Assessment of Pillar and Interburden Stability in Ultra-Close Multiple-Seam Mining Using Finite Element Modeling

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Abstract. Our primary evaluation tool for coal pillar designs is the Analysis of Coal Pillar Stability (ACPS) program, which is based on an empirical database of case histories. We apply the Rocscience RS2 two-dimensional finite-element modeling program to ultra-close multiple-seam scenarios to enhance existing methods in three main areas: 1) multiple-seam scenarios beyond the working limits of ACPS and the LaMode boundary element modell; 2) multiple-seam scenarios involving more than two seams, and 3) evaluation of interburden stability. In the first presented example, the severity of multiple-seam interaction is assessed by using the change in σ_1, while in the second presented example, plastic material properties are incorporated to predict failure potential in the interburden strata.

Examples of analyses from mining in eastern Kentucky's Upper Alma-Lower Alma-Pond Creek sequence and the Elkhorn No. 1-Elkhorn No. 2 sequence are presented, with results substantiated by field observations. In general, modeling results suggest that thick, strong sandstone units in the interburden inhibit multiple-seam interaction. The thickness of interburden, presence of sandstone, presence of joints, and width of underlying voids influence interburden failure.

Keywords: coal-mining · pillar · multiple-seam

1 Introduction

The Roof Control Division (RCD), performs approximately one hundred technical reviews of coal pillar designs per year. A handful involve mining in coal seams separated by an interburden thickness of less than 40 feet (12m), a configuration known as ultra-close mining [1]. The RCD's primary evaluation tool for coal pillar stability is the Analysis of Coal Pillar Stability (ACPS) program [2]. For multiple-seam configurations, experience is limited to an interburden of 40 feet [1]. ACPS calculates a Stability Factor to characterize the strength of pillars on a retreat-mining section. The Stability Factor is defined as the ratio of the Load-Bearing Capacity of pillars within the breadth of the Active Mining Zone (AMZ) to the sum of the loads acting on the AMZ. The AMZ is encompassed by the width of the panel and the distance from the retreating pillar line on the active section, given by $5\sqrt{\text{depth}}$. Determination of an overall Stability Factor for the pillar system provides a readily determined value that can be easily compared to the

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case history database to determine the likelihood of success or failure. It is, however, limited to assessing interactions between only two coal seams. The RCD also routinely applies the LaModel boundary element program to multiple-seam evaluations involving up to four seams [3]. However, the lamination thickness, which represents one of the main parameters of the program, has a lower limit of 50 feet (15m) before results become unreliable [4].

The RCD complements these methods by applying the Rocscience RS2 two-dimensional finite element modeling program. This paper will discuss two case studies from the eastern Kentucky coal field of the southern Appalachian Basin, where RS2 was applied to ultra-close mining situations involving room-and-pillar development mining.

2 Methodology

Cross sections were constructed in RS2 at the confluence of maximum depth, location of gob-solid boundaries or areas of pseudo gob, and minimum interburden. The models used unrestrained upper boundaries with sides constrained only in the x direction, with gravity as the primary loading mechanism. For simplicity and consistency, a minimum number of rock types are used, represented by coal, sandstone, and shale using Mohr-Coulomb criteria (Table 1).

One purpose of the models is to predict the stress effect from remnant pillars in previously mined seams on development mining. RS2 can be used to complement ACPS by multiplying the ACPS single-seam development Stability Factor by the ratio of RS2-determined single-seam to multiple-seam σ_1 to generate a modified multiple-seam ACPS Stability Factor, as summarized in Eq. 1:

$$SF_{RS2} = SF_{ACPS(SS)} \times \sigma_{1RS2SSavg}/\sigma_{1RS2MSpillar} \quad (1)$$

Table 1. Materials properties used in the RCD's RS2 models, in psf (pounds per square foot) and pcf (pounds per cubic foot).

