Dynamic Failure in Deep Coal: Recent Trends and a Path Forward

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ABSTRACT

Mining coal in deep, gassy strata is difficult, particularly in deep mines of the west. Dynamic failure (bumps, bounces, etc.) is commonplace, particularly where strong sandstone strata are encountered in the overburden. The disaster potential posed by dynamic failure in these mines is examined and found to be significant. Recent trends in MSHA reportable bumping of deep western coal mines have been increasing. Recent clusters of bumps are explored, a number of which have ended badly. The mechanisms of these bumps and their interactions with geologic structures are explored. Significant progress in controlling these hazards depends on a full understanding of their interaction with geologic conditions. It is apparent that not all MSHA reportable bumps have the same mechanism. These reports describe bumping of pillars, rolling of ribs, outbursts of coal, heaving of floor, shaking-induced roof falls, etc. Progress depends on understanding the underlying mechanisms of these events, and then determining which are potentially active at a particular location. Designs and other protective measures can then be adapted and deployed appropriately. Explicit consideration of mechanisms also supports extrapolation beyond experience as design extends into new mine geometries, geologies, mining methods and increasing depth. Finally, the goal should not be only to design hazard out of mines, but also to provide assurance that this, in fact, has occurred. Pursuit of this goal has been taken up by a major NIOSH research project. The centerpiece of this project is development of a Dynamic Failure Control Program to monitor evolution of dynamic failure hazards with changing geologic conditions to assure that control and protective measures are appropriately deployed.

INTRODUCTION

The potential for fatal injury and disaster posed by dynamic failure in deep coal mines has concerned researchers at the National Institute for Occupational Safety and Health (NIOSH). This concern led to a research proposal entitled "Dynamic Failure Control Program for Deep Coal" that was completed on August 1st of 2007. Of course, this concern was all too quickly realized in the tragedy of Crandall Canyon. This paper presents an overview of the trends and dynamic failure mechanisms that focused this concern, and the path forward. NIOSH has since initiated a major research project based on this proposal.

Dynamic failure

Mining at depth necessarily includes yielding of the host geology. Yield often occurs in a controlled manner, but can also occur dynamically, releasing seismic energy. As a matter of custom, dynamic failures are called bumps or bounces, depending on local usage. Sudden failures that expel large quantities of rock, coal or gas are called rock bursts, coal outbursts and gas outbursts, respectively. In addition, seismic energy released by a dynamic failure may cause additional damage in insufficiently reinforced areas, sometimes called "shakedown damage." Terminology varies widely with locale and may include the terms shock bump, district bump, mountain bump, pillar bump, face bump, etc. These terms have a variable and at times, tenuous, link to a specific failure mechanism that varies with locale. MSHA reporting requirements are based on the impact of events, uniformly called bumps, with no reference to mechanism. This paper follows terminology used by the original source in reviewing past events, but the more general term "dynamic failure" is used for discussion.

Experience gained through many sectors of the mining industry has shown that dynamic failures can be classified into three broad classes based on mechanics. These are: (1) brittle failure of the immediate margin of an opening that expels material into the opening (outbursts); (2) brittle failure of an entire pillar; and (3) failure of strata in the roof or floor, including rock remote from the opening. Damage can be direct and/or through seismic shaking. The importance of this classification is that each of these mechanisms interacts differently with mine geology, ground support systems, mine design and active hazard reduction measures. In fact, it is possible that measures taken to control hazards from one mechanism will be ineffectual, or even counterproductive, in controlling hazards from another.

Dynamic failure of deep mines is a longstanding hazard that figures prominently in historical disasters. In additional to physical trauma, dynamic failure in underground coal mines can release large quantities of gas, destroy ventilation controls, and provide an ignition source – both directly and through damage to equipment. Asphyxiation and gas poisoning are also a threat. While disasters are relatively rare, incidents involving damage to ventilation controls, disruption of mining, injuries and fatalities in coal mines are not.

Thus, maintaining control of the yield process and its consequences is essential for mining safely, especially as yielding increases with depth. The maximum depth of mining for modern shield-based longwall systems was reported as 900 m (3000 ft) over 25 years ago (1). This limit is rarely breached to this day, in part because of dynamic failure hazards.

Dynamic failure and deep coal mining

Recently, an increasing number of dynamic failures in deep mines of Colorado and Utah have caused injuries or disrupted the mine sufficiently to be defined as MSHA-reportable coal bumps (figure 1). This increase occurred despite a relatively flat level of production. Still, these bumps represent only a very small portion of the dynamic ground failure events detected by seismic monitoring systems. Dynamic ground failure is a common feature of underground coal mining, especially for longwall mining in the west (2; 3). Many of these have released sufficient seismic energy to appear on earthquake monitoring networks, some with magnitudes in excess of 4.0 (figure 2).

The potential for disaster associated with dynamic ground failure is difficult to ascertain, and most of the dynamic failures captured in figure 2 posed little threat to miners, and had virtually no disaster potential. In fact, many of these occur as caving of strata shifts stress from panels to gob, a shift that works to reduce bump hazard. Some others, however, do represent a potential hazard but that potential does not correlate with the amount of seismic energy released. Historical cases show that the disaster potential can be significant and can take a variety of forms. These include both direct impact and creation of an explosive atmosphere through gas release and damage to the ventilation system. Damage to ventilation disrupts removal of methane, potentially creating an explosive atmosphere regardless of whether the event releases additional methane.

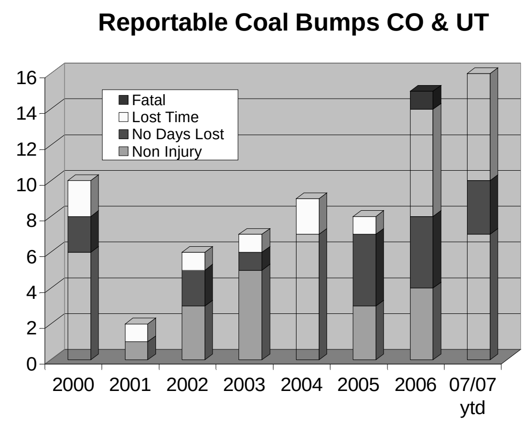


Figure 1. Recent reportable dynamic failure accidents and incidents for 14 deep longwall coal mines in Utah and Colorado.

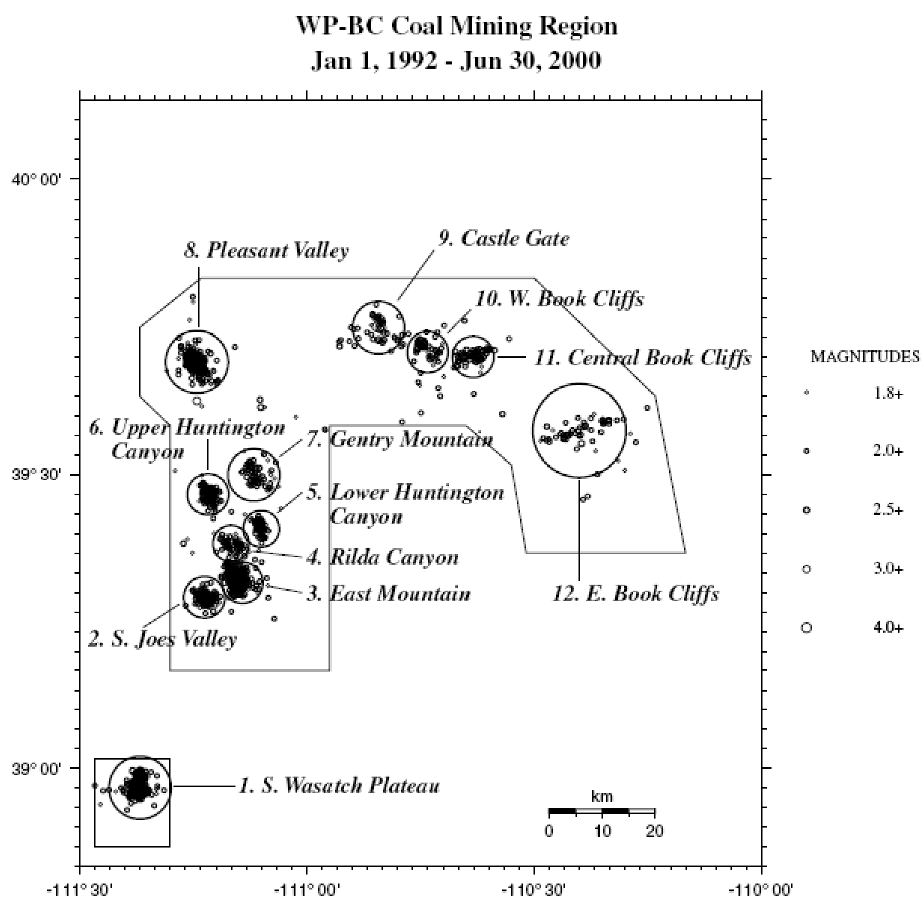


Figure 2. Concentrations of mining-related seismic events with magnitude 1.8 and greater in the Wasatch Plateau and Book

