# Effects of Overburden Characteristics on Dynamic Failure in Underground Coal Mining

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## ABSTRACT

Dynamic failures, or "bumps", remain an imperative safety concern in underground coal mining, despite significant advancements in engineering controls. While many factors have been empirically linked to the occurrence of dynamic failure events, identifying a consistent, repeatable set of criteria within a field setting has proven elusive; conditions generally associated with dynamic failure might produce an event at one site, but not another. Conversely and more troubling, dynamic failure could occur where relatively few of these factors exist. The presence of spatially discrete, stiff roof units, such as paleochannels, are one such feature that has been linked to the occurrence of dynamic failure events. However, an empirical stratigraphic review investigating the relative frequency of discrete units in bumping versus non-bumping deposits indicates that no significant difference exists based on this criterion alone, and that instead an apparent relationship exists between reportable bump history and the overall character of the host rock with respect to stiffness. Due to the complexity of the bump problem, however, these results are not conclusive, as they do not take into account any variable other than the presence or absence of stiff members in the roof lithology; To weight the relative impact of changes in a single variable, such as the thickness or location of sandstone members, it must be examined in isolation—i.e. in a setting where all other variables are held constant. Numerical modelling provides this setting, and the effects of variability in a stiff discrete member in a hypothetical longwall mining scenario are investigated within the context of three stratigraphic "types", as determined by the ratio of stiff to compliant stratigraphic members; Compliant, Intermediate and Stiff. A modelling experiment examines changes in rupture potential in stiff roof units for each stratigraphic type as discrete unit thickness and location are manipulated through a range of values. Results suggest that the stiff-to-compliant ratio of the host rock has an impact on the relative stress-inducing effects of discrete stiff members. In other words, it is necessary to consider both the thickness and the distance to the seam, within the context of the host rock, to accurately anticipate areas of elevated rupture-induced hazard; acknowledging the presence of a discrete unit within the overburden in general terms is an insufficient indicator of risk. Through modelling of anticipated changes in the placement and dimensions of discrete units within their stratigraphic setting, elevated rupture-induced bump hazard can be anticipated on a case by case basis. Were similar modelling studies conducted at minesites in tandem with tracking of problematic discrete stiff units, areas of elevated rupture risk could be anticipated in advance of mining. Developing this predictive capability beyond identifying rupture potential in discrete roof members is essential to the eventual elimination of dynamic failure related worker injuries and fatalities. As stress is a necessary component in the occurrence of dynamic failure events, this finding helps to refine our understanding of the role of individual stiff, strong roof members in bumping phenomena, and suggests that a more holistic view of overburden lithology, combined with site-specific numerical modelling, may be necessary to achieve greater miner safety.

## INTRODUCTION

Dynamic failures, also termed "bumps", "bounces" and "bursts", may be defined as the violent ejection of coal or rock into a mine opening (Peng, 2008). Despite evolving mining techniques and practices, these events continue to occur. Between 1983 and 2013, there were nearly 400 cases of reportable dynamic failure accidents in coal and nonmetal mines, resulting in 20 fatalities, 155 lost-time accidents, and an estimated 48,000 lost man hours. These events have been documented for well over 100 years within the American underground coal mining industry. Over this period of time, mining practices and support technologies have evolved considerably, resulting in an overall decrease in the rate of dynamic failure-related injuries and fatalities. However, despite this overall decrease in event rate, bump-related injuries and fatalities continue to occur. The events at Crandall Canyon, Utah (MSHA, 2008) and the Brody No. 1 Mine in West Virginia (MSHA, 2014) are two recent failure events that resulted in a total of eleven fatalities. MSHA data further indicates that although reported incidents of these events are relatively rare, they result in worker injury up to and including death in more than 60% of cases. This is in contrast to injuries from the more common ground failure event of roof falls, which result in worker injury in less than 25% of cases (Figure 1a and Figure 1b). Clearly, dynamic failure events remain an imperative safety concern. Furthermore, their continued occurrence indicates that current engineering controls have proven inadequate at wholly mitigating the problem. The study described in this paper is part of a larger effort by NIOSH researchers that seeks to advance our current understanding of the causative factors behind dynamic failure phenomena, thereby allowing for more effective mitigation techniques.

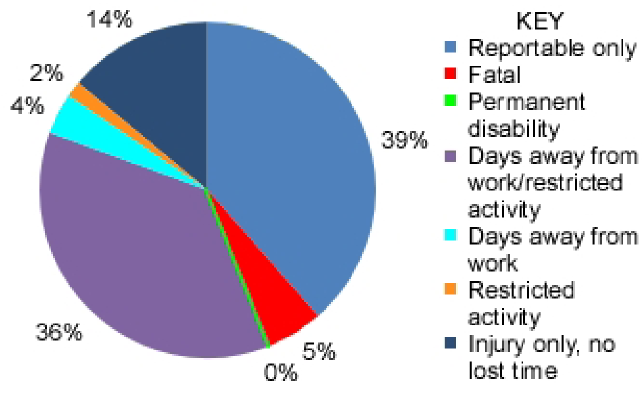


**Figure 1a. Degree of Injury as reported to MSHA for bump accidents between 1983 and 2014.**

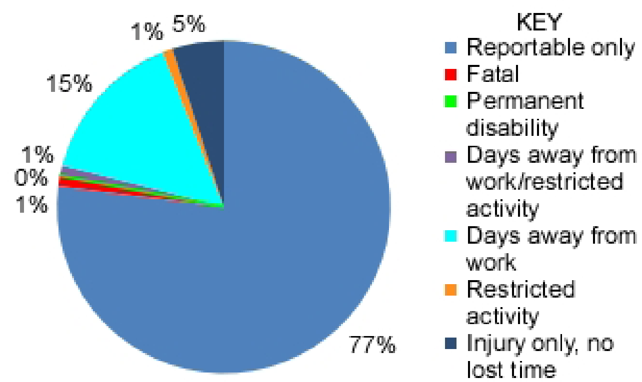


**Figure 1b. Degree of Injury as reported to MSHA for reported roof fall accidents between 1983 and 2013.**

## BACKGROUND

Many characteristics have been empirically linked to the occurrence of dynamic failure events, including design parameters, extraction techniques, and geologic factors. Identifying a set of conditions that will consistently produce bumping, however, has proven elusive; that is conditions generally associated with dynamic failure might produce an event at one site, but not another. Conversely and more troubling, dynamic failure could occur where relatively few of these factors exist.

The mechanical response of geologic structures plays a critical role in the development of dynamic failures. Regions that lack brittle strata are less prone to dynamic failure, although they may still experience roof falls, pillar failures, and other ground control difficulties. As a part of a larger effort to better define the role of geologic risk factors in the occurrence of dynamic failure events, an empirical study was designed to examine the correlation of discrete stiff units to a reported history of bump phenomena. The role of discrete stiff units, such as massive sandstones and near-seam features, has been identified as a contributing factor to increased bump hazard.

Iannacchione and Tadolini (2015) define several fundamental factors contributing to dynamic failure occurrence. Among these are strong strata surrounding the coalbed, which may "[resist] failure from elevated load conditions, and . . . apply considerable stress and confinement to the pillars, increasing the potential for coal burst," and strata caving characteristics, in which "massive strata will often cantilever over areas . . . causing excessive levels of stress on coal pillars." Whyatt and Varley (2009) also describe failure of cantilevered, strong members as a significant mechanism of dynamic events.

Mark and Gauna (2015) provide a practical overview and generalized risk assessment matrix for bump events. In their study, they describe several conditions of the overburden that have been associated with dynamic failure phenomenon, including thickness and location of near-seam strong or stiff units. They also note the lack of a quantitative, universal rating system for bump-risk identification, and identify as a qualitative intermediate risk factor, those roof conditions which are "typical Western US or Central Appalachian stratigraphy." While soft, compliant stratigraphic units are unambiguously not conducive to dynamic failure, and lithologies dominated by strong, stiff units are conducive to dynamic failure, the range of stratigraphic characteristics that pose an intermediate risk are less clearly defined.

The density of mining operations within the Western and Appalachian coalfields is illustrated in Figures 2 and 3. Progress toward clarifying the degree of risk in these intermediate areas would benefit a significant number of active coal mines. The question, then, becomes: What are the critical thicknesses and locations of discrete stiff units, such as sandstones or competent limestones, at which they become truly hazardous to mining operations? This is by no means an easy question to answer, as influences on bump-proneness are multifaceted and identifying degrees of influence of these factors in a field setting remains elusive.

