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Coal pillar mechanics of violent failure in U.S. Mines

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ABSTRACT

This paper seeks to enhance the understanding that the horizontal stresses build up and release during coal pillar loading and unloading (post-failure) drawing upon three decades of observations, geomechanical monitoring and numerical modeling in bump-prone U.S. mines. The focus is on induced horizontal stress in mine pillars and surrounding strata as highly stressed pillars punch into the roof and floor, causing shear failure and buckling of strata; under stiff stratigraphic units of some western US mines, these events could be accompanied by violent failure of pillar cores. Pillar punching eventually results in tensile stresses at the base of the pillar, facilitating transition into the post-failure regime; this transition will be nonviolent if certain conditions are met, notably the presence of interbedded mudstones with low shear strength properties and proper mine designs for controlling seismicity and dynamic loads. The study clearly shows high confining stress build-up in coal pillars resulting in up to twice higher peak vertical stress and high strain energy accumulations in some western US mines in comparison with peak stresses predicted using common empirical pillar design methods. It is the unstable release of this strain energy that can cause significant damage resulting from pillar dilation and ground movements. These forces are much greater than the capacity of most common internal support systems, resulting in horizontal stress-induced roof falls locally, in mines under unremarkable far-field horizontal stress. Attention should be placed on pillar designs as increasing support density may prove to be ineffective. This mechanism is analyzed using field measurements and generic finite-difference stress analyses. The study confirms the higher load carrying capacity of confinement-controlled coal seams in comparison with structurally controlled coal seams. Such significant differences in confining stresses are not taken into account when estimating peak pillar strength using most common empirical techniques such as those proposed by Bieniawski and Salamon. While using lower pillar strength estimates may be considered conservative, it underestimates the actual capacity of pillars in accumulating much higher stress and strain energies, misleading the designer and inadvertently diminishing mine safety. The role of induced horizontal stress in mine pillars and surrounding strata is emphasized in coal pillar mechanics of violent failure. The triggering mechanism for the violent events is sudden loss of pillar confinement due to dynamic loading resulting from failure of overlying stiff and strong strata. Evidence of such mechanism is noted in the field by observed red-dust at the coal-rock interfaces at the location of coal bumps and irregular, periodic caving in room-and-pillar mines quantified through direct pressure measurements in the gob.

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1. Introduction

This paper seeks to enhance the understanding of horizontal stress build up and release during coal pillar loading and unloading (post-failure) drawing upon three decades of observations, geomechanical monitoring and numerical modeling in bump-prone mines. Rock bursts and coal bumps are defined as sudden, violent failure that occur near mine entries that are of such a magnitude that they expel large amount of rock and/or coal (5–100 tons commonly) into an excavation, restricting safe and efficient access to the working area [1]. Recognizing that the violent failure of coal pillars is a multi-faceted problem, the author has focused on coal pillar mechanics using the long-term observations and measurements in western US burst-prone coal mines. Dynamic loading from overburden and underburden strata, including unstable slip along structural trends/discontinuities, triggering violent failure of marginally stable coal pillars, is analyzed elsewhere using seismic monitoring and FLAC3D modeling [1–3]. These studies clearly show the seismic potential of stiff, near seam stratigraphic units in producing events up to 2.6 on the Richter scale for the analyzed longwall mining conditions, in good agreement with microseismic monitoring results. The study utilized regional and site specific

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seismic monitoring systems operated by the University of Utah in cooperation with USGS [4].

Coal pillar design in the 21st Century, still relies heavily on the use of empirical pillar strength formulas, originally developed for South African Mines, and the use of boundary-element techniques most commonly LaModel. These approaches have significant shortcomings by excluding any examination of stress concentration within mine pillars and surrounding strata and excluding site specific conditions for US coal seams. It is this concentration of horizontal/vertical/shear stresses, calibrated against field measurements, that is critical to examination of stability and mode of failure, i.e., gradually or in a violent fashion. Finite-element or finite-difference modeling techniques have better capabilities for analyzing stress concentrations and calculation of the factor of safety using Mohr-Coulomb failure criterion among others [5].

Using empirical formulations proposed by Bieniawski or Salamon, for instance, the confining stresses are not directly taken into account for estimating peak pillar strength by using site-specific far-field horizontal stress and material properties [6,7]. On the contrary, the empirical formulas developed by Maleki are based on U. S. stress measurements and have provisions for incorporating higher confining stress for some U.S. coal seams and lower strength for structurally controlled coal seams i.e. those with cleating and interbedded enclosing strata [8,9]. NIOSH has recently undertaken a new research in examining and expanding the use of U.S. empirical formulas, including those proposed by Maleki and Holland-Gaddy, for inclusion into boundary element modeling [8,10].