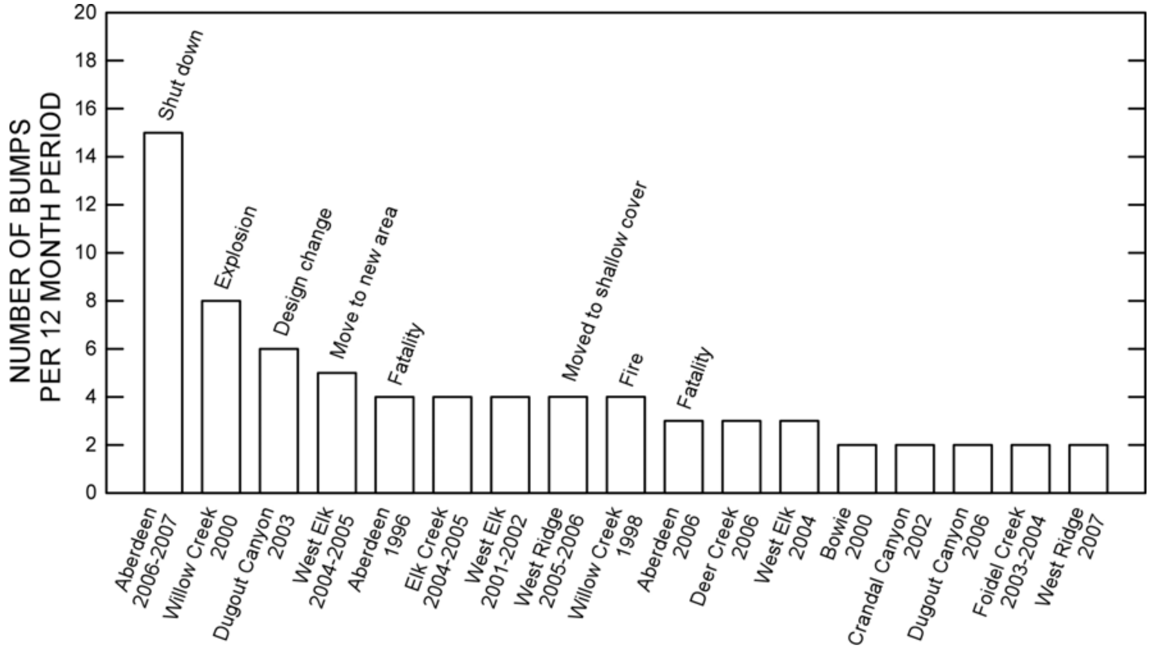


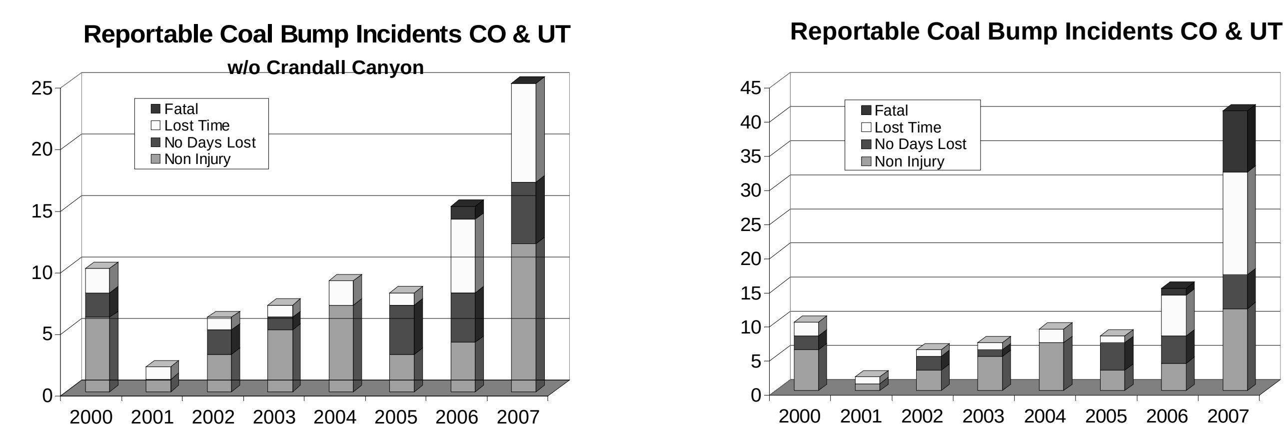
Figure 3. Reportable bumps grouped into clusters by mine and 12-month period through July of 2007.

These bumps have tended to occur in clusters as particular mines encounter challenging mining conditions (figure 3). Clusters are identified as 2 or more reportable bumps occurring within a 12-month period. Of these clusters, the largest recently ended with closure of the Aberdeen mine. Among the remaining 6 clusters of three or more events since 1999, 2 ended without apparent incident, 2 ended with a design change or move to a new area, 1 ended with a fatal accident, and 1 with a fire and explosion. Clusters also preceded two earlier instances, the 1998 Willow Creek fire and the 1996 fatal bump accident at Aberdeen.

Bumps continue to occur, as do their impacts on industry. Figure 4 contains updated versions of Figure 1 that show the continuing escalation of bumping, including, in figure 4B, the Crandall Canyon tragedy.

Dynamic failures pose a variety of hazards. Direct impact is, of course, a primary threat. For instance, two fatal accidents at the Aberdeen mine (1996 and 2006) occurred as outbursts of coal from the longwall face (figure 5). Such outbursts are not isolated instance – accounting for many of the MSHA-reportable bumps reviewed. Many outbursts are not included as their impact did not rise to reportable thresholds. In some cases, this may have been a matter of luck.

Direct impact injuries from massive strata failures, as opposed to local outbursts, have been comparably rare but can have more widespread impact. The Springhill Mine, Nova Scotia Disaster of 1958 is a well documented example (4; 5). That disaster involved sudden failure of massive strata around three adjacent longwall panels (450 m [1500 ft] total width) retreating under 1325 m (4350 ft) of overburden. Bumping at the mine had been common, beginning at an overburden depth of about 610 m (2000 ft), but had increased exponentially prior to the disaster (figure 6). Injuries rose dramatically as well; 26 injuries from 12 bumps over 26 years (1932 through March, 1958) to 49 injuries from 16 bumps in the 6 months prior to the disaster. The panels had been carefully aligned in June and July, in an attempt to reduce



A **B**

Figure 4. An update to figure 2 to the end of 2007 (A) without and (B) with the Crandall Canyon disaster.

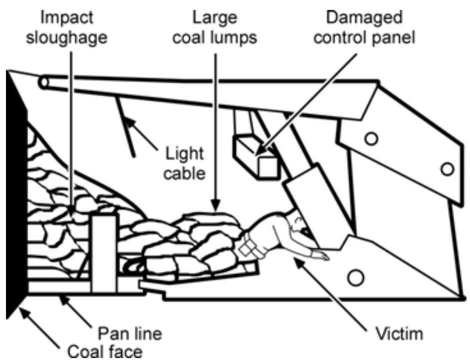


Figure 5. Fatal injury from coal outburst at the Aberdeen mine (MSHA fatalgram, 1996).

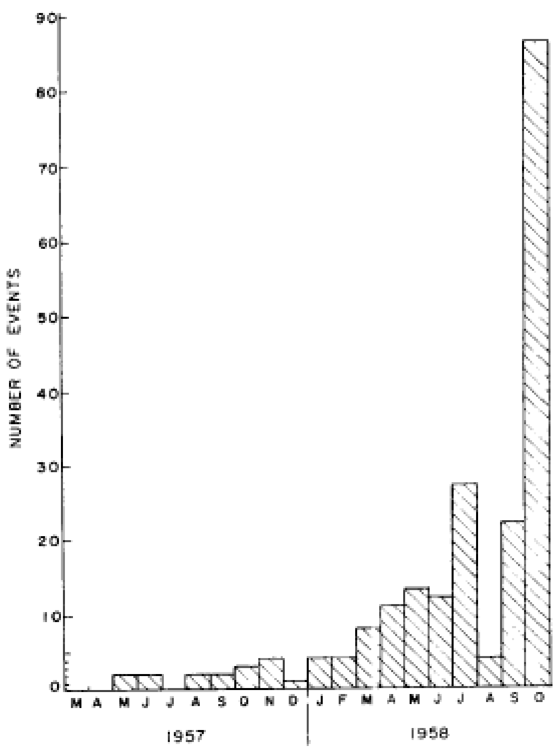


Figure 6. Histogram showing quasi-seismic events per month during mining of the last three longwalls at Springhill Mine (3).

bumping. Notley (4) conducted an energy release rate analysis, showing that alignment of the panels actually increased bump potential, accounting for the sudden increase in damage severity that killed 75 miners. Ignition of the explosive atmosphere created by this failure could have killed many of the rescuers and 100 miners who escaped.

