

## Decreasing coal bump risk through optimal cut sequencing with a non-linear boundary element program

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**ABSTRACT:** In room and pillar coal mining, violent coal bumps can occur during the retreat mining phase when stress levels in pillars adjacent to the gob area reach their maximum. Proper mining sequences can decrease the risk of bumps. This paper describes a non-linear boundary element program, MULSIM/NL, used to evaluate cut sequences for retreat mining that decrease the coal bump risk.

Program MULSIM/NL features six material types (linear and non-linear) and an energy subroutine to obtain energy release rate (ERR) values for a mining sequence. The ERR gauges the coal bump risk and the relative desirability of different mining sequences. ERR studies with MULSIM/NL suggest the Olga Mine method's superiority for retreat mining in bump prone conditions over other methods such as single split and fender, pocket and wing or open ending.

### 1 INTRODUCTION

In room and pillar retreat mining, stresses in the rows of pillars adjacent to an expanding gob area reach their maximum. A difficult design question facing mine operators is mining method selection that helps reduce the risk of coal bumps. Judicious use of numerical models and the energy release rate concept can help engineers select proper retreat mining cut sequences that may minimize this risk.

The Bureau has developed numerical analysis tools to minimize the bump hazard. This paper describes development and use of MULSIM/NL which features non-linear in seam material properties and energy release rate (ERR) calculations. This model and the ERR concept are used to select retreat mining cut sequences that minimize coal bump risk.

### 2 THE BEM PROGRAM MULSIM/NL

MULSIM/NL is a boundary element method (BEM) program that calculates three dimensional stresses and displacements caused by mining tabular deposits like coal seams. Recent additions to a related program (Beckett and Madrid, 1988) include non-linear material properties, multiple mining steps and ERR calculations. MULSIM/NL analyzes single or multiple coal seams at any orientation with respect to the virgin stress field. It calculates stress and displacement (convergence) in a modeling grid within each seam plane. MULSIM/NL allows an 80 X 80 coarse block array and a 100 X 100 fine mesh element array.

As with most BEM programs, a linear elastic rock mass surrounds the seams; however, additional material models were developed for the in seam block and element materials. The non-linear material models facilitate calculations of stresses and displacements more akin to those observed and measured in the field. Figure 1 shows these stress strain models which include: 1) linear elastic for coal, 2) strain softening, 3) elastic plastic, 4) bi-linear hardening, 5) strain hardening, 6) linear elastic for gob. The first three are intended for the unmined, in-seam coal material, while the latter are for the broken gob material left in the wake of mining. Model 2 (strain softening), after Crouch and Fairhurst (1973), approximates the "yielding" behavior of small pillars or large pillar perimeters while model 3 (elastic plastic) approximates a "pseudo-ductile" behavior in pillar cores. Model 5 (strain hardening) allows the gob material to increase in stiffness as it consolidates under increasing load. Model 4 (bi-linear hardening) permits a certain amount of deformation to occur prior to introducing stiffness. Models 1 and 6 are basic linear elastic models for coal and gob respectively.

Implementation of these non-linear material models required major changes in the MULSIM/NL solution procedure from an induced stress formulation to a total stress approach. Non-linear stress strain behavior is accomplished by adjusting the secant modulus for each element during the iterative equation solving process. Convergence is achieved when equilibrium stresses and strains at each element lie on the failure locus defined by the element's stress-strain curve.

Since mining is a progressive activity, MULSIM/NL also has multiple mining step capabilities. Each mining step represents the mine geometry at one point in time. The multiple mining step feature enables calculation of stress and displacement changes essential for ERR calculations.