Property	**Coal**	**Shale**	**Strong Sandstone**	**Weak Sandstone**
Density	85 pcf	146 pcf	165 pcf	150 pcf
Poisson's Ratio	0.3	0.2	0.1	0.1
Young's Modulus	$3.3\text{x}10^7$ psf	$2.88\text{x}10^8$ psf	$4.3\text{x}10^8$ psf	$2.3\text{x}10^8$ psf
Peak Tensile Strength	42,953 psf	58,464 psf	432,000 psf	97,000 psf
Friction Angle	35°	30°	35°	32°
Cohesion	30,076 psf	33,754 psf	302,490 psf	61,175 psf
Residual Friction Angle	30°	27°	30°	28°
Residual Cohesion	17,364 psf	29,788 psf	174,642 psf	32,527 psf

Where

$SF_{ACPS(SS)}$ is the ACPS single-seam development Stability Factor;
$\sigma_{1RS2SSavg}$ is the average single-seam development stress as determined by RS2 for all pillars in the cross section;
$\sigma_{1RS2MS(pillar)}$ is the average multiple-seam development stress as determined by RS2 for the pillar subject to greatest stress.

An average σ_1 value is first determined for six evenly spaced points through the core of each pillar along the cross section of interest. The average of those values is used to characterize all pillars along the cross section profile. Next, previous mining in overlying and underlying seams is added, and the pillar in the active seam that shows the highest average σ_1 value is identified. This value is considered the multiple-seam σ_1, or $\sigma_{1RS2MS(pillar)}$. The ACPS program determines the multiple-seam Stability Factor by multiplying the single-seam development Stability Factor by the ratio of single-seam development stress to single-seam + multiple-seam stress, with multiple-seam stress determined for the pillar subject to maximum stress by an internal boundary element algorithm known as Lam2D. With the RS2 method, the ACPS development Stability Factor is multiplied by the ratio of $\sigma_{1RS2SSavg}$ / $\sigma_{1RS2MS(pillar)}$ to maintain consistent methodology with ACPS. Alternatively, if a single pillar is of interest, the safety factor of that pillar can be determined by calculating the ratio of the pillar's strength as determined by the Mark-Bieniawski pillar strength formula to the RS2-determined σ_1 [5]. A comparison of safety factors can then be made between the development and multiple-seam stages to assess the effect of multiple-seam interactions on that pillar.

The second purpose of the models is to assess possible failure of strata in the interburden between the active and previously mined seams. In order to simulate predicted failure, plastic material properties are used and the model stages follow the actual sequence of mining.

3 Case Studies

3.1 Example 1

Proposed mining was assessed in the Lower Alma Seam, separated from the overlying Upper Alma Seam by an interburden of 35 feet (~11m), and from the underlying Pond Creek Seams by an interburden of 85 feet (~26m). The entirety of the interburden between the Upper and Lower Alma is represented by a single layer of gray sandstone, with 74% of the interburden between the Lower Alma and Pond Creek Seams represented by gray sandstone occurring as a 5.60-foot (1.7m) and 36.90-foot-thick (11.2m) layer. An additional 20.70-foot-thick (6.3m) layer is interpreted as weak sandstone for model purposes because it hosts coal streaks (Table 1). Depth reaches a maximum of nearly 400 feet (122m) beneath a narrow ridgetop and pillars between Entries #5–7 are subject to overlying and underlying gob-solid boundaries in the Upper Alma and Pond Creek, respectively (Fig. 1).

The pattern of σ_1 distribution shows stress concentration on the right side of the panel near the stacked gob-solid boundaries in the Upper Alma and Pond Creek, accentuated by depth (Fig. 2).