Reported cases show that dynamic failure can initiate a disastrous chain of events in a variety of ways. These include release and/or ignition of methane (or other volatiles), destruction of ventilation controls necessary to remove methane, release of asphyxiating or poisonous gas, air blast and/or inundation.

Li et al. (6) described a major disaster that killed 214 miners at Sunjiawan coalmine in Fuxin city, China on February 14, 2005. The disaster was initiated by a dynamic failure, detected as a 2.7 magnitude seismic event that released methane into an already gassy mine. Li et al. attribute ignition, some 14 minutes later, to sparks induced by "rock movement" (presumably, by continued collapse of weakened roof and/or gob). The gas explosion was detected as a 0.6 local magnitude seismic event.

The Dutch Creek No.1 disaster of 1981 was initiated by a sudden outburst of methane and coal dust (7), whose subsequent ignition by flawed machinery caused 15 fatalities. Bump initiation of a fire was reported by Jackson and Merritts (8) at the Kenilworth Mine. The role of dynamic failure in the Willow Creek fire and explosion is possible but less certain. McKinnery et al. (9) report "a sudden release of methane into the face area caused the shearer to de-energize" about 90 minutes prior to the first explosion and that "interruptions in production caused by methane were common." They attribute ignition to "a roof fall in the headgate fringe of the gob" without further elaboration. Bumps and outbursts were described as common occurrences.

In other cases, dynamic failure initiates release of other gases and/or water, resulting in poisoning, asphyxiation and/or drowning. The Solvay mine collapse of 1995 was the most notable of these events. Fortunately, the 5.2 magnitude, 2 square km collapse did not cause fatal injury directly or through ignition of the substantial release of methane. It did, however, result in one fatality from ammonia poisoning.

These events are consistent with the overall history of bumping in coal mines. Iannacchione and Zelanko (10) constructed a database from MSHA (and earlier, USBM) reportable accidents and incidents between October 12, 1936 and January 21, 1993. The database contained 172 specific bump events that caused 87 fatalities and 163 injuries. These events are a small minority of coal bumps, but are the most severe, causing injury and/or a significant disruption of mining activity.

The database includes 36 bump events associated with longwall mining, the first in 1970. Of these, 12 occurred along the longwall face, 7 within the tailgate, 2 within the headgate, 13 along the face and tailgate (combined), and 2 in longwall setup or bleeder entries. The most significant hazard was found to be ignition (by the bump and/or of gas released by the bump). Four such events were found, all in western longwall mines. Coal beds were included in each entry, allowing identification of bump-prone seams, nearly half of which were located in Colorado and Utah. Thus, there is good reason to believe that dynamic failures of ground have the potential to cause disastrous events in deep western coal mines.

Geologic features and dynamic failure

Dynamic failures are often associated with particular geologic features, including discontinuities, sand channels, brittle intrusions, etc., although these relationships are often mine specific. Such features may concentrate stress, increase brittleness, reduce mine stiffness and/or locally weaken the rock mass, thereby nucleating a dynamic failure. Recognition of geologic features that have this potential, and knowledge of their location, is central to any control effort.

Considerable efforts have been made to identify geologic features associated with ground hazards in deep western coal mines, many of which are regional in scale. Phillipson (11) reviewed ground conditions and associated geology in nine western coal mines (Colorado, New Mexico and Utah). All but one of these mines used a longwall method, and all were located in or near the Piceance, Uinta and San Juan basins. Roof and pillar failures were found to be associated with "subtle joint zones, and subtle low-angle fault zones that are suggestive of bedding plane faults." Phillipson found that these controls to be independent of more well known sedimentary controls on ground instability (compaction, slickensides, weak lithology) and to be "relatively continuous along strike at the mine scale." Thus, these features can be projected from single encounters within gateroads.

Relevant sedimentary features include sand channels and facies changes in surrounding strata create a locally strong roof (or floor). Cantilevers of strong strata over the gob and/or bridging of the gob concentrate stress on nearby pillars and abutments. Dynamic failure can occur in the highly stressed abutments or as cantilevers and bridges fail (which can cause an air blast as well). Such failures are a characteristic of western coal mines. Koehler (12) documents this relationship through the long history of Utah's Sunnyside mine. Osterwald (13) and Osterwald et al. (14) provide comprehensive reviews of geologic features related to bumps in the Sunnyside District (Carbon County, Utah).

Discontinuities within strong strata are often important, particularly where clamping stresses are weak, allowing caving and subsidence of even massive strata. For example Osterwald et al. (14, p. 43) found subsidence propagating through massive sandstone strata above the Sunnyside coal bed, including the Castlegate Sandstone, from mining 2400 ft below surface. Most subsidence was found to follow joints and faults, particularly where lateral constraining pressure is low. In addition, Osterwald et al. describe subsidence cracks developing in massive strata daylighting in cliffs, sometimes decades after completion of mining.

Maleki (15) describes north-south and east-west trending joint sets that persist throughout the geologic column. The east-west orientation is dominant in the Book Cliffs region (rotating locally to the northwest at Dugout Canyon and Soldier Creek). Generally, Books Cliffs joints are poorly developed with rough, undulating surfaces, low-to-medium persistence along both strike and dip, and filled with calcite at depth (16).