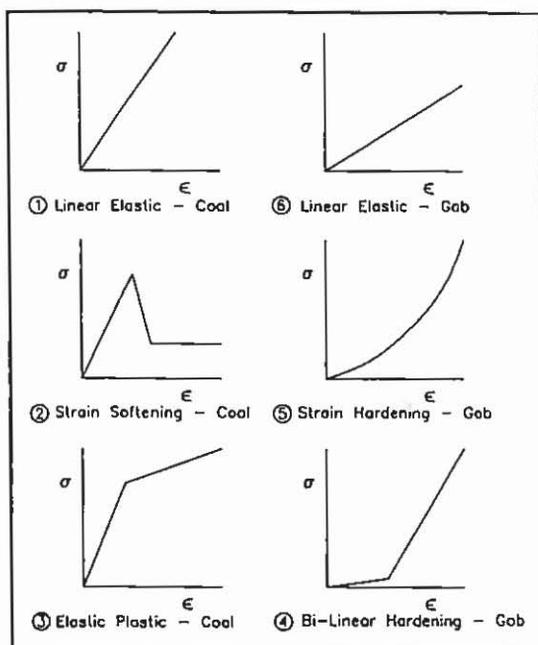


Figure 1. Stress-strain models for MULSIM/NL.

### 3 ENERGY CALCULATIONS IN MULSIM/NL

Studying the enormous energy changes occurring in the rock mass during mining led to the ERR concept (Cook et al., 1966) that has since become an important tool in rock burst hazard abatement. Creating an opening underground increases the potential energy of the overall rock mass system. Part of the energy is stored as elastic strain energy while the rest is dissipated or released, mostly as heat. A very small fraction

of the energy release may appear as seismic energy in the form of a damaging rock burst or coal bump; hence the correlation between ERR and the incidence or risk of damaging rock bursts.

The concept has seen limited application in bump control for coal mines. Crouch and Fairhurst (1973) used a variation of ERR to demonstrate the superiority of longwall extraction over various pillar extraction techniques for decreasing the ERR hence decreasing the risk of coal bumps. Similarly, Maleki et al. (1987) also used a non-linear BEM program and ERR to examine different extraction sequences and justify an increase in barrier pillar width to decrease bump risk.

MULSIM/NL contains an energy subroutine that uses the calculated stress and displacement fields to obtain ERR values for each mining step. Salamon (1984) provides the theoretical basis with the following relationship:

$$W_R = U_M + \frac{1}{2} \int_{S_M} \sigma_{i-1} \Delta u_i \, dS + \frac{1}{2} \int_{S_B} (1 - \alpha_i) \Delta \sigma_i \Delta u_i \, dS$$

where:

$W_R$ = total energy release during "i" step	$\sigma_{i-1}$ = prior stress in coal
$U_M$ = strain energy release from mined coal	$\Delta \sigma_i$ = stress change ( $\sigma_i - \sigma_{i-1}$ )
$S_M$ = area mined during "i" mining step	$\Delta u_i$ = disp. change ( $u_i - u_{i-1}$ )
$S_B$ = total gob area	$\alpha_i$ = non-linearity factor

Salamon (1984) discusses how this energy relationship exhibits a mining step size dependence. When the step size becomes infinitesimally small, then the second and third terms approach zero and the total energy release equals the strain energy release in the mined material. In practical BEM calculations, the second term (kinetic energy release) usually dominates the first term (strain energy release) and the third term (non-linear backfill energy release) by a factor of 10. Sometimes in practical BEM calculations, the kinetic energy release (second term) is the only ERR term actually calculated as was done by Maleki et al. (1987). The energy subroutine in MULSIM/NL is complete in that the smaller terms are retained. This completeness may be essential when coupling the energy subroutine with other numerical procedures such as finite element methods. In addition, the MULSIM/NL energy subroutine calculates the strain energy density in each element of the mesh. While the ERR provides a global indicator of the bump potential for a particular mine model, the elemental strain energy density identifies specific areas of the model prone to bump.

#### 4 CUT SEQUENCE MODELS

During room and pillar retreat mining in bump prone conditions, properly sequencing the cuts may help decrease the coal bump risk. Many other rock mechanics factors such as panel width and barrier pillar size also require consideration; however, this study focuses on the cut sequences used to recover pillars adjacent to a gob area when the greatest bump risk exists. ERR serves as the criteria for selecting the best method from: 1) Single Split and Fender (SSAF), 2) Pocket and Wing (PKAW), 3)

Open Ending (OPEN) and 4) Olga Mine Method (OLGA). Kauffman et al. (1981) document the first three methods in their study of room and pillar retreat mining methods while Campoli et al. (1989) discuss the Olga Mine method in their geotechnical study of room and pillar mining under bump prone conditions. Figure 2 illustrates the basic BEM model used to analyze each of these four methods and shows the 12 cuts used to extract a pillar in the mine plan.