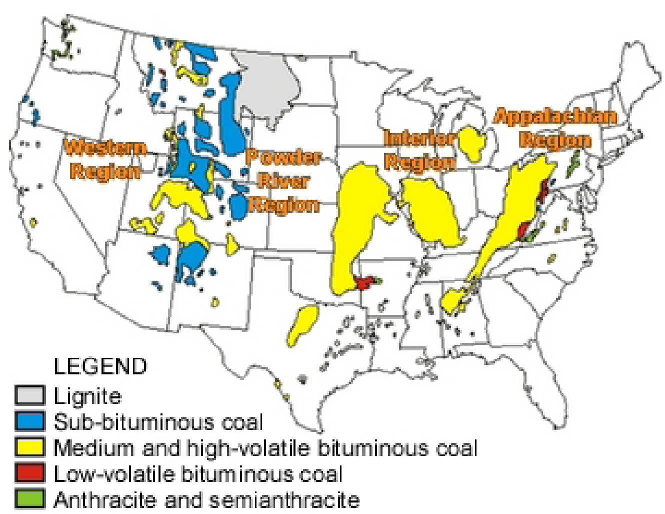


**Figure 2. Coal mining regions in the United States. (Minerals Education Coalition (MEC) of SME, 2016).**

Larson et al. (2015) demonstrate that load transfer distance correlates with different geology classifications (Figure 4). These classifications fall into seven categories based on the proportion of sandstone (stiff) members to shale (compliant) members in the overburden, as well as the presence or absence of one or more massive or semi-massive stiff units. Strong, stiff strata may have the effect of increasing load transfer distances and resisting caving and loading of the gob, thereby increasing stresses in panel abutments.

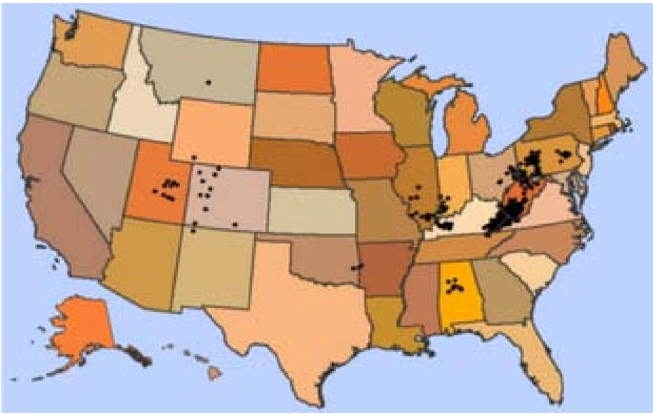

**Figure 3. Active underground coal mining operations within the United States, as of 2014.**

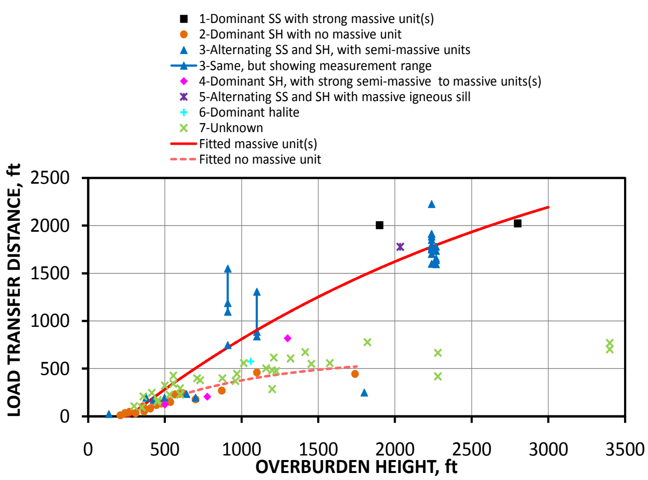


**Figure 4. Load transfer distance with respect to the geology of the overburden (Larson et al., 2015).**

The presence of stiff units in the overburden have the capacity to influence dynamic failure occurrence in two primary ways: First, failure of strong, brittle near-seam strata is likely to produce a seismic event. Second, bridging and cantilevering of strong strata shifts stress from gob to abutments. This paper seeks to identify the point at which these features transition from benign to hazardous. Toward this end, a review of reported failures was first compared to typical stratigraphy for that county, and contrasted to stratigraphy in counties in which bumps have not been reported. However, this empirical portion of the study does not account for changes in mining practices, design parameters or other factors contributing to dynamic failure. Variations in any of these factors will also impact the capacity for bump occurrence. To weight the relative impact of changes in a single variable, such as the thickness or location of sandstone members, it must be examined in isolation—i.e. in a setting where all other variables are held constant. As nature defies the simplified and consistent conditions required to validate findings of the empirical study, parameter studies using numerical models of typical stratigraphic "types", as defined by the stratigraphic review, were constructed to explore how the location and thickness of strong strata influence loading.

## STRATIGRAPHY AND DYNAMIC FAILURE

To begin to address this problem, core data was collected from the National Coal Resources Data System (NCRDS). The NCRDS is a compilation of core, chip, and drilling data that is made publicly available through the United States Geological Survey (USGS). Lithologic data was examined from 95 sets of log data, representing 22 different counties and 18 different coal seams or coal seam splits. These 95 core logs were then cross-referenced with a database of reported dynamic failure-related accidents and fatalities to determine the status of the seam and the county, individually, as either bump-positive or bump-negative.

The database used for identification of bump status includes 369 individual cases reported to the Mine Safety and Health Administration (MSHA) within the United States between 1983 and 2009. MSHA does not include information regarding the mined seam in these accident statistics. Consequently, an attempt was made to reconstruct this data for the 82 mines represented by the database, through publicly available lease information, MSHA Reports of Investigation, and state Coal Associations. These efforts were successful for 35 of these mines. The coal seams identified as having been excavated by mines with a history of dynamic failure phenomena were cross-referenced with the original 95 lithologic records collected through the NCRDS. Those records representing a seam correlating with a mine in which bump events had been reported were designated as "bumping." If no association existed between a given coal seam and one of these 35 mines, it was designated as "non-bumping."

There is some inherent error in identifying the bump status of records in this way, due to our inability to reconstruct seam information for each mine represented within the database of reported bump incidents. Some records identified as bump-negative, could, in fact, be bump-positive. Geographic data for both coal records and MSHA accident reports, however, is readily available. Given our ability to verify that bump-negative seams come from counties in which no bumps were reported ensures that the magnitude of this error for this study is relatively small. Likewise, identifying all seams within a county that have been associated with reported bumping allows us to exclude other seams present within the stratigraphy from "bumping" status. While error could exist in the identification of bump-negative seams, no such error exists in those that have been designated as bump-positive.

Counties were categorized independently as either "bumping," indicating a history of dynamic failure events reported to MSHA within that county, regardless of seam; or "non-bumping," that is, no reported history of dynamic failure events between 1983 and 2009[1]. This approach allows for isolating characteristics of the stratigraphy from those unique to the seam itself. This resulted in the following categories for the lithologic records, or cases: Non-bumping seam/non-bumping county, bumping seam/non-bumping county, bumping seam/bumping county, and non-bumping seam/bumping county.

1 The database of reported dynamic failure events contains event records from 1983 to 2009. If bumps have been reported in a seam before or after this range, they may be erroneously designated as non-bumping.

The empirical portion of this study examined log data for the presence of strong, stiff units within the overburden relative to a given seam position. Of particular interest were strong, massive units whose thicknesses exceeded 40 ft. and were located at any point above the seam; and near-seam units whose thicknesses exceeded 4 ft. and whose presence was considered to be most significant within the first 25 ft. above the seam. Results indicated that the frequency of occurrence of these stiff members in the bumping and non-bumping sample sets was very similar. In other words, the presence of these units did not correlate with a history of dynamic failure (Figures 5 and 6). It is important to note, however, that the log data used for this portion of the study may be widely spaced, and not directly proximal to mine workings[2]. Furthermore, this portion of the study does not take into account any variables other than stratigraphy. Given the uncertainties inherent to this preliminary study, the findings are somewhat ambiguous, but provided guidance for designing more controlled studies.

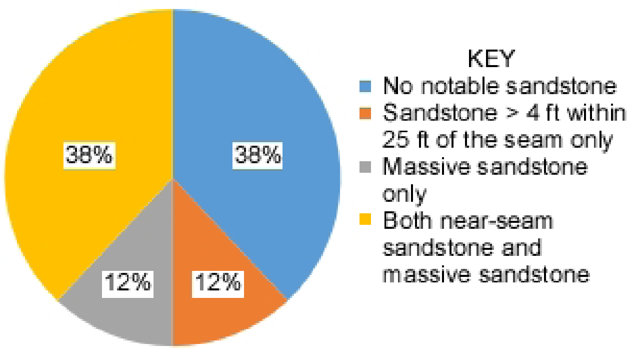


**Figure 5. Distribution of stiff unit data within the Non-Bumping Seam/Non-Bumping County data subset of the 95 USGS core logs examined during the empirical study.**

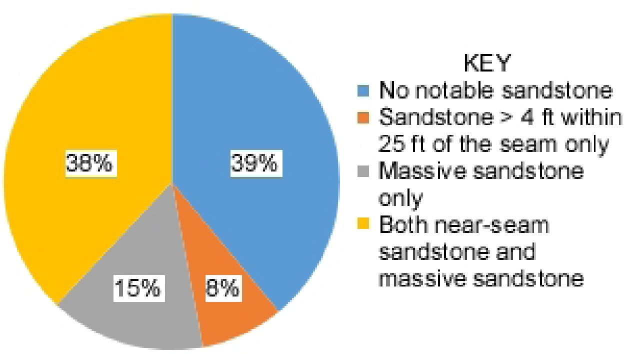


**Figure 6. Distribution of stiff unit data within the Bumping Seam/Bumping County data subset of the 95 USGS core logs examined during the empirical study.**

Most of the factors that may influence dynamic failure occurrence could not be reconstructed using the available data. However, depth of cover was readily available with respect to seam depth. Although isolated instances of bumping behavior have been documented under relatively low cover (Peperakis, 1958), it is likely that exacerbating influences, such as unusual faulting conditions, existed at the event locations and that these do not represent typical dynamic failure scenarios. Generally speaking, aside from these atypical cases, overburden depth may arguably be one of the most critical factors impacting the likelihood of the occurrence of dynamic failure phenomena. Within the original sample set, it was found that an overlapping range of overburden depths between 800' and 1400' contained both bumping and non-bumping cases. All logs where coal seam depth fell outside of this range were eliminated from the study, leaving 21 remaining logs. Of these, three were designated as non-bumping seam/bumping county and came from very tightly spaced drill holes. These cases were eliminated from the study, as they would not have been representative of the category as a whole, but rather only the local geology at that location. Of the 18 logs remaining, there were 12 different seam-county combinations. The number of non-bumping seam/non-bumping county deposits was 11, the number of bumping seam/non-bumping county deposits was 4, and 3 were from bumping seam/bumping county deposits. While this dataset is too small to produce meaningful results using statistical methods, it does make more detailed investigation of the complete stratigraphic information for each log feasible. The log records were reconstructed in detail, and the pertinent geologic variables available through these records were examined for correlation with bump history.

In this more limited empirical study, some correlation does appear to exist between bump history and the overall ratio of stiff-to-compliant units in the overburden as a whole, and subsequently with the presence or absence of discrete stiff units (Figure 7). However, this raises the question of whether or not the discrete units are significant in and of themselves, or rather symptomatic of the overall character of the host rock. Interestingly, a range of stiff-to-compliant values appears to exist for each sample subset; however, significant overlap exists between the non-bumping seam/non-bumping county and bumping seam/non-bumping county sample subsets. These ranges indicates that these groups represent general lithologic "types" that may be consistent across mining regions, and that it may in fact be these types that are most influential on dynamic failure phenomena, rather than the presence of discrete units alone.

From evaluation of typical stratigraphies in these core logs, three generalized stratigraphic columns were constructed: Compliant - corresponding to the non-bumping seam/non-bumping county dataset; Intermediate - corresponding to the non-bumping seam/bumping county dataset; and Stiff - corresponding to the bumping seam/bumping county dataset. The average ratio of stiff-to-compliant members for each group was 0.06, 0.5, and 2.87, respectively. It is important to emphasize, however, the large degree of overlap in the stiff-to-compliant ratios of the non-bumping seam/bumping (Intermediate) county and non-bumping seam/non-bumping (Compliant) county categories. In fact, the Intermediate category may only represent the upper range of the Compliant stratigraphic "type." Regardless, the Intermediate category provides a case study for a more transitional stratigraphy for use in numerical modelling studies. Three generalized stratigraphic columns were modelled after these types and are presented in the Appendix. The generalized columns were modeled after the specific stratigraphies in the available USGS columns, to maintain as close a semblance to real-world conditions as possible.

2 In several instances, logs did, in fact, indicate that the coal seam had been mined out. However, this was not a universal feature of log data.

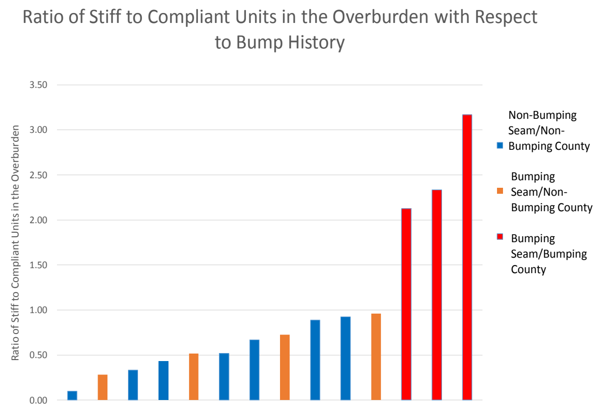


**Figure 7. The overall ratio of stiff-to-compliant stratigraphic members in the overburden as a whole for the non-bumping seam/non-bumping county dataset (blue), the bumping seam/ non-bumping county dataset (orange), and the bumping seam/ bumping county dataset (grey).**

To evaluate the relative influence of discrete stiff units versus lithologic stiff-to-compliant ratio, a series of numerical modeling parameter studies were designed using the generalized stratigraphic columns generated by the stratigraphic review. These examine the effects of modifying discrete member thickness and location relative to the seam within each of the aforementioned stratigraphic types, to determine how the character of the host rock will impact the capacity of discrete units to induce stress.

## OVERBURDEN EFFECTS ON STRESS

A parameter study using FLAC3D (Itasca Consulting Group, 2013) was conducted to determine the effect on the risk of coal bumps produced by the thickness and location of stiff members in three different coal mine roof "types": Compliant, Intermediate, and Stiff. A 1-ft-thick vertical cross section perpendicular to the gateroads of a longwall system with three 20-ft-wide entries, an 840-ft-wide longwall panel, and 140-ft-wide pillars was modeled. Depth of cover was set as 1200 feet. Vertical lines through mid-span of the longwall and middle gateroad served as symmetry lines. This configuration represents the state of stress at the completion of a developing panel, where redistributed stress from longwall extraction is directed primarily to the gateroad pillars.

Elastic and strength properties used in the numerical model were obtained from published values, and are listed in Table 1. The relationship between unconfined compressive strength and Young's Modulus is shown in Figure 8. Poisson's ratio was 0.25 for all units. Specific density was 150 lb/ft$^3$ for all units, except for coal, which was 80 lb/ft$^3$. Reported strength values for siltstone (Goodman, 1989) were reduced because the siltstone was interbedded, with bed thicknesses on the scale of several feet, rather than massive, where unit thicknesses may be on the scale of tens of feet.

The stress-versus-strain relationship for the gob in the numerical model was calculated by using LamPre, the preprocessor of LaModel 3.0 (Heasley, 2010), as illustrated in Figure 9. An 840-ft-wide gob was modeled at a depth of 1200 feet. Input parameters are listed in Table 2. LamPre default values were used for all other input parameters.

The double-yield model available in FLAC3D was then fit to the LamPre curve with the results shown in Figure 9. All mined panel zones were assigned the double-yield material model. The gateroad adjacent to the panel was not assigned the double-yield model, because of lack of caving that is generally observed in this area. This observation was confirmed by many results of a caving model (FLAC3D) using a wide range of input parameters.