The north-south joint set, non-parallel with major grabens formed in tension, is dominant in the Wasatch Plateau. Jointing is better developed, surfaces are smoother and persistence is medium to high, particularly for the north-south set. Underground measurements show the north-south set is the only well-pronounced set in the Blackhawk formation that overlies a number of coal seams, and underlies the Castlegate sandstone. Strike-slip faults are oriented NE/SW and NW/SE. Horizontal stress measurements show a continued relaxation of east-west stress.

Defects in hard sandstone strata have also been suggested by seismic analysis. Boler et al. (17) analyzed a 3.6 magnitude seismic event that occurred at the Soldier Creek Mine, adjacent to the Dugout Mine, in the Book Cliffs District of Utah. The event completely destroyed twenty-four 18 by 18 m (60 by 60 ft) pillars, turning them into "piles of broken coal." The pillars were being mined in retreat in a 480 ft wide panel isolated from a neighboring panel by a 18 m (60 ft) barrier. In addition, a row of pillars was left on either side of the barrier. The failed pillars were beneath 380 m (1250 ft) of cover, but overburden varied widely, ranging from 300 to over 450 m within this 425 m long panel.

The event buried a worker up to his chest in fine coal and initiated an air blast. Floor heave of up to 1.2 m (4 ft) occurred in several places, primarily involving 0.5 m (1.5 ft) of bottom coal. Seismic first motions from regional nets were uniformly implosional. Boler et al. placed the event origin in strong sandstone well above the mining horizon, and argue that failure likely occurred on a pre-existing normal fault (although any plane of weakness would likely have sufficed).

Agapito and Goodrich (18) characterize geology of the region relevant to dynamic failure as follows (quoting):

1) Thick, competent overburden strata that tend to bridge and interlock, creating high abutment stresses.
2) Numerous channels that cause high stress concentrations.
3) Very competent and strong immediate roof and floor sandstone/siltstone strata that confine/load the coal and resist breakage.
4) Uncleated or poorly cleated, strong coal that sustains high stress and tends to fail suddenly.

They also note the occurrence, in places, "of very soft shales and mudstones in the immediate roof" that are prone to bump-triggered falls.

In situ stress characteristics can also be important. Agapito et al. (19) report on a 3.4 Magnitude floor bump at the West Elk Mine in Colorado that caused floor heave of as much as 2.5 m. The heave was located in a 3 entry tailgate between mined panel and a barrier abutment, under 640 m of overburden. A nearby stress measurement found horizontal principal stresses of 5.5 and 24.2 MPa. The maximum horizontal stress at this site is significantly higher than the trend established by six other stress measurements at the mine, suggested existence of a local stress concentration. A survey of stress measurements at North Fork Valley mines shows a consistently strongly biaxial stress field, with the maximum horizontal stress trending parallel to the valley (roughly ENE).

Elevated horizontal stresses also figure in a dynamic failure within the Lorraine coal field (France). Driad-Lebeau et al. (20) reported that a fatal accident resulted from a 3.6 magnitude dynamic failure that occurred 1250 m below surface, damaging the main gate 200 m in front of a 250 m wide longwall panel. Multiple panels, separated by barriers, had largely shielded the panel from vertical stress, which was measured to be only 20% of overburden. However, a strong sandstone underlying mining, combined with a high horizontal stress field, was not destressed. Previous significant seismic events (to 2.5 magnitude) did not suggest the hazard. They had been concentrated in barrier pillars between panels that were carrying largely vertical stress.

The importance of geologic work in support of coal mine design, and the costs of inadequate geologic support, is widely recognized. For instance, Kelly (21) found that that "many coal mining projects in Australia have suffered as a result of inadequate or incorrect geologic assessment." Moreover, problems have often occurred despite good geologic work because of "poor communication through project phases as well as an insufficient understanding of consequence" related to a particular structure.

In a telling example, Ghose (22) attributed the Kottadih panel collapse in India to "inadequate support capacity where the support design had been based on data from a single borehole which failed to detect the massiveness of overlying strata." The collapse destroyed 55 of 83 shields and initiated a spontaneous combustion event (23). The oversight was not isolated. Singh (24) attributed failure of a number of high-profile longwall projects in India to "a single technical reason – the presence of massive over-lying roof strata." In some cases, the oversight was likely in anticipating the consequences, rather than the physical presence, of massive strata.

Rixon (25) discussed mine mapping in the context of longwall mining in Australia. Mapping is defined as "systematic recording of mine geology, mine roadway stability and geotechnical conditions," placing a firm emphasis on ground behavior. Simple observations that can be made and mapped include estimates of roadway closure, support deformation, deformational features (fault slip, etc.). These observations should address four questions as follows:

1) Is any deformation related to minor geological structures, or is it of a more pervasive nature?
2) Do systematic differences exist in the locus of failure in weaker areas?
3) What inferences can be made about the stress field?
4) Has the initial design been validated?

Such observations augment records from instrumentation, especially of the longwall (shield leg pressures, closure, etc.). Rixon argues that "current good practice is to continuously close design loops by observation and measurement of mine geology and geotechnical performance, which can then be compared with the initial information and design assumptions."

Iannacchione et al. (26) review use of hazard maps, rock mass classification systems and monitoring data for assessing roof fall risk. Maps show where deterioration is expected, providing an opportunity for reinforcing support prior to development of a significant hazard. However, an inspect and correct loop does not work well for anticipation of dynamic failure hazards for a number of reasons. These include:

- Dynamic failure may nucleate remote from accessible mine openings.
- Structure loading and local stiffness matter, but are difficult to observe.
- Dynamic failure occurs suddenly, there is no weakening process in time.
- Gas pressures and content are not directly observable.

However, comparing maps of actual roof fall hazards, as noted during pre-shift and other inspections with hazard maps reveals where ground conditions are deviating markedly from expectations. Deviations caused, perhaps, by undiscovered or unappreciated geologic conditions, some of which might increase the potential for dynamic failure. Significant deviations from expected conditions should be taken as a clear warning that the chance of a surprise, perhaps even a disaster, are increased. Such a deviation also calls into question the reliability of design decisions made to maintain safety and preclude disaster.