Calculating the ERR for these four cut sequence models proceeded in two phases: first linear elastic and then non-linear. Back calculation from stress and displacement data obtained in a large field study at the Olga Mine (Campoli et al., 1989) determined the basic material property values for numerical modeling. Best estimates of the modulus values for the surrounding rock mass, the coal and the gob are 20,000 MPa (2,900,000 psi), 500 MPa (72,500 psi) and 50 MPa (7250 psi) respectively.

The non-linear studies utilized two elastic plastic models for those coal elements adjacent to and one row in from a mined out opening. Modulus is 500 MPa (72,500 psi) for both while the "yield" stress is 10 MPa (1450 psi) for the outer elements and 20 MPa (2900 psi) for the inner elements. A vertical stress of 10 MPa (1450 psi), equivalent to about 400 m (1300 ft) depth, is applied to the model while the horizontal stress is zero. Experience with this program suggests that horizontal stress has little influence on the ERR calculations.

## 5 MODEL COMPARISONS

The two ERR criteria used to evaluate the bump potential are first the maximum ERR in a mining sequence and second the uniformity of ERR during a sequence. Cook et al. (1966) developed a correlation between ERR and the number of damaging rockbursts per area mined in South African gold mines. Note that ERR correlates with the number of rockbursts and is not a threshold for the onset of these events. South African studies have also noted that a uniform ERR during a mining sequence is less burst prone than a highly variable ERR. By analogy, a

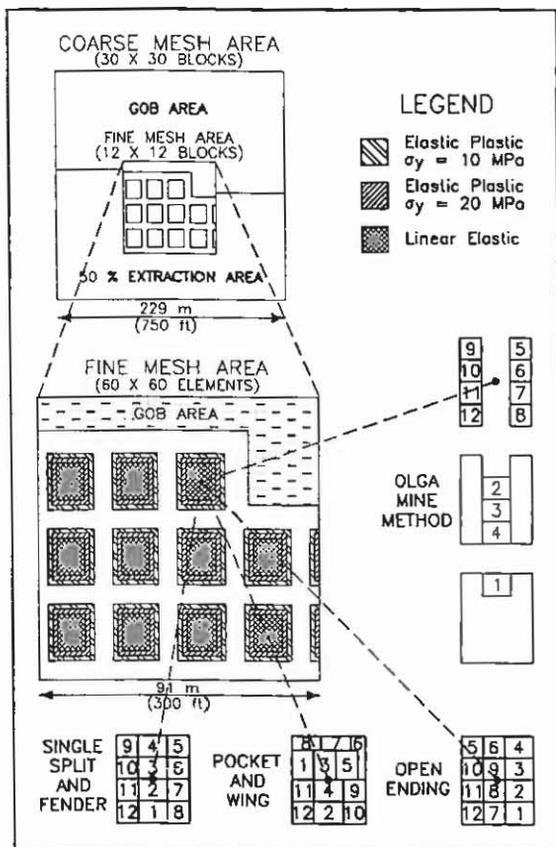


Figure 2. Basic BEM cut sequence models.

mining sequence with a low maximum ERR as well as a uniform ERR has less risk of experiencing a bump and hence is a safer, more desirable alternative.

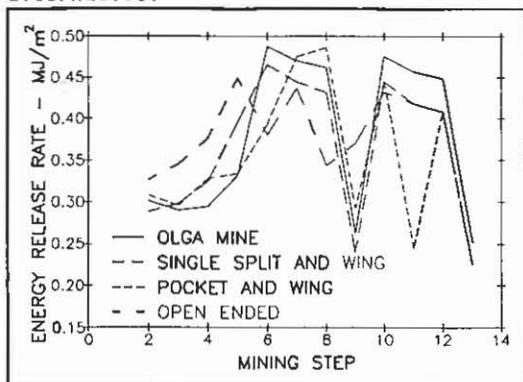


Figure 3. ERR versus mining step - linear models.

Figure 3 plots the calculated ERR versus mining step for the four linear cut sequence models. Table 1 compares maximum ERR and the uniformity in ERR. The maximum ERR occurs early in the cut sequence (around steps 4 through 7 depending on method) during pillar core extraction. Maximum ERR differs by no more than 9% with the open ending method having the lowest maximum ERR. This difference is not very great thus the amplitude of the ERR may not be a reliable indicator of the bump-proneness

of a particular mining method or cut sequence.

ERR uniformity (or the rate of increase of ERR) is measured as the percent increase between local lows and highs in the ERR sequence. A lower % increase indicates greater ERR uniformity hence less bump risk. With the uniformity criterion, the mining steps associated with pillar core extraction are given more weight in the evaluation. The increase in ERR between mining steps 9 and 10 for the OLGA, SSAF and PKAW methods is discounted because it is presumed associated with the extraction of broken or "yielded" coal left in the original pillar edges. However, the fact remains that this large increase in ERR does occur in the numerical calculations, and it may represent yet another serious shortcoming of the ERR technique in evaluating the bump-proneness of a particular mining method or cut sequence. During pillar core extraction the uniform ERR criterion indicates that the open ending method is best, and there is no significant difference between the other methods. The linear models indicate superiority of the open ending method; however, since these models do not calculate observed stresses and displacements well, the ERR calculations are suspect.

Table 1. Linear Models - Maximum ERR Comparison and Significant Increases in ERR

Model	Maximum ERR MJ/m <sup>2</sup>	Step	% Higher Than Base	Begin Step	End Step	% Incr. in ERR
OLGA	0.488	5	+9%	2	5	+68%
SSAF	0.465	5	+4%	1	5	+61%
PKAW	0.486	7	+8%	2	7	+64%
OPEN	0.449	4	0%	1	4	+38%
				5	6	+15%
				7	9	+26%

Figure 4 presents the calculated ERR versus mining steps for the four non-linear cut sequence models. With non-linear coal seam behavior, calculated stresses and displacements adequately reflect field measurements. As shown in Table 2, by a lowest maximum ERR criterion, the Olga method is marginally better than open ending and single split and fender and much better than pocket and wing. The differences in ERR amplitude are small (except for the PKAW method), and they may be insignificant.

The real advantage to the Olga method lies in its uniform ERR which only increases slightly at one point. As with the linear models, the mining steps associated with pillar core extraction are given more weight in the evaluation, and the increase in ERR occurring between mining steps 9 and 10 is discounted. ERR for the Olga method remains constant or else decreases; however, the rate of increase of ERR ranges from 10 to 42% for all other methods. With the non-linear models, low maximum ERR and uniform ERR criteria suggest superiority of the Olga Mine cut sequence method.

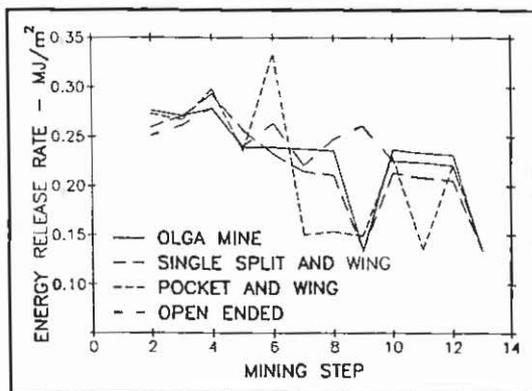


Figure 4. ERR versus mining step - non-linear models.

Table 2. Non-Linear Models - Maximum ERR Comparison and Significant Increases in ERR

Model	Maximum ERR MJ/m <sup>2</sup>	Step	% Higher Than Base	Begin Step	End Step	% Incr. in ERR
OLGA	0.278	3	0%	2	3	+3%
SSAF	0.293	3	+5%	1	3	+13%
PKAW	0.334	5	+20%	2	3	+12%
				4	5	+42%
OPEN	0.279	3	+1%	1	3	+11%
				4	5	+10%
				6	8	+18%

## 6 POTENTIAL PITFALLS OF ERR CALCULATIONS

Certain precautions are required for valid ERR comparisons both between mining steps within a model and between different models. First, the area mined per step must remain constant or nearly constant, and second, comparisons between different models must always use the same rock mass modulus. Finally, ERR criteria may not always provide a clear discrimination between the relative merits of various mining methods or cut sequences.