Various thicknesses of the "Strong Sandstone," which is used as the stiff member variable in the different host rock settings, and whose properties are listed in Table 1, were inserted into each stratigraphic type in the numerical model at varying locations above the mine roof to determine the effect of this stiff unit on creating a bump risk factor. Placement and thickness of the stiff sandstone unit in each stratigraphic type was varied, as follows:

- The location relative to the coal seam of a 16-ft-thick stiff sandstone. The stiff beam member was moved up through the mine roof in 6-ft increments, beginning directly overlying the seam to a maximum distance of 66 ft above the coal seam.
- The thickness of a stiff sandstone unit located directly above, and adjacent to, the coal seam. This stiff beam member's thickness was incremented in 6-ft increments, from 6 ft to a maximum thickness of 96 feet.

The choice to use these particular thicknesses was guided by the work of Mark and Gauna (2015) and others (Maleki, 2006; Maleki and White, 1997; Iannacchione, 1990; Maleki, 1995; Agapito and Goodrich, 2000), who cite stiff units with similar thicknesses as increasing bump risk when proximal to the mine roof.

Failure of strong strata is likely to occur suddenly and induce a seismic event. Additionally, changes in abutment and pillar loading may increase the potential for bursting in the coal seam, whether sudden or as a result of stress distribution when strong strata is intact. Failure may also induce a "shock" bump, which occurs "where a strong massive stratum, either immediately over the coal or higher up if not too far above, ruptures as a beam of flat arch and a ground wave is imparted to an already highly loaded pillar support" (Rice, 1936). Rice stated that this is the principal type of bump observed in coal mines and postulated that when "the immediate roof is strong and elastic like a dense sandstone, it not only springs down and back to its former position but may also be set in vibration under certain conditions of an elastic roof layer and crushed pillars." For most of these cases, rupture of the strong member is an important factor.

The following conditions in the numerical model were used as criteria to identify the potential rupture of a strong massive stratum:

- Reduced thickness of a stiff member caused by partial failure, resulting in an "effective" thickness. It was assumed that risk of rupture was proportional to effective thickness.
- Zones of low factors of safety in stiff units.

These criteria were applied only for the case when the entries and longwall were excavated. Prior failures of stiff units were not evaluated.

**Table 1. Material properties for stratigraphic units used in the numerical model.**

| Lithology | Young's Modulus (psi) | Unconfined Compressive Strength (psi) | Friction angle (deg) | Cohesion (psi) |
|---|---|---|---|---|
| Strong Sandstone | 10000000[a] | 15288[a] | 44.5[a] | 3205[a] |
| Limestone | 7900000[b] | 5379[e] | 35[e] | 1400[e] |
| Sandstone-dominant interbedded unit | 5000000[b] | 4474[c] | 34[c] | 1189[c] |
| Siltstone | 3810000[a] | 3984[b] | 30 | 1150 |
| Mudstone | 3000000[c] | 3461[c] | 25[c] | 1102[c] |
| Shale | 1210000[b] | 1791[e] | 12[e] | 725[e] |
| Coal | 238000[d] | 900[f] | 30[g] | 260[d] |
| [a]Pariseau (2012) | | | | |
| [b]Goodman (1989) | | | | |
| [c]Lama and Vutukuri (1978) | | | | |
| [d]Chi and Yuwei (2013) | | | | |
| [e]Blyth and de Freitas (1984) | | | | |
| [f]Mark (2006) | | | | |
| [g]Calculated from unconfined compressive strength and cohesion | | | | |

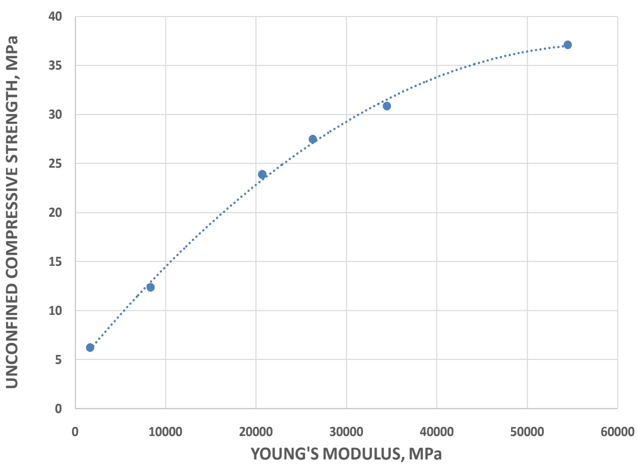


**Figure 8. Relationship between strength and stiffness for various rock types used in the numerical model.**

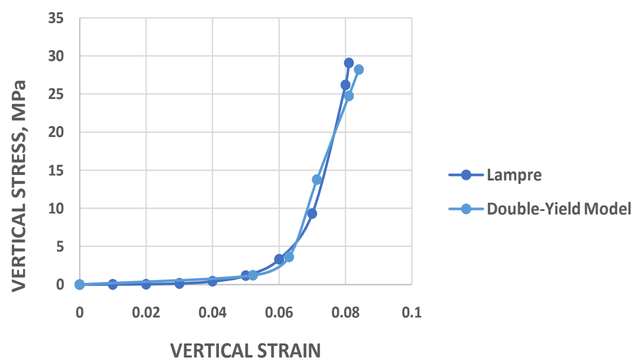


**Figure 9. FLAC3D double-yield model fit to gob stress-versus-strain curve developed by using Lampre.**

**Table 2. Material properties for stratigraphic units used in the numerical model.**

| | |
|---|---|
| Young's Modulus of coal seam (psi) | 238,000 |
| Unconfined compressive strength of coal seam (psi) | 900 |
| Poisson's ratio of rock mass | 0.25 |
| Vertical stress gradient (psi/vertical ft) | 1.0417 |
| Element width (ft) | 10 |

## COMPLIANT STRATIGRAPHY

Mining of the entries and longwall without the addition of the stiff member inserted in the Compliant host rock type resulted in a failure zone extending 400 ft into the roof, to include the 20-ft-thick interbedded sandstone unit and the 10-ft-thick limestone unit. That is to say, this failure zone represents the failure condition of the host rock alone, prior to the inclusion of the experimental variable. The Compliant stratigraphic column is available in Appendix 1-A.

The effect of altering the thickness and proximity to the coal seam of the stiff beam member on the potential for rupture in the Compliant lithology was similar to that found for the Intermediate lithology type, as discussed in greater detail in the next section. The driving factor behind this similarity is the composition of the immediate mine roof, which is shale in both cases.

When the location of the 16-foot-thick stiff member was incremented up through the stratigraphic column, it became apparent that a risk of rupture existed for a 16-ft sandstone unit of any height above the coal seam. This is due to the partial failure of the member and reduction of beam thickness to about 4 ft. The energy released by the rupture would decrease relative to the unit's height above the seam based on the maximum compressive stress in the unit. Put more simply, the energy decreases because of less stress on the beam.

When the thickness of the stiff member directly overlying the coal seam was incremented from 6 to 96 ft, it was discovered that for the Compliant case study, the highest risk of rupture was at a thickness of 12 feet. This may indicate a critical thickness for this unit when it is directly on top on the seam. Intuitively, rupture risk decreased with increasing thickness beyond this point. Results of this experiment are similar to those shown in Fig 13, which shows the stiff unit's effective stiffness relative to its initial thickness, through the range of experimental values.

Several caveats are noted with regard to conducting these modelling studies within the Compliant and Intermediate host rock types. The introduction of a stiff member will alter the stiff-to-compliant ratio of the overburden, and this ratio will naturally increase as the thickness of this unit increases. These studies are designed to evaluate the effects of discrete, or—in other words—spatially discontinuous units in lithology that may otherwise be identified as Compliant or Intermediate in nature. These are intended to simulate paleochannels or other unanticipated shifts in stratigraphy, which may not become apparent during mining until they have become problematic. Furthermore, due to the experimental nature of these studies, the boundaries of these features have been pushed far beyond what would reasonably be expected in a natural setting; it is unlikely, for instance, that a unit 96 feet thick would be unexpected or spatially discrete. These extremes have been included in the experimental studies in the interests of diligence and conservatism.