Stewart et al. (27, 28) describe a systematic effort to use stability mapping software (30) to anticipate difficult mining conditions. The software was used to create a hazard map of expected conditions (figure 7) that was used to plan local variations in roof support. One interesting feature is inclusion of a simple elastic model. Geology and yielding are ignored in calculating stresses, but are then added empirically as another hazard "factor." The actual hazard level plotted is the weighted sum of a variety of factors, typically adjusted to reflect local experience. This approach is a good starting point for developing hazard maps specific to dynamic failure. The chief requirements for such an extension would be improved insight into key geologic conditions, specific consideration of different modes of dynamic failure and identification of observations and measurements that are sensitive to failure potential.

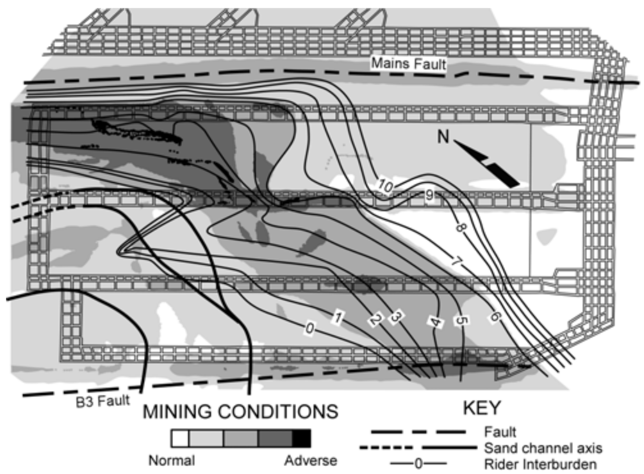


Figure 7. Longwall panel hazard map (27).

A Way Forward

Dynamic failure is often unpredictable in both space and time because of our limited geologic insight, and the highly nonlinear nature of event initiation. However, it is equally clear that these events should not be ignored, but actively managed. In each of the clusters with an adverse outcome, initial events rising to the level requiring reports to MSHA occurred before later events with more severe consequences. It is also probable that other events and conditions arose that indicated heightened risk.

Detection of events and conditions indicative of heightened hazard requires an ongoing, organized program that does not now exist in deep coal mines in the western U.S. This lack is both operational and regulatory. NIOSH proposes to address this gap by developing a **Dynamic Failure Control Program** with specific measures for implementation in deep western coal mines (figure 8).

The Dynamic Failure Control Program is a framework for actively managing dynamic ground failure hazards that includes site assessment, design, monitoring, active hazard reduction and miner protection elements. These elements function within an ongoing feedback loop (figure 8) that detects and responds to variations in site conditions, ensuring operation within bounds of a safe design throughout the life of a mine in spite of unexpected and varying geologic conditions. The loop can function within a variety of management structures – the key is continuous attention to hazard changes. Over the long term, the feedback loop should improve as well as maintain the inherent safety of both mining operations and emergency response plans.

Implementation of the program in deep western coal mines requires specific developments throughout the framework

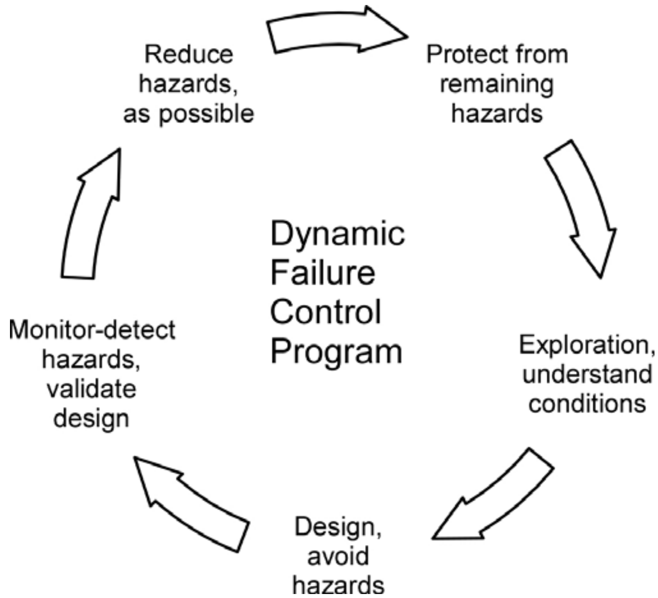


Figure 8. Elements of the Dynamic Failure Control Program.

elements for each of three dynamic failure mechanisms. These mechanisms are sudden failure of pillars, outbursts of coal and gas from highly stressed ribs, and the breakage (caving and heaving) of strata. The aims are to [1] develop a method for identifying observations and accessible measurements that reflect the level of dynamic failure hazard and threshold values at which these hazards become significant, [2] identify and/or develop practical means for making such observations and measurements in a fast-moving longwall panel, [3] establish a safe, effective means for reducing dynamic failure hazard, and [4] evaluate and adapt measures to protect miners from dynamic failure.

Implementation of the framework is based on an existing site model and associated mine design. The geomechanical model underlying the design is necessarily built upon incomplete and imperfect information. Ideally, the design will explicitly state important assumptions and expected behaviors that can be checked and monitored during mining. A program of observation and monitoring should also be implemented to detect local occurrences of hazardous geologic and stress conditions. This program will determine where active measures should be employed to mitigate hazards and the degree to which hazards are actually removed. Protective measures should be employed where significant hazards remain. Experience gained in monitoring conditions and hazards are used to identify further exploration needs and hence, to refine the geomechanical model and design. In developing this framework and associated measures, priority is given to: first designing hazard out of the mine; then to actively reducing remaining hazards wherever possible; and finally to applying protective ground support measures. This sequence could also be described as a best-practices decision tree. Continuous application of the framework should improve inherent design safety while facilitating adaptation to changes in geology and ground conditions.