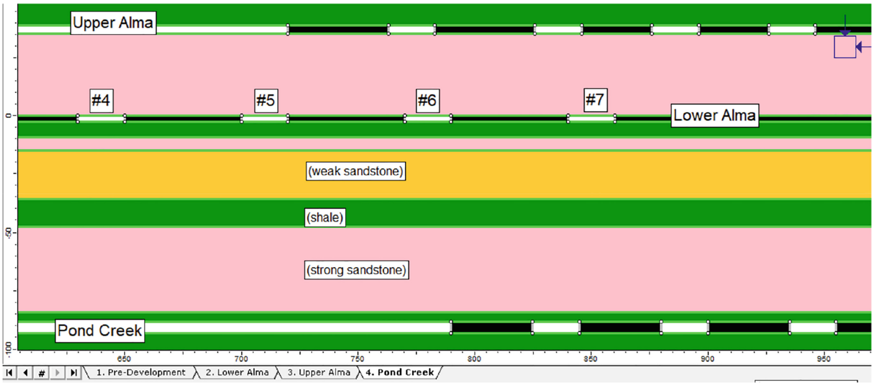

Fig. 1. Detailed strata and mining configuration on right-hand side of panel.

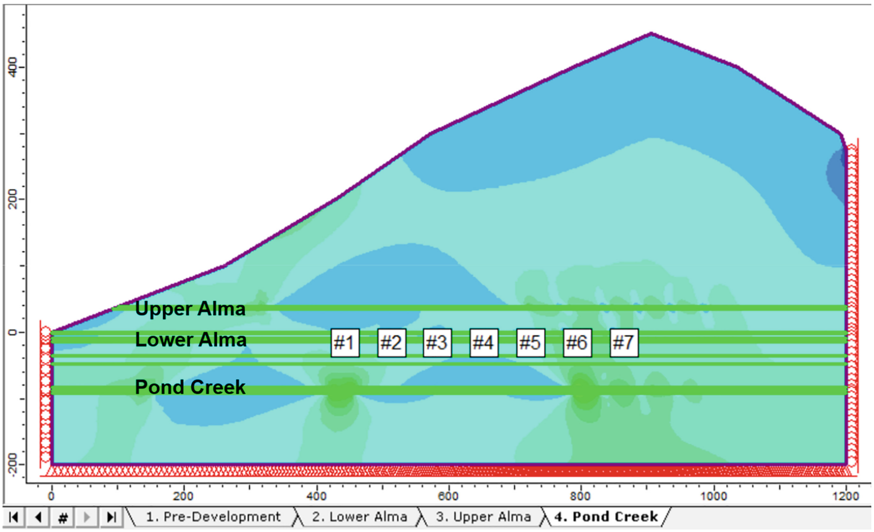

Fig. 2. Distribution of σ_1 when all three seams have been mined. Deeper blue represents low stress areas, particularly above gob. Darker green indicates higher stress concentration.

A single-seam development stress for the Lower Alma is determined for the pillar between Entries #6 and #7 (Fig. 3). Next, the multiple-seam development stress is determined by adding the Upper Alma and Pond Creek Seams (Fig. 4). This results in a change at the middle of the interburden sandstone from 64,000 psf (312,475 kg/m^2) to 113,500 psf (554,155 kg/m^2), an increase of 77%, with 344 psi attributable to multiple-seam influence. This represents the equivalent of adding 312 feet (95m) of depth to the single-seam configuration. Most of this change is attributable to the Upper Alma, with only 10% contributed by the underlying Pond Creek, suggesting that the substantial sandstone interburden effectively shields the Lower Alma from previous Pond Creek mining influence.