## INTERMEDIATE STRATIGRAPHY

In the Intermediate host rock type, a 40-ft-thick limestone unit was located above the massive shale roof, and positioned between shale units with lower elastic moduli. This hypothetical stratigraphic case study was influenced by core log data examined during the stratigraphic review in which a massive or semi-massive limestone unit was found in the overburden above the seams of interest. This condition was unique to Eastern deposits, or those within the Appalachian coalfields. However, strong sandstone units commonly associated with Western coalfields would, in theory, produce similar outcomes. It was determined that for the Intermediate host rock type that this geological configuration may contribute to a bump, independent of the introduction of a variable stiff member and based on the assumed criteria that rupture of overlying strata facilitates bumping behavior in coal mines. This limestone feature was fairly common in the available core log data, and is representative of an authentic stratigraphic condition. Failures induced during modelling experiments in the limestone unit reduced its effective intact thickness to 11 ft as shown in Figure 10, which then subsequently increased the potential of the remaining intact portion to rupture. The horizontal extent of the failed zones plot in Figure 10 is limited to two gate roads, one pillar, and part of the gob section of the mined panel.

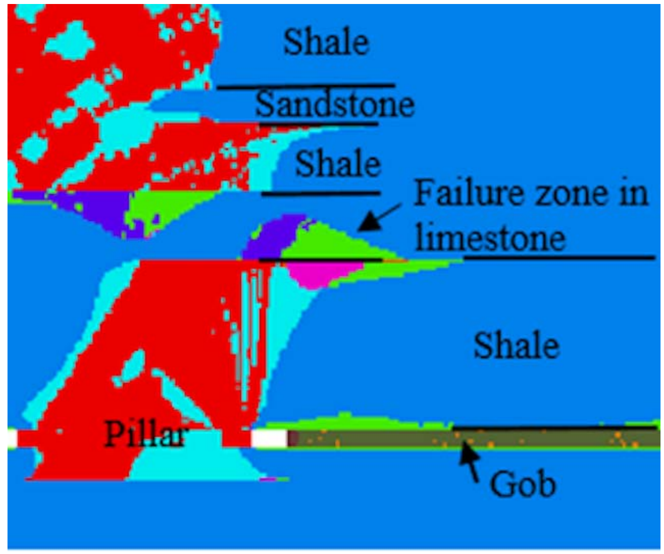


**Figure 10. Failed zones produced by the numerical model for Intermediate stratigraphy. Colors other than blue background or white gateroads denote a failure zone.**

### Effect of a 16-Ft-Thick, Stiff Sandstone Unit in Intermediate Stratigraphy

A 16-ft-thick, stiff sandstone unit was inserted into the Intermediate stratigraphy above, and adjacent to the coal seam, and then moved up through the mine roof in 6-ft intervals. The effect of this unit on bump potential was highest when it was located directly above the coal seam and in the path of redistributed stress from the mined longwall. This location resulted in two failed zones, which reduced the effective thickness of the stiff sandstone unit to 6 feet, as shown in Figure 11. The presence of the stiff sandstone unit adds to the bump potential that is already posed by the limestone unit. Instantaneous failure in the stiff sandstone unit remains feasible as the distance between the stiff unit and the coal seam increases, but less energy would be released as indicated by the decrease in maximum compressive stress in this unit as shown in Figure 12.

### Effect of a Stiff Unit with Increasing Thickness in Intermediate Stratigraphy

Two geological configurations were critical in producing possible ruptures when a stiff sandstone unit of increasing thickness was placed on the coal seam. The first case was for a 12-ft-thick unit placed directly above the coal seam. The risk of rupture in the stiff unit decreased as the unit became thicker, as illustrated by the increase in effective thickness as shown in Figure 13. However, the risk of rupture in the limestone unit increases as the thickness of the stiff unit increases—even though the rupture potential of the stiff member itself decreases. Location of imminent failure based on effective thickness changes from the stiff unit to the limestone unit when the initial thickness of the stiff unit is 18 feet, as shown in Figure 13.

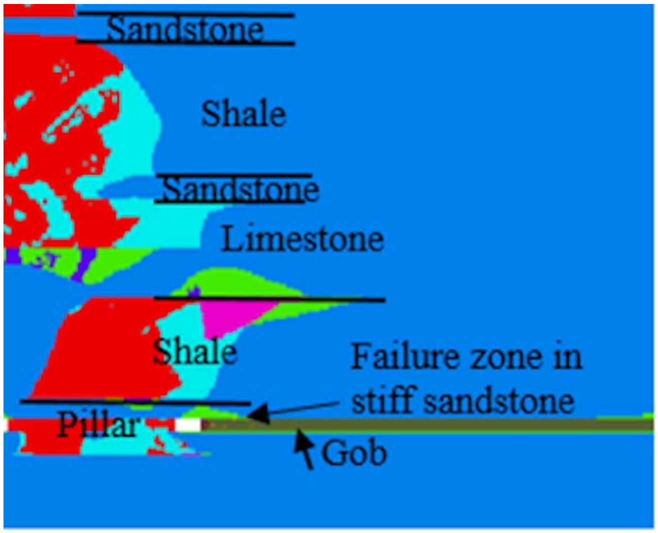


**Figure 11. Failed zones produced by the numerical model for Intermediate stratigraphy with a 16-ft-thick sandstone unit inserted directly above, and adjacent to, the coal seam. Colors other than blue background or white gateroads denote a failure zone.**

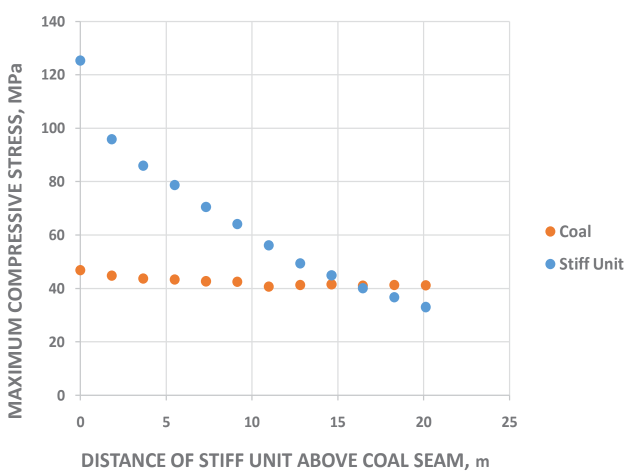


**Figure 12. Maximum compressive stress in a 16-ft-thick, stiff sandstone unit and coal seam for Intermediate stratigraphy.**

## STIFF STRATIGRAPHY

A Stiff lithology is less inherently likely to contribute to a potential rupture, based on the established rupture criteria, compared to an Intermediate stratigraphy, because the effective thickness of the siltstone is 90 feet, as shown in Figure 14, compared to 11 feet for the limestone in the Intermediate lithology, as shown in Figure 10. Development of this stratigraphic column was influenced by two Western deposits and one Eastern deposit, all of which have experienced bumps. It seems likely that real-world bumps in these settings may be the result of pressure, as well as other dynamic failure-inducing mechanisms. As this study examines the potential for the rupture mechanism only, pressure-induced bumps may not be represented in the numerical models. As such, it can be stated that this particular case study may be at

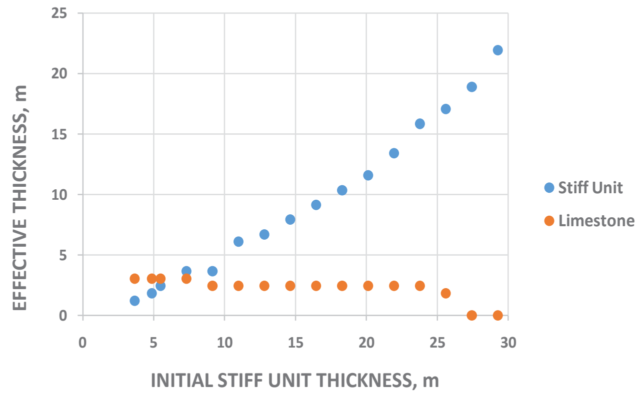


**Figure 13. Reduction in thickness of stiff unit caused by partial failure of the unit in Intermediate stratigraphy.**

low risk for rupture of roof units prior to introduction of the stiff member variable, but this does not discount the potential for other types of dynamic failure events.

