provisional" at this point, because they are based on a small number of observations; and also because these motions, and their necessary conditions, are poorly understood. These characteristic motions include the following.

- Dynamic Closure and Gaps

First, and most common, is overshooting of seam closure where roof is strong and remains intact. The full dynamic compressive load drives failure in the coal and/or floor that effectively shortens segments of coal seam, leaving a gap between coal and roof upon rebound.

- Dynamic Opening and Slender Support

Observations of props falling over in a South African gold that motivated this work are similar to reports from coal mines, particularly the Book Cliffs event (Boler et al., 1997) and possibly, props in the Crandall Canyon rescue event. Standing support that will not stand without axial loading appears to be vulnerable to any surface motion that includes dilation of the mined opening.

- Dynamic Lateral Movements

A number of observations include lateral movement of objects. In many cases such movement is unlikely to be noted as the original position is uncertain. However, movement of rail cars relative to (and off) the track is a clear indication, although such movements are likely accompanied by vertical motion.

- Complex Dynamic Motions

More complex motions, including sequences of lateral and vertical motions, are likely needed to explain movement of objects in contact with roof and floor, including packs and intact sections of coal seam. Clearly, dilation is needed to remove clamping and thereby frictional forces that would resist movement and disorder the moving object. Downward movement of the floor as part of this dilation would help explain how clamping due to object weight might be removed and how a timber pack might open up. Lateral movements immediately before dilation might impart a lateral velocity. Regardless, though, an adequate explanation of such complex motion rests on an understanding of the simpler motions described above.

DYNAMIC BOUNDARY ELEMENT MODEL

This study simulated observed surface motions of coal seam roof and floor as a linear elastic problem in dynamics. In such a problem, movement is instigated by simple source, like shear on a plane (fault). The effect of the disturbance is traced through an elastic, homogeneous medium containing mine openings. The simulation includes both body waves propagating between source and coal panel, and surface waves propagating along the surfaces, primarily roof and floor, of the panel. As such, the simulation entirely ignores geology. However, it is three-dimensional since sources are locations, not lines, and may be located randomly with respect to a panel.

The boundary element method (BEM) chosen has two distinct advantages over volume-based (finite element and finite difference) methods for these highly idealized simulations. First, BEM requires discretization of source and mine surfaces only – not the entire rock mass volume – a significant shortcut in both formulating and solving problems. Second, the BEM formulation automatically satisfies the correct boundary conditions at infinity (radiation conditions) without further formulations (dynamic boundaries).

The FORTRAN BEM program SLIP (Loken, 1992) was resurrected, updated and revised for this project. This program is a numerical implementation of Maruyama's three-dimensional displacement discontinuity solution in elastodynamics (Maruyama, 1963). The program was developed for the Chamber of Mines Research Organization in the 1990's to investigate rock burst behavior in deep underground mines in South Africa. The program is capable of investigating elastodynamic effects from a variety of

sources, including point, crack, and volume sources in an infinite domain. The program was modified to include the following features (1) inclusion of traction free surface elements so that body waves produced by remote dynamic sources become surface waves, (2) extension of boundary types and shapes (stopes and/or cracks using quadrilaterals and triangles), (3) estimation of failure at prescribed locations, and (4) video sequences of time-space output results in prescribed "field-point" windows.

TEST CASE: INFERRED MOTIONS AND POSSIBLE SOURCES

The Book Cliffs case study by Boler et al., 1997, reviewed previously, provides a convenient test case. Seismic records analyzed by Boler et al., indicated slip on a normal fault somewhere above the damaged panel, most likely in the overlying Castlegate Sandstone, was the most likely cause (Figure 8).
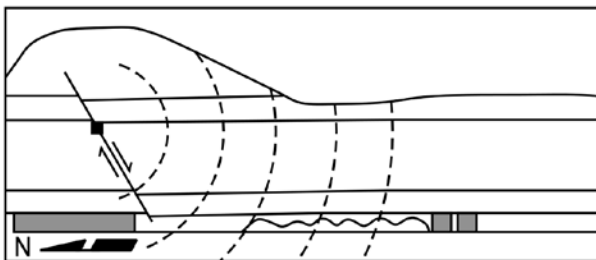

Figure 8. Preferred failure mechanism for the Book Cliffs mine case proposed by Boler et al., (1997).