Active management of dynamic failure has been accomplished for mining of other commodities (gold, etc.) and elsewhere in coal (30) but site-specific elements of these programs have yet to be successfully adapted to contemporary deep western coal mine conditions. As noted in the review, some previous attempts were blamed for hazardous bumps. As a result, the prevailing industry view appears to be that control methods have "not yet demonstrated satisfactory results under continuous operating conditions" and "can be hazardous if not properly implemented" (18).

This project is designed to overcome these objections by developing and, with the assistance of collaborating mines, implementing and optimizing a program tuned for deep western coal conditions. This goal requires development of supporting technical means in a number of areas. These have been organized into 7 technical products. These products are:

1) Guidelines for assessing the robustness of designs for dynamic failure control. That is, for assessing the sensitivity of designs to departures from key assumptions and errors in key inputs.
2) Method for estimating potential methane release from dynamic failure.
3) Guidelines for monitoring design performance in controlling dynamic failure hazard and disaster potential.
4) Recommendations for longwall panel hazard assessment and monitoring.
5) Characteristic site models for assessing dynamic failure mechanisms in deep western coal mines.
6) Recommended methods for active management of dynamic ground failure hazard.
7) Recommended ground support measures for containing dynamic failure hazard.

SUMMARY

Mining under threat of dynamic failure is a challenge to many sectors of the mining industry, many of whom have made remarkable progress in control. Dynamic failure hazards are a fact of life in deep western coal mines in the U.S. While a variety of methods and tools have been developed for addressing these hazards in various districts worldwide, none have been successfully adapted to deep U.S. coal conditions, particularly those of deep western coal. Moreover, there is a conspicuous lack of a program for dynamic failure control, as has been developed elsewhere (e.g. Germany – see Brauner (30)).

Nonetheless, a number of promising elements and trends are in place that could be brought together to form such a program. A first element (and essential foundation) is a fundamental understanding of dynamic failure mechanisms and methods for modeling their occurrence. These are sudden failure of pillars, outbursts of coal and gas from highly stressed ribs, and the breakage (caving and heaving) of strata. Some methods exist for assessing the potential for the occurrence, but these have not been extended to monitoring points or "sentinel measurements" that indicate the level of hazard – or even whether fundamental mine design assumptions have been violated. Some progress has been made in considering the influence of geology but these have been aimed primarily at roof falls. Generally, then, there is a lack of insight into the level of dynamic failure hazard.

A variety of tools for removing and/or controlling hazards have been developed, but none have been successfully adapted to routine use in deep U.S. conditions – and some have a reputation as being hazardous in these conditions. Development and adaptation of such tools is discussed in a companion paper at this conference. Overall, selection and adaptation of appropriate tools is needed, but little progress is evident. One exception may be recent attempts to limit miner exposure through automation of longwall faces.

A good foundation is required for reducing this hazard – a foundation that includes good fundamental understanding, advancing technical tools, and good examples of hazard control programs operating in reasonably similar geologic settings. Moreover, favorable trends in coal bed methane recovery and longwall automation promise to increase the range and feasibility of both hazard assessment and control within an integrated **Dynamic Failure Control Program**. However, successful development will require active collaboration between government, industry and academia; a collaboration that NIOSH is actively pursuing.

Our conclusions echo those of many others with interests in deep coal mining. For instance, Agapito and Goodrich (18) concluded that "safety problems caused by bumps in the Wasatch -Book Cliffs region of Utah highlight the need for improvement in avoiding, predicting and mitigating these events. This is critical as mines become deeper." They made five more specific recommendations for minimizing and mitigating bump hazards more generally (i.e. not limited to potentially disastrous bumps. These were, paraphrasing [1] detection of geologic structures that exacerbate bumping, [2] mine design that minimize high stresses, [3] longwall equipment that protects miners, [4] operational practices that limit miner exposure to high stress areas, and [5] develop and demonstrate safe destressing methods.

Finally, Agapito and Goodrich called for seeking improvement "in a cooperative manner between the mining industry, equipment manufacturers, and research and regulatory agencies." We concur, and hope to build cooperative relationships between NIOSH and other interested parties to achieve our common goals. Hopefully, this paper marks NIOSH's entry into the discussion – and efforts to reduce the disaster potential of dynamic failure in deep western coal mines.

REFERENCES

1. **Souder, W.E. and E.R. Palowitch.** Growth of longwall technologies in the United States. Chapter 1 in Longwall-Shortwall Mining, State of the Art, R.V. Ramani (ed), Society of Mining Engineers, New York, 1981, pp. 3-9.

2. **Arabasz, W.J., S.J. Nava and W.T. Phelps.** Mining seismicity in the Wasatch Plateau and Book Cliffs coal mining districts, Utah, USA. Rockbursts and seismicity in mines – RaSIM4, Proc. of 4th Int. Symp. on Rockbursts and Seismicity in Mines, 11-14 August 1997, Krakow, Poland, Gibowicz and Lasocki (eds), Balkema, pp. 111-116.

3. **Arabasz, W.J. and J.C. Pechmann.** Seismic characterization of coal-mining seismicity in Utah for CTBT monitoring. UCRL-CR-143772. Online: http://www.seis.utah.edu/Reports/llnl2001/LLNLRept.pdf.

4. **Notley, K.R.** Rock mechanics analysis of the Springhill Mine disaster (October 23, 1958). Mining Science and Technology, 1984, 1, 149-163.

5. **Hasegawa, H.S., R.J. Wetmiller and D.J. Gendzwill**. Induced seismicity in mines in Canada – An overview. PAGEOPH, 1989, Vol. 129, Nos. 3/4, pp. 423-453.

6. **Li, T., M.F. Cai and M. Cai.** Earthquake-induced unusual gas emission in coalmines – A km-scale in-situ experimental investigation at Laohutai mine. International Journal of Coal Geology (in press), 2006.