As related to the mechanics of violent failure, however, the importance of confining stress on some bump-prone coal seams has been recognized for decades. USBM research has attributed the elevated coal burst potential to the ability of strong stratigraphic units in providing confinement to the pillars [11,1]. Using laboratory measurements, USBM points to the loss of confinement as primary mechanism affecting coal bump potential [12]. Absent from USBM research is the mechanism responsible for loss of confinement in the field.

Using measurements from three mines, in this paper, the author provides evidence of high horizontal stress built-up within coal pillars, roof and floor strata. The intent is to study the effects of confinement stresses on pillar strength, post-failure characteristics, roof/floor stability and support performance. Data on the post-failure coal pillar behavior is limited to laboratory measurements for samples with different width-height ratios, limited South African and US field measurements [6,8]. Salamon proposed a criterion for assessing mine stability (not coal bump potential) using the concept of mine stiffness [13]. Maleki proposed a strata stiffness index, the ratio of strata stiffness-strength to that of the coal seam, for identifying bump-prone conditions [1]. Without much additional discussion of these and other criteria, the author considers the case study mines presented in this paper to be potentially bump prone based on the stiffness index and decades of geotechnical monitoring data.

These case studies are most closely representative of confinement-controlled coal, however, the significance of having somewhat softer, laminated strata within the immediate roof and floor is addressed using field measurements and stress analyses. Other case studies excluded from this paper show that structurally-controlled coal seams can also become bump-prone, although at lower stress levels with lower energies, depending on pillar designs, and stiffness and cavability of overburden strata [1,14].

Within the past four decades, mining companies have extracted more than 200 million tons of coal from the study area, efficiently and safely. Coal bumps have been a local, isolated problem and controlled through the use of stress control technologies, and utilization of properly designed longwall mining techniques [15,16]. Presence of weaker, carbonaceous layers at coal seam boundaries has provided a generally stable mechanism for release of confining stress.

All three study mines are located in the Wasatch Plateau of central Utah in the upper Blind Canyon and Hiawatha coal seams. The immediate roof and floor of both seams consist of mudstones, siltstones, and sandstones. The rock quality designation (RQD) ranges from 50 to 100, uniaxial compressive strength varies from 69 GPa to 100 MPa, and Young's modulus ranges between 19.3 and 39.3 GPa. There are a number of thick-bedded, competent, and stiff units in the roof that resist regular caving and transfer loads to the face during retreat operations (rock mass rating 52–88). Both coal seams (2.7 m thick) have similar strength properties with uniaxial compressive strength exceeding 22 MPa and Young's modulus of 3.4 GPa [1]. Measured far-field horizontal stress is unremarkable (<7 MPa) in this coal field in comparison to the vertical stresses [15].

2. Case study 1, evidence of horizontal stress build-up in the pillar

This case study quantifies the magnitude of horizontal stress build-up in relatively narrow coal pillars in the Upper Blind Canyon Seam and its significance in elevating peak pillar strength. Mine 1 has used longwall mining methods with yielding gate pillars successfully for more than three decades [15]. Existing designs consist of 220 m wide panels and two-entry gate roads possessing 9 m wide "yield" pillars which were developed and verified based on numerous field measurements since 1988 [1,15].

The first extensive field study was initiated by the mining company to investigate the in situ behavior of 9 m wide by 24 m long "yielding" pillars in the Upper Blind Canyon Seam at a depth of 610 m [17,1]. These Upper Blind Canyon Seam pillars exhibited high strength and resistance to yielding. In fact, if not for the near-ideal yielding of the mine floor and prudent mine designs, the Upper Blind Canyon Seam pillars could have experienced minor bumps.

Average measured pillar strength was 27.5 MPa in the Upper Blind Canyon Seam; this in situ strength was higher than the uniaxial compressive strength of coal (22 MPa), indicating pillar strengthening because of the confining horizontal stresses. Additional field investigations and numerical modeling have confirmed high peak pillar strength approaching 27.5 MPa at multiple other locations in the neighboring mines [15,5].

Fig. 1a demonstrates the buildup of horizontal and vertical stresses within the instrumented gate pillars during the retreat of the longwall face toward the instruments. Vertical and horizontal stresses in Fig. 1a are calculated on the basis of borehole pressure cell data oriented both horizontally and vertically and the procedures developed by USBM [1].

The confining horizontal stresses generally increased until the face passed the instruments by about 19.8 m. Vertical stresses dropped, but quickly rebounded; beyond this distance, there were numerous bounces in the area that were related to failure of surrounding strata. Nevertheless, confining stresses were significantly high in the pillar, exceeding 18 MPa; the pillar eventually unloaded after the face retreated 244 m beyond the instruments.

Fig. 1b illustrates pillar dilation history, confirming development of yield zones within the pillar as the face approached the instruments; pillar dilation was calculated by placing several anchors within the pillar and measuring the changes in the distance between these anchors and a fixed reference point on the opposite side (solid block). The measurements were taken using a tape extensometer.

Roof-floor convergence measurements had a similar trend as shown in Fig. 1c; convergence increased significantly in the entries

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