A simple model of this geometry was formulated, consisting of a slip surface with a sudden shear displacement and a simple panel without pillars (Figure 9). The assumed material properties of the elastic medium were: mass density $\rho = 2700$ kg/m^3, longitudinal wave velocity $\alpha = 5367$ m/s, and transverse wave velocity $\beta = 3267$ m/s. The boundaries of the fault surface and the mined opening were approximated by equally-sized square boundary elements of dimension 3 m by 3 m. A 1 m slip was assumed. While this value is relatively large, it's convenient for scaling results to any desired slip magnitude. That is, a 10 cm slip would realize 10% of the modeled motion. The total simulation time was 0.5 s, using 200 time steps of equal time step length (0.025 s).

The calculated relative displacement history (closure) at the center of the panel is plotted in Figure 10. It consists of an initial dilation followed by closure to a short-lived maximum and then rebound to the static closure value. Dilation, or opening of the panel, is roughly 15% of maximum dynamic closure and nearly half the resulting static closure. Relative horizontal displacement (ride) is also plotted. Ride is very small during initial dilation but is significant at later times.

This pattern correlates well with the in-mine observations reviewed earlier. Recapping, these were (1) dilation of the coal seam that temporarily freed timber props without strong lateral movement and (2) dynamic compression of pillars by an elastic roof that rebounded from its maximum closure, leaving a gap between pillar remnant and roof. Boler et al.'s inference that movement between timbers and wedges indicated dilation before compressive "retrapping" of the timber-wedge column is consistent with figure 11; thus the model captures both the observed behavior and their inferred order of occurrence. The sensitivity of this result
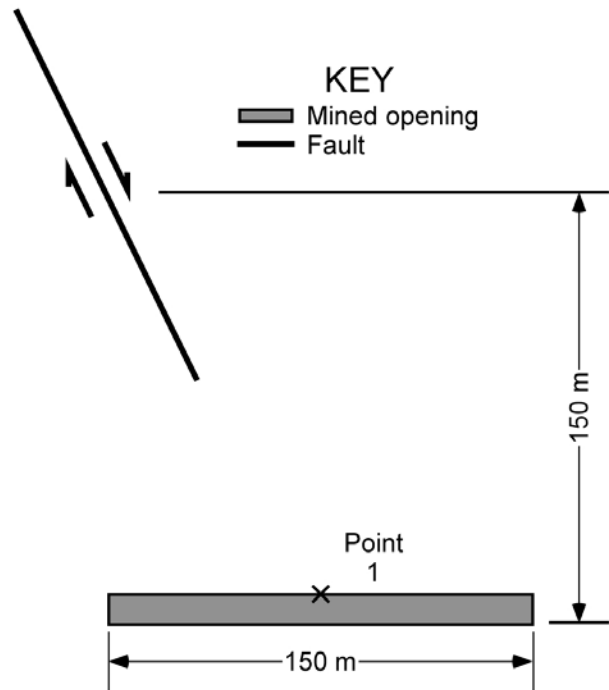

Figure 9. Simplified model geometry. Closure was tracked at point #1, located at the midpoint of the panel.
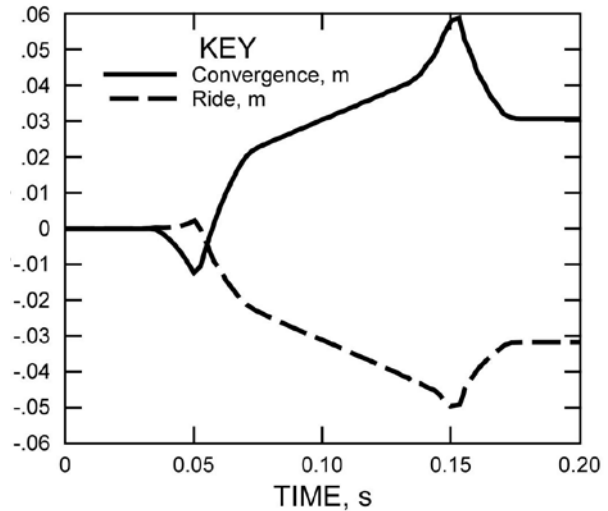

Figure 10. Calculated dynamic closure and ride (relative lateral displacement) between roof and floor at mid-panel.

to changes in the location, orientation and sense of slip is being examined.