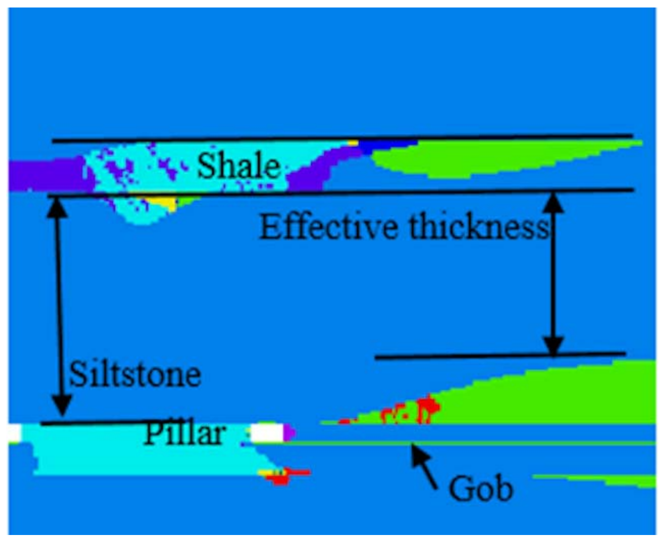


**Figure 14. Failed zones produced by the numerical model for Stiff stratigraphy. Colors other than dark blue or white gateroads denote a failure zone.**

### Effect of a 16-Ft-Thick, Stiff Unit in Stiff Stratigraphy

The effect of inserting a 16-ft-thick stiff sandstone unit into Stiff stratigraphy was assessed by using factors of safety zones less than 1.1, because failure did not occur in the 16-ft units and there was little failure in the massive siltstone roof. Absence of failure in the 16-ft-thick, stiff unit can be attributed to the relatively high stiffness of the immediate mine roof carrying some of the redistributed stress from longwall excavation. In Figures 15-21, factors of safety from 1.0, up to but not including 1.1, are denoted by color gradation from orange to background blue. Background blue denotes factors of safety greater than or equal to 1.1

The most significant effect of the stiff sandstone unit on the factor of safety occurred when the stiff unit was directly on the

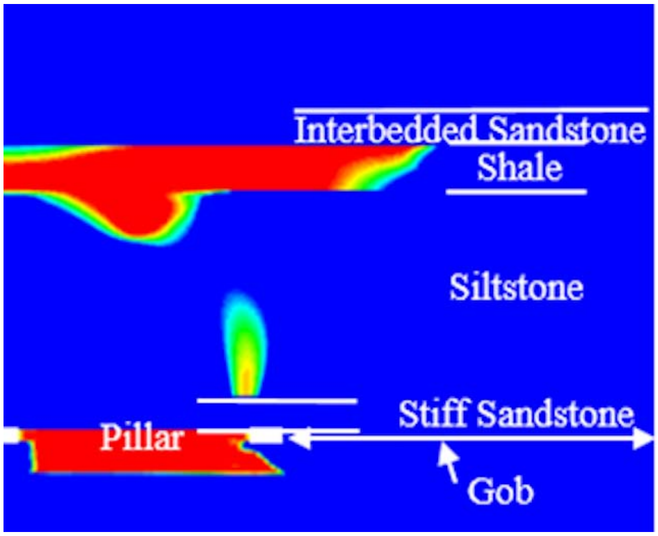


**Figure 15. Factors of safety for Stiff stratigraphy with a 16-ft stiff sandstone unit inserted on the coal seam.**

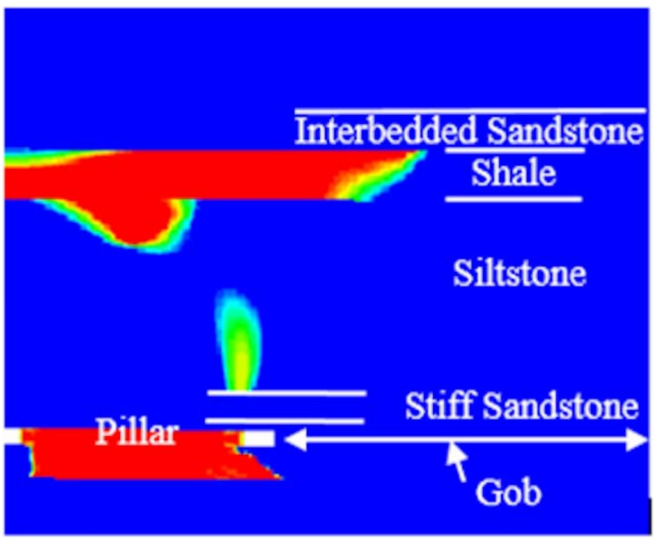


**Figure 16. Factors of safety for Stiff stratigraphy with a 16-ft stiff sandstone unit inserted 6 ft above the coal seam.**

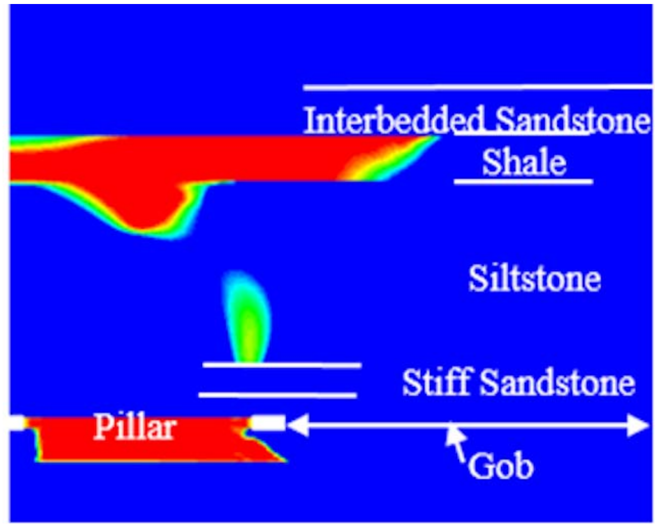


**Figure 17. Factors of safety for Stiff stratigraphy with a 16-ft stiff sandstone unit inserted 12 ft above the coal seam.**

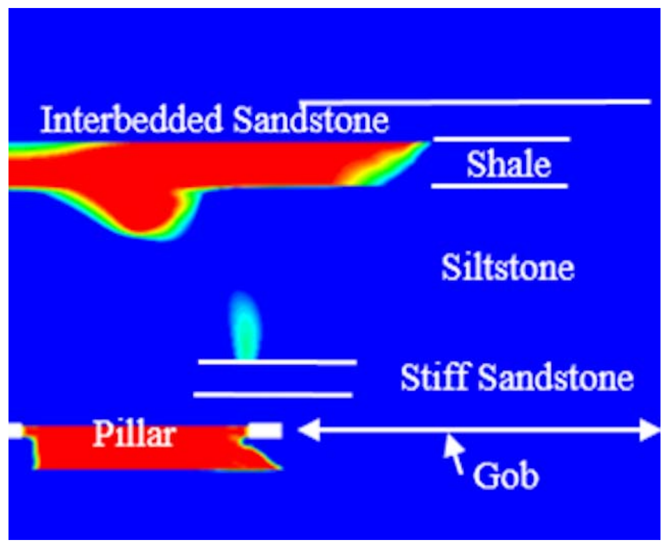


**Figure 18. Factors of safety for Stiff stratigraphy with a 16-ft stiff sandstone inserted 18 ft above the coal seam.**

coal seam as shown in Figures 15-18. The low factor-of-safety zone that was introduced into the siltstone by the stiff unit was caused by the limitation of vertical displacement, resulting in a shift of horizontal stress from compression to tensile. The effect of the stiff sandstone unit on factors of safety less than 1.1 decreased as the 16-ft-thick unit was moved up through the stratigraphy and above the redistributed stresses from longwall excavation.

**Effect of a Stiff Unit with Increasing Thickness in Stiff Stratigraphy**

The area of factor of safety less than 1.1 in the massive siltstone roof increases with increasing thickness of a stiff sandstone unit placed directly above the coal seam, as shown in Figures 19-21. Areas of low safety factor adjacent to failed zones are susceptible to microseismic activity (Andrieux et al., 2008), which could trigger complete failure of the siltstone roof. The upper and lower factor of safety zones in the siltstone became contiguous when the thickness of the stiff unit was 24 feet. The height of the contiguous zone was 115 feet. This scenario, illustrated in Figure 21, shows a zone of failure spanning up through the overburden from the stiff member to the shale unit. This zone grows progressively larger as the thickness of the stiff member variable increases in thickness up to 24 feet. At this point, failure becomes nearly continuous with the zone of failure in the overlying shale unit, effectively severing the massive siltstone roof from the overburden. This would have the potential to cause a large shock bump, were this siltstone to fall, and would stress the pillars as the weight previously supported by this stratum is redistributed. This example illustrates one potential mechanism for bump development in stiff host rock settings where a weaker more compliant bed may also be present.