7. **Dobroski, H. Jr., C. Stephan and R. Conti.** Historical summary of coal mine explosions in the United States: 1981-1994. USBM IC 9440, 1996, 137 pp.

8. **Jackson, E. O. and W. M. Merritts.** Water infusion of coal pillars before mining, Kenilworth mine, Independent Coal & Coal Co., Kenilworth, Utah. USBM RI 4836, 1951, 25 pp.

9. **McKinney, R., W. Crocco, J. Tortorea, G. Wirth, C. Weaver, J. Urosek, D. Beiter and C. Stephan.** Underground Coal Mine Explosions, July 31 – August 1, 2000, Willow Creek Mine – MSHA ID. NO. 42-02113, Plateau Mining Corporation, Helper, Carbon County, Utah, MSHA Report of Investigation CAI -2000-18/19, 2001, 52 pp.

10. **Iannichionne, Anthony T. and Joseph C. Zelanko.** Occurrence and remediation of coal mine bumps: A historical view. In Proceedings: Mechanics and mitigation of violent failure in coal and hard-rock mines. Hamid Maleki, Priscilla Wopat, Richard Repsher, and Robert Tuchman (eds), USBM Special Publication 01-95, 1995, pp. 27-67.

11. **Phillipson, S.E.** Laramide orogeny-related controls on coal mine ground instability in Cretaceous coal seams, southern Rocky Mountain foreland. International Journal of Coal Geology 64, 2005, 20-43.

12. **Koehler, J.R.** The history of gate road performance at the Sunnyside mines: summary of U.S. Bureau of Mines field notes. USBM IC 9393, 1994, 43 pp.

13. **Osterwald, F.** USGS relates geologic structures to bumps and deformation in coal mine workings. Mining Engineering, April, 1962, pp. 63-68.

14. **Osterwald, F.W., C.R. Dunrud and D.S. Collins.** Coal mine bumps related to geologic features in the northern part of the Sunnyside District, Carbon County, Utah. USGS Prof. Paper 1514, 1993, 76 pp.

15. **Maleki, Hamid.** Caving, Seismicity and Mine Design in Four Utah Mines. Proceedings of the 25th International Conference on Ground Control in Mining. Morgantown, WV, West Virginia University, Aug. 2006, Peng SS, ed., pp. 268-276.

16. **Maleki, H., R. Olson, D. Spillman and M. Stevenson.** Development of geotechnical procedures for analysis of mine seismicity and pillar designs. Proceedings of the 22nd International Conference on Ground Control in Mining. Morgantown, WV, West Virginia University, Aug. 2003, Peng SS, ed., pp. 270-277.

17. **Boler, F.M., S. Billington and R.K. Zipf**. 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., 1997, Vol. 34, No. 1, pp. 27-43.

18. **Agapito, Joe F. T., and Rex R. Goodrich.** Five stress factors conducive to bumps in Utah, USA, coal mines. Proceedings of the 19th International Conference on Ground Control in Mining. Morgantown, WV, West Virginia University, Aug. 2000, Peng SS ed., pp. 93-100.

19. **Agapito, J.F.T.,** Leo Gilbride and Wendell Koontz. Implication of highly anisotropic horizontal stresses on entry stability at the West Elk Mine, Somerset, Colorado. Proceedings of the 24th International Conference on Ground Control in Mining. Morgantown, WV, West Virginia University, Aug. 2005, Peng SS ed., pp. 196-202.

20. **Driad-Lebeau, L., F. Lahaie, M. Al Heib, J.P. Joisen, P. Bigarre and J.F. Noirel.** Seismic and geotechnical investigations following a rockburst in a complex French mining district. International Journal of Coal Geology 64, 2005, 66-78.

21. **Kelly, M.** 3D Aspects of Longwall Geomechanics. In Ground Behaviour and Longwall Faces and its Effect on Mining, Exploration and mining report 560F, ACARP project C5017, 1999, 28 pp.

22. **Ghose, A.K.** Why longwall in India has not succeeded as in other developing country like China. IE(I) Journal- MN, Vol. 84, August 2003, pp. 17-20.

23. **Bhowmick, B.C., N. Sahay, I. Ahamad and S.M. Verma.** Significant improvement in effectiveness of nitrogen infusion technology for control of fire by dynamic balancing of pressure – A case study of powered support longwall face. CIM bulletin, 2000, vol. 93, No. 1038, pp. 74-80.

24. **Singh, R.** Mining methods to overcome geotechnical problems during underground working of thick coal seams – case studies. Transactions. Section A, Mining Industry, 1999, Vol 108: A, pp A121-A131.

25. **Rixon, L.K.** Mine mapping: an important component of integrated mine characterization. Symposium on Geology in Longwall Mining, 12-13 November 1996, G.H. McNally and C.R. Wards (eds), pp. 119-125.

26. **Iannacchione, A., T. Bajpayee and L. Prosser.** Methods for determining roof fall risk in underground mines. SME Annual Meeting Feb. 25 – 28, 2007, Denver, CO, preprint 07 -090, pp. 8.

27. **Stewart, Collin, Greg Hunt and Christopher Mark.** (2006a) Geology, ground control, and mine planning at Bowie Resources, Paonia, CO. Proceedings of the 25th International Conference on Ground Control in Mining. Morgantown, WV, West Virginia University, Aug. 2006, Peng SS ed., pp. 284-290.

28. **Stewart, Collin, Ry E.** Stone and Keith A. Heasley (2006b) Mine stability mapping. Proceedings of the 25th International Conference on Ground Control in Mining. Morgantown, WV, West Virginia University, Aug. 2006, Peng SS ed., pp. 277-283.

29. **Wang, Q. and K. Heasley.** Stability Mapping System. 24th International Conference on Ground Control in Mining, Peng (ed), 2005, pp. 243-249.

30. **Brauner, G**. (1994) Rockbursts in coal mines and their control, DMT, Essen, Germany, Balkema, 144 pp.