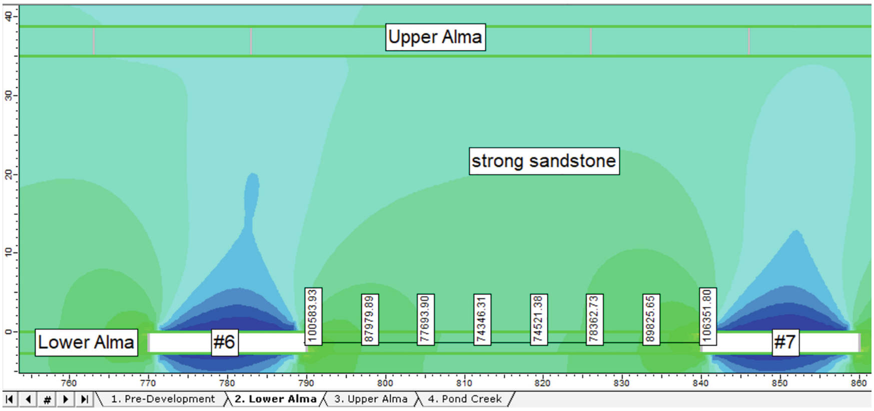

Fig. 3. Distribution of σ_1 in sandstone interburden between Upper Alma and Lower Alma after single-seam development of Lower Alma, with σ_1 values in pillar core between Entries #6–7 indicating average value of 80,461 psf (392,845 kg/m^2). Interburden is 35 ft. (10.7 m).

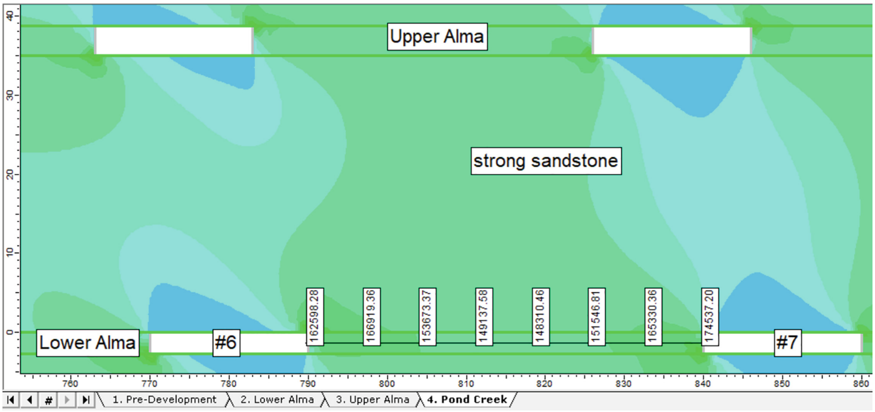

Fig. 4. Distribution of σ_1 in sandstone interburden between Upper Alma and Lower Alma after adding mining in both the Upper Alma and the Pond Creek Seam. Average σ_1 value in pillar core is 155,816 psf (760,760 kg/m^2)

ACPS would characterize the Lower Alma pillars with a Stability Factor of 5.19 for the interaction with a gob-solid boundary in the Upper Alma, and with a Stability Factor of 3.77 for the interaction with an isolated remnant pillar in the Pond Creek. Using the method described previously for modifying the ACPS Stability Factor, the single-seam development Stability Factor of 9.18 is multiplied by the ratio of RS2-determined single-seam σ_1 to multiple-seam σ_1, which is 67,253 psf/155,816 psf or 0.43, to obtain a modified ACPS Stability Factor of 3.96. Therefore, the effect of multiple-seam interaction reduces the Stability Factor by 56%. When assessing individual pillars, those between Entries #5 and #7 are of greatest interest because they are subject to the greatest depth and are proximal to gob-solid boundaries in the overlying and underlying

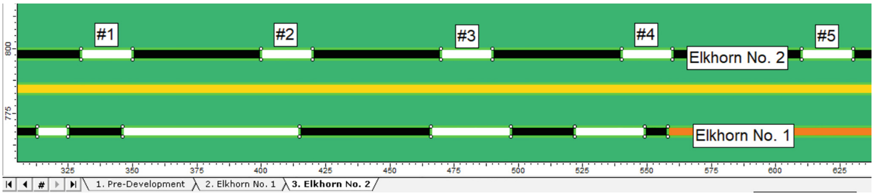

Fig. 5. Cross section showing mining configuration in Example 2.