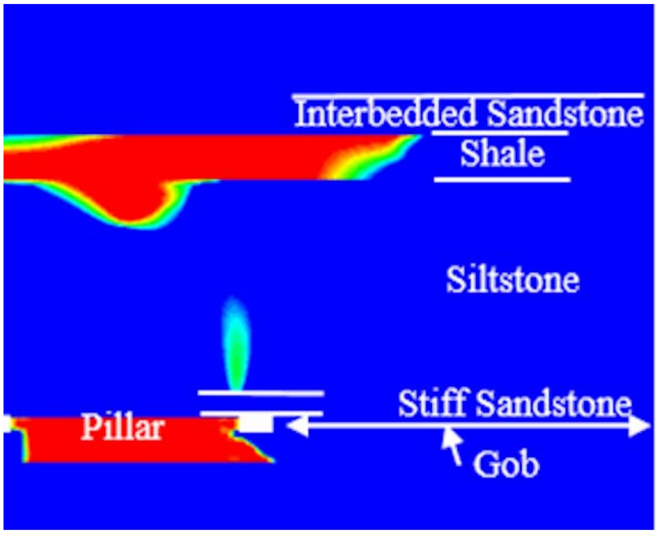


**Figure 19. Factors of safety for Stiff stratigraphy with a 12-ft stiff sandstone unit inserted on top of the coal seam.**

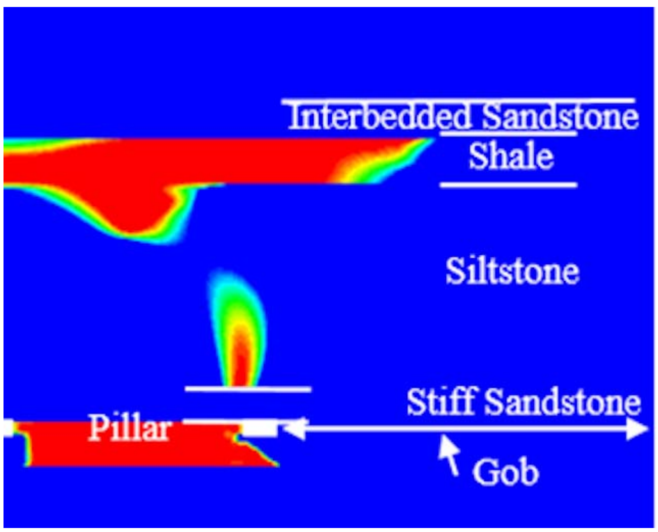


**Figure 20. Factors of safety for Stiff stratigraphy with an 18-ft stiff sandstone unit inserted on top of the coal seam.**

## CONCLUSIONS

The relationship of coal bump potential to the ratio of the overall stiff-to-compliant strata thickness could not be explained solely by the stress state produced by a two-dimensional numerical model of a longwall system. However, when a stiff sandstone unit of various thicknesses and locations was inserted into three different lithologies, the numerical model was useful in identifying areas that were near failure, which, if ruptured, could possibly produce a coal bump. The effect of the stiff sandstone unit on large-scale roof failure and potential coal bumps associated with this failure depended on the location of the unit in the stratigraphic column, the relative stiffness and strength of other structural members, and stress concentrations caused by mining.

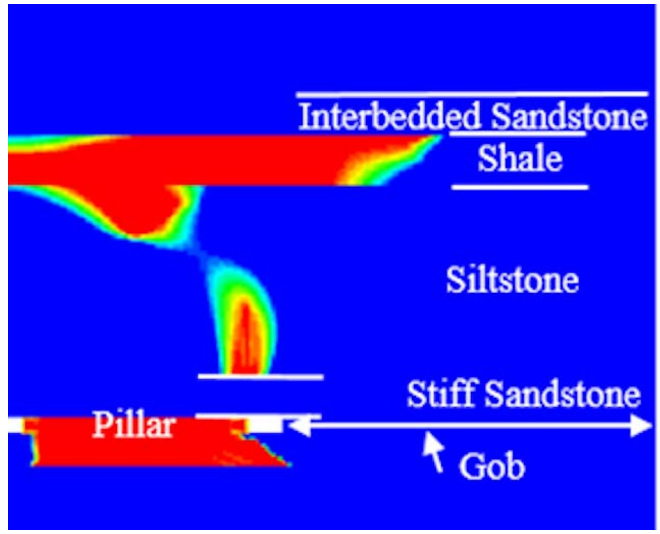


**Figure 21. Factors of safety less than or equal to 1.1 for Stiff stratigraphy with a 24-ft stiff sandstone unit inserted on top of the coal seam.**

Failure zones developed in a 16-ft stiff sandstone unit inserted into a relatively compliant shale roof, producing a risk of rupture in the sandstone. This risk existed for all heights of the sandstone above the coal seam, but maximum compressive stress in the sandstone, and probable energy released by its rupture, deceased with its height above the coal seam. The risk of rupture of the sandstone was coupled with the risk of rupture of a stiff limestone above the massive shale. On the other hand, failure zones developed above a 16-ft stiff sandstone beam inserted into a relatively stiff siltstone roof. The risk of rupture of the siltstone deceased as the sandstone unit moved up and away from the coal seam, and the stress concentration caused by longwall panel extraction.

The risk of a rupture of a stiff sandstone unit inserted on top of a coal seam in massive shale mine roof decreased as the unit became thicker. Failures occurred in units of all thicknesses but the effective thickness of these units also increased, which reduced rupture potential. The critical thickness of a stiff sandstone unit inserted on top of a coal seam in a massive siltstone roof was 24 feet. The presence of the sandstone created a 115-ft-thick zone of low safety factors in the siltstone.

Parameter study findings suggest that, for the experimental scenario, bump risk factor generally correlates with stiff-to-compliant ratio. The introduction of a very stiff member into the geological setting causes a concentration of stresses in stiffer strata, frequently resulting in a band of low factors of safety through the entire thickness of these members. This effect depends on the thickness of the introduced beam, the location of this beam in the geological setting, and the stiffness of the surrounding strata. When a stiff member delays caving, the risk of a dynamic event increases, either through eventual failure of the stiff member so that coal away from the fulcrum of the cantilever is dynamically impacted, or coal near the fulcrum is loaded to the point that strain bumping occurs. The ability to store potential energy increases the risk of a dynamic event. In this parameter study, a large stiff-to-compliant thickness ratio generally has a higher risk of bumps than a small stiff-to-compliant thickness ratio, but individual cases of stratigraphy need to be considered for bump risk factor.

Results suggest that the stiff-to-compliant ratio of the host rock has an impact on the relative stress-inducing effects of discrete stiff members. In other words, it is necessary to consider both the thickness and the distance to the seam, *within the context of the host rock*, to accurately anticipate areas of elevated rupture-induced hazard; acknowledging the presence of a discrete unit within the overburden in general terms is an insufficient indicator of risk. The case studies used in this experiment are modelled after common stratigraphies associated with non-bumping or bumping scenarios and can be expected to be realistic. Failure of stiff beam members may trigger strain- or strata-failure-driven bumps (Whyatt and Varley, 2009) in stiff host rock. Results shed light on the relative stress-inducing effects of individual stiff beam members relative to the nature of the host rock. However, the significance in these results is not that these critical thicknesses and distances should be applied outside of the case studies used here; rather, through modelling of anticipated changes in the placement and dimensions of discrete units within their stratigraphic setting, elevated bump hazard can be anticipated on a case by case basis. Were similar modelling studies conducted in tandem with tracking of problematic discrete stiff units, it may be possible to anticipate areas of elevated risk in advance of mining.