SUMMARY AND CONCLUSIONS

This review of odd observations of dynamic behavior during coal bumps showed there are consistencies, despite the apparent fantastical nature of some accounts. Carefully documented cases from the Book Cliffs and Crandall Canyon provide added credence

to historical descriptions. The existence of these cases may encourage increased reporting of similar phenomena.

A dynamic boundary element program was developed to examine these phenomena. While the full complexity of these movements has yet to be modeled, a simple model of one case succeeded in showing that the proposed normal fault slip mechanism (based on analysis of seismic data) was consistent with underground observations. These observations include apparent movement of timbers relative to wedges – suggesting a period of initial dilation – and creation of spaces above crushed pillars – consistent with dynamic closure of the seam followed by rebound. These movements are also consistent with a number of the other cases reviewed.

Commonalities in historical cases and initial computational results suggest that these odd dynamic observations, including apparent movement of intact barrier pillar remnants at Crandall Canyon, cannot be discounted. Indeed, they may provide important insight and constraint to source mechanisms. They also provide insight into complex dynamic loading that may be exerted on mine support. One aspect of this loading, the possibility of net dilation of the panel, is particularly important to the performance of support that relies on clamping forces for stability, like slender standing support. Such support is inappropriate for some dynamic failure mechanisms and mine geometries. The full range of such conditions remains to be defined.

Ongoing work is aimed at improving modeling capabilities and simulating more complex movements. It aims to confirm the validity of more of these odd observations. It also aims to explore what these observations imply about source mechanisms, damage mechanisms, and appropriate design of dynamic support elements.

REFERENCES

Ashmead, D. (1924). Bumps and Shocks Disturb Johnson Colliery. Coal Age, November 6, 1924. pp. 641-643.

Boler, F., S. Billington and R. Zipf (1997). Seismological and energy balance constraints on the mechanism of a catastrophic bump in the Book Cliffs Coal Mining District, Utah, USA. Int. J Rock Mech. Min. Sci. Vol. 34, No. 1, pp. 27-43.

Gates, R., M. Gauna, T. Morley, J. O'Donnell, Jr., G. Smith, T. Watkins, C. Weaver and J. Zelanko (2008). Report of Investigation — Fatal Underground Coal Burst Accidents, August 6 and 16, 2007, Crandall Canyon Mine, Genwal Resources Inc, Huntington, Emery County, Utah. Department of Labor, Mine Safety and Health Administration, ID No. 42-01715, 472 pp.

Greene, M. (2003). Last Man Out: The Story of the Springhill Mine Disaster. Harcourt, NY, 342 pp.

Herd, W. (1930). Bumps in No. 2 Mine, Springhill, Nova Scotia. AIME Trans., 88, 151-191.

Loken, M. (1992). A Three-Dimensional Boundary Element Method for Linear Elastodynamics. Ph.D. thesis, University of Minnesota, 237 pp.

Maruyama, T. (1963). On the Force Equivalents of Dynamical Elastic Dislocations with Reference to the Earthquake Mechanism. Bulletin of the Earthquake Research Institute, Vol. 41, pp. 467-486.

McCall, T. (1934). Further Notes on Bumps in No. 2 Mine, Springhill, Nova Scotia", AIME Trans., Vol. 108, pp. 41-70.

Napier, J. (2009). Personal Communications.

Notley, K. (1980). Analysis of the Springhill Mine Disaster (October 23, 1958), Ph.D. dissertation, Queen's University, 185 pp.

Rice, G. (1924). Occurrence of Bumps in the Springhill No. 2 Mine of the Dominion Coal Company, Limited, Department of Public Works, Nova Scotia, Office of King's Printer, Halifax, Nova Scotia, 78 pp.

Teaster, E. and J. Pavlovich (2008). Independent Review of MSHA's Actions at Crandall Canyon Mine Genwal Resources, Incorporated Huntington, Emery County, Utah. Mine Safety and Health Administration report, 46 pp. Available at: http://www.msha.gov/CCreview/CrandallCanyonIRComplete.pdf