seams. To apply the previously described method of evaluation for individual pillars, the calculated pillar strength of 6,579 psi determined by the Mark-Bieniawski pillar strength formula [5] is divided by the single-seam RS2-determined σ_1 to obtain single-seam safety factors of 12.43 and 11.79, respectively, for the pillars bounded by Entries #5–6 and #6–7. The pillar strength is also divided by the multiple-seam RS2-determined σ_1 to obtain multiple-seam safety factors of 8.45 and 6.08, respectively, for the same pillars. While representing a decrease in safety factor of 32% and 48%, respectively, the calculated safety factors are still well above unity. Despite the 77% increase in σ_1 within the sandstone in the interburden, the high pillar safety factor suggests that the Lower Alma pillars are being shielded from the effects of stress concentration by the strong sandstone interburden. Inspectors noted no influence on roof or pillar conditions near the Upper Alma gob-solid boundaries, suggesting validation of the RS2 predictions.

3.2 Example 2

Proposed mining in the Elkhorn No. 2 Seam is underlain by abandoned workings in the Elkhorn No. 1 Seam, separated by an interburden of only 25 feet (7.6m) of shale with an intervening 4-foot-thick (1.2m) layer of weak sandstone (Fig. 5). Plastic material properties are used to assess the potential for failure within the interburden. The discussion references the interaction below the #1 and #2 Entries in the Elkhorn No. 2 Seam because of the wide void situated beneath the pillar.

A cross section indicates elements failed in shear extending from the margins of the Elkhorn No. 1 void upward into the interburden to the margins of the pillar separating the #1 and #2 Entries (Fig. 6). These failed elements are predicted to be restricted to the shale, and do not penetrate the weak sandstone, although failure penetrates the sandstone when joints are added. The models suggest that failure of the interburden is possible for a critical void width, especially in the presence of jointing. This interpretation and results of modeling were validated when development mining in the Elkhorn No. 2 advanced for a short distance from outcrop and encountered open fractures in the floor, from which "gob gas" was emanating, resulting in termination of mining.

4 Summary and Conclusions

The RCD employed the Rocscience RS2 two-dimensional finite element modeling program to assess ultra-close mining scenarios. RS2 can enhance existing ACPS pillar stability analyses by comparing the distribution of σ_1 values in the development stage

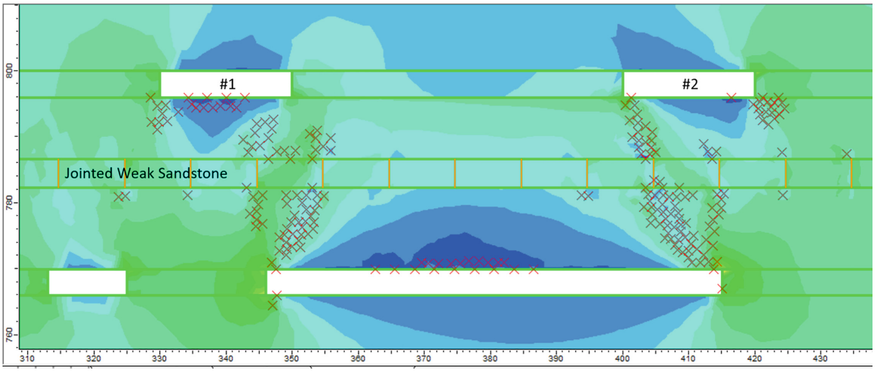

Fig. 6. Distribution of σ_1 with X's representing failed elements. Vertical orange lines in 4-foot-thick (1.2m) weak sandstone in interburden between Elkhorn No. 1 and Elkhorn No. 2 represent joints.

and multiple-seam stage. The change in RS2-determined σ_1 can be assessed at various points of interest in the interburden or individual pillars to characterize the effect of previous mining, either by direct comparison of raw values or by comparison of modified ACPS Pillar Stability Factors. RS2 predicts little stress transfer between subjacent seams when thick, strong sandstone is present in the interburden, particularly at shallow depths.

RS2 offers a way to assess the potential for interburden failure in ultra-close mining scenarios when plastic material properties are used. Interburden stability appears to be an interplay between span, rock type, rock strength, and interburden thickness, and may be influenced by the presence of joints.

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