This study represents a beginning stage for the accurate weighting of dynamic failure risk factors, and with further research, ultimately predictive capability. Developing this predictive capability beyond identifying rupture potential in discrete roof members is essential to the eventual elimination of dynamic failure related worker injuries and fatalities. As stress is a necessary component in the occurrence of dynamic failure events, this finding helps to refine our understanding of the role of individual stiff, strong roof members in bumping phenomena, and suggests that a more holistic view of overburden lithology, combined with site-specific numerical modelling, may be necessary to achieve greater miner safety. Stress analysis conducted with detailed geology and combined with the monitoring of bumps offers a possible tool for more accurate risk assessment of bump potential in underground coal mining.

## APPENDIX

See Figure 22, Figure 23, and Figure 24.

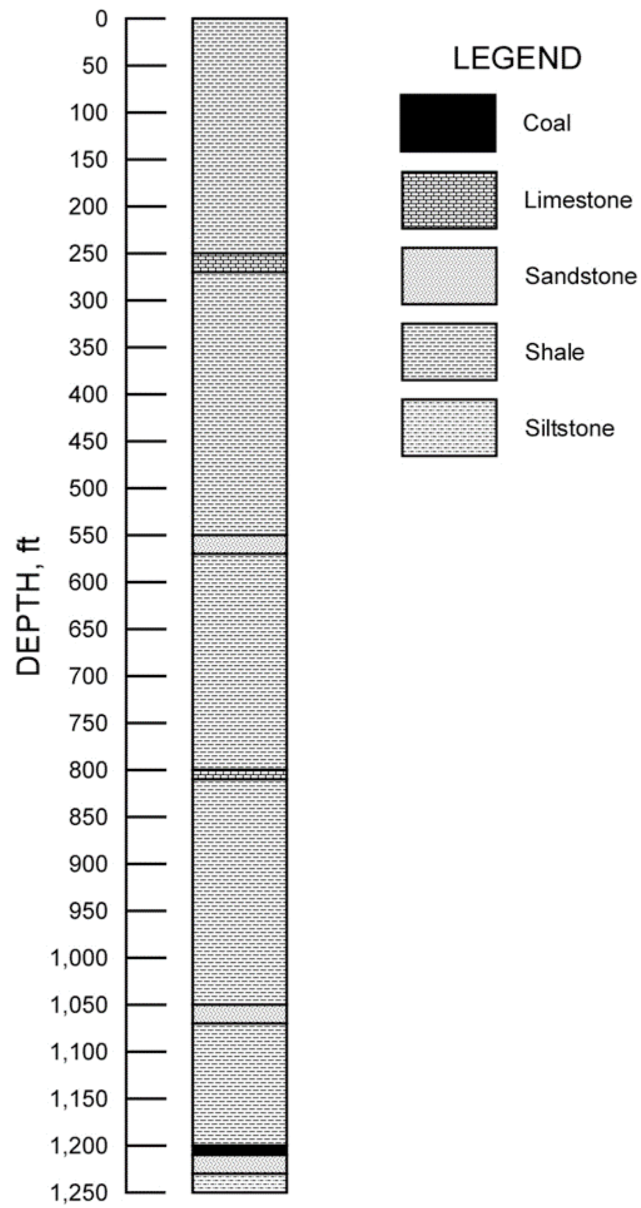


**Figure 22. Generalized stratigraphy for the non-bumping seam/ non-bumping county or Compliant dataset.**

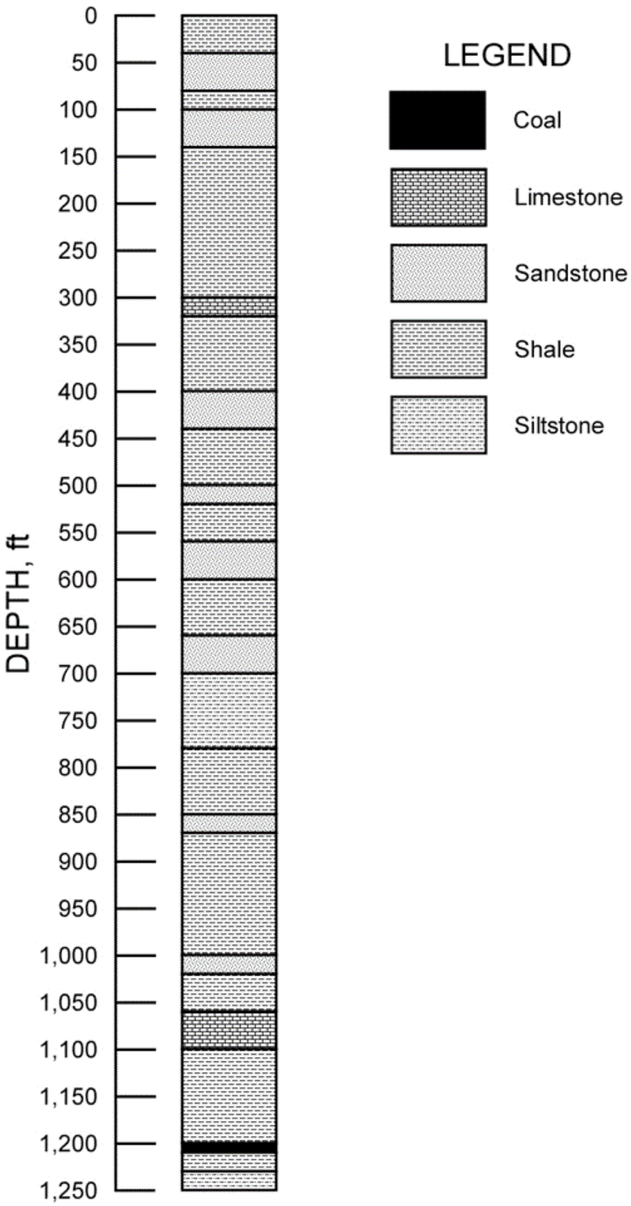


**Figure 23. Generalized stratigraphy for the bumping seam/non-bumping county or Intermediate dataset.**

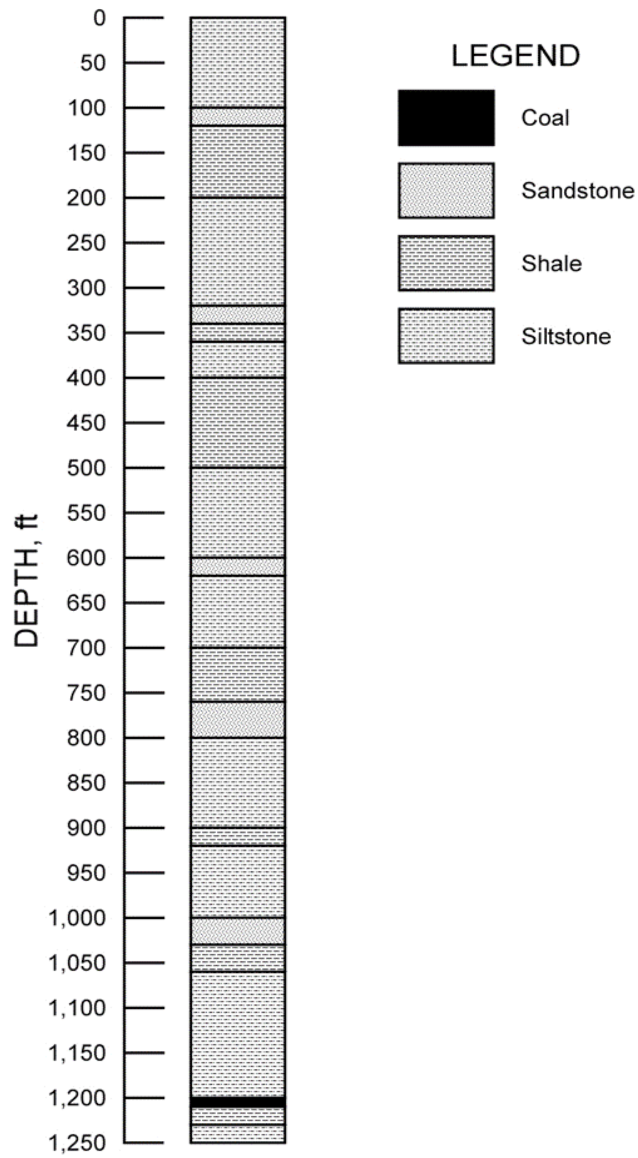


**Figure 24. Generalized stratigraphy for the bumping seam/ bumping county or Stiff dataset.**

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