ERR is an average energy release for all the elements extracted in that step. Considerable variance may exist among the energy releases for the elements mined that step. Large extraction areas (large numbers of extracted elements) tend to mask energy release highs within that

step and may give a false impression of uniformity. Since ERR averages the energy release for each element mined that step, better comparisons result when the number of elements mined per step remains constant or nearly constant. Ideally, each mining step should extract the smallest area possible i.e. one element per step; however, the modeling effort must balance this ideal with available computing resources.

The second requirement calling for the same rock mass elastic modulus when comparing different models stems from a paradox regarding ERR as applied to coal bumps. Many researchers have noted that coal bumps occur in seams surrounded by stiff, massive, competent strata such as thick sandstone layers and not in seams surrounded by incompetent strata such as shales. This argument assumes that sandstone equates to a high modulus rock mass and shale to a low modulus rock mass. In BEM calculations, ERR varies inversely as the rock mass modulus. Therefore, the ERR calculated for a low modulus rock like shale is greater than the ERR for a high modulus rock like sandstone, and one could erroneously conclude that mining coal seams surrounded by shales presents a greater bump hazard than mining seams within sandstones - quite contrary to observation.

Existence of this paradox does not negate ERR's value. Valid ERR comparisons between different models or mine sites must use the same rock mass modulus. Furthermore, ERR cannot provide a universal threshold value marking the onset of bumps in mines. It may only serve as a relative indicator of the bump hazard to evaluate mining methods and cut sequences at one site or group of sites with the same rock mass modulus value.

As shown in figures 3 and 4, ERR criteria do not always provide a clear discrimination between the relative merits of various cut sequences for pillar recovery in bump prone conditions. First of all, a non-linear model is required to obtain results bearing some semblance to field observations and experience. Second, the differences between the maximum magnitude of ERR are small (usually < 10%). Finally, there are difficulties associated with the ERR uniformity criterion requiring a small rate of increase in ERR. Large increases in the rate of ERR also occur during extraction of split pillar remnants in addition to those increases during pillar core recovery. This analysis discounted the former increases and only considered those increases occurring during pillar core recovery. Justification for this observation is based on the general observation that coal bumps may be associated more with pillar core extraction than with the extraction of broken or yielded coal left in the pillar edges.

## 7 SUMMARY AND CONCLUSIONS

The BEM program, MULSIM/NL, used to study stresses and displacements in coal mining, features six linear and non-linear material types plus an energy subroutine to obtain energy release rate (ERR) values for a mining sequence. The use of non-linear material models is essential to obtain numerical calculations of stress, displacement and ERR consistent with field observations of bump-proneness. A mining sequence with low maximum ERR and uniform ERR may have less bump risk and hence may prove a safer alternative. Evidently, the rate of change of ERR (or uniformity of ERR) is more important than the amplitude of ERR in determining bump proneness.

This study demonstrates MULSIM/NL by examining the following mining cut sequences used for pillar recovery in retreat mining: single

split and fender, pocket and wing, open ending and the Olga Mine method. Analysis proceeded in two phases: linear then non-linear. With the linear models, calculated stresses and displacements do not agree well with field measurements. Based on ERR criteria, the open ending method is marginally better than the other methods which are indistinguishable from one another. Introducing non-linear seam materials makes calculated stresses and displacements much more realistic. The ERR criteria indicate superiority of the Olga Mine pillar recovery method. The Olga method, practiced in a bump prone coal mine, gradually decreases pillar stiffness several rows ahead of the advancing gob line. Progressively softening several rows of pillars tends to decrease the overall stored strain energy levels in the system and therefore decreases the maximum energy release rate and helps keep it uniform.

With a non-linear BEM program like MULSIM/NL, ERR can evaluate different mining sequences to decrease coal bump risk in mines provided that certain precautions are observed such as constant area mined per step and constant rock mass modulus. While ERR cannot provide a universal threshold value marking the onset of bumps in mines, it may serve as a relative indicator of the bump hazard to evaluate mining methods and cut sequences at one site or group of sites with the same rock mass modulus value.

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