Panel–scale Modeling of a Deep Longwall Panel: the MULSIM Alternative

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ABSTRACT

Panel-scale modeling of stress changes induced by longwall coal mining is a challenging problem, particularly in deep mines of the western United States. Two common approaches to this problem are the empirical and boundary element modeling methods. One boundary element method, LaModel, was recently calibrated to field measurements at a mine in Colorado (Larson and Whyatt, 2012). However, the calibrated overburden properties were extreme, resulting in very low estimates of gob loading. Next, the empirical method was calibrated to field measurements and applied to the problem, but this approach clearly extrapolated this method well beyond the characteristics of underlying cases. This paper examines a third option, the elastic continuum boundary element program Mulsim. The program was expanded to handle LaModel-size meshes in a version dubbed Mulsim/Large. Properties for the elastic, homogeneous overburden model in Mulsim were estimated as a thickness-weighted average of typical published elastic properties for each major stratum. These properties, along with a commonly used pillar strength equation and coal properties, produced the measured load transfer distance and reasonable gob loading without further calibration. Given the number of input parameters required for all of these methods, it is not surprising that LaModel and the empirical approach could be adjusted further to incorporate similar gob loads. However, these extraordinary measures failed to bring gate road pillar loading in line with Mulsim results. Differences in pillar load estimates continued to be significant (as large as 65% in this study). These results demonstrate that, for this particular case, the choice of analysis method impacts results in ways that cannot be removed by calibration of input parameters. Finally, the natural fit between the Mulsim model and mine conditions suggests that approximating overburden at the particular site used for this research as an elastic continuum is superior to the alternatives examined.

INTRODUCTION

The success of underground mining rests, in part, on chain pillars and abutment areas safely supporting loads induced by mining. Overstressed regions may collapse or deform in a variety of ways, some of which are potentially hazardous. Thus, the Office of Mine Safety and Health Research (OMSHR) of the National Institute for Occupational Safety and Health (NIOSH) has been investigating various methods of producing, refining, and confirming estimates of mining-induced loading of these areas. These methods are simple models that seek to represent dominant mechanisms (e.g., loading by deforming elastic beam or plate) of ground response to mining. While no model can include all the complexities of overburden over a longwall panel or district, it is important that principal assumptions are in line with dominant mechanisms at a particular site. Indeed, a model that is well suited for one site may be poorly suited for another. This investigation examines performance of three models of overburden behavior at a particular deep western longwall coal mine. It builds on a previous study that examined the consequences of modeling method for a hypothetical longwall mine operating in strong strata (Larson and Whyatt, 2009).

The first model is empirical—that is, it is not based in physics, but rather on a functional form that best fits the measured observations, using regression to determine the model parameters. It follows, then, that the empirical method may not reflect a particular physical model of overburden behavior.

The other two models are based on physical models. The first, LaModel, assumes overburden (as well as strata below the coal seam) to act like a stack of elastic plates with frictionless interfaces. The second model, Mulsim, assumes a homogeneous elastic continuum.

The empirical and LaModel methods were applied to modeling of load transfer distance at this site in a previous paper by Larson and Whyatt (2012). Results were not entirely satisfactory as the empirical approach was applied in conditions far removed from underlying cases, and the LaModel calibration called for extremely stiff overburden properties that precluded development of gob loading. These results led to a search for an alternative model that settled on the Mulsim program (Zipf, 1992a, 1992b), which was updated and recompiled for this study. The bulk of this paper concerns the application of Mulsim and an examination of how results are impacted by changing the analysis method.

METHODS AND CALIBRATION

The first step in the calibration process is to adjust rock mass stiffness to achieve load transfer distance (Heasley, 2008, 2009;

Heasley, et al., 2010).This step, covered by Larson and Whyatt (2012), is briefly reviewed here along with a description of these methods.

Empirical Method

The empirical approach used here combines two equations based on observations from a few cases. The first, proposed by Peng and Chiang (1984), defines load transfer distance (LTD) as a function of overburden depth (H) based on a small number of observations. This equation is

$$LTD = 9.3\sqrt{H} \tag{1}$$

The second equation describes the decay of mining-induced stress, σ, as a function of distance from the abutment rib, *x*, within the region between the edge of an area of gob and the LTD. This rule, proposed by Mark (1990), is based on a curve fit of a small group of pressure measurements. The magnitude of mining-induced stress carried in a two-dimensional slice within this region, *L*, depends on the angle, β, which governs partitioning of undermined overburden loading between abutments and gob. (See Figure 1, where *L* is represented by L_s or L_{ss}.)

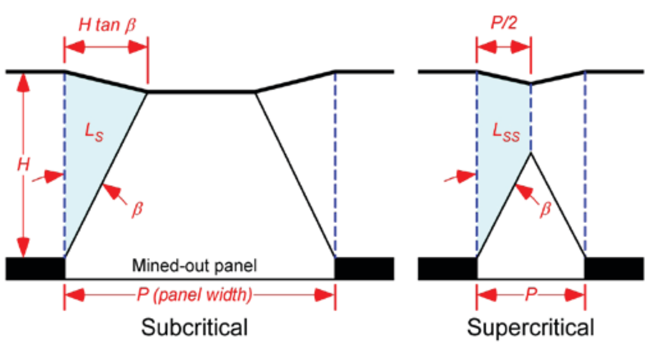

Figure 1. Conceptualizations of the side abutment load, patterned after King and Whittaker (1970). (Figure after Mark, 1990.).

$$\sigma = \frac{3L(\beta)}{(LTD)^3}\left[(LTD) - x\right]^2 \tag{2}$$

The part of the overpanel weight that is not derived from the volume in *L* is that which is transmitted through the gob. This proportion is determined by β, *H*, and *P* (the panel width).

These calculations are easily executed and adjusted in a fairly simple spreadsheet, which is the approach taken in this study. Lawson et al. (2013) explore this approach in considerable detail in a companion paper. This implementation provides ready access to calculations, easily illuminating which parameters (such as *H*, *P*, β, or LTD) dominate results, and providing opportunities to revise both equations and parameters to reflect local ground response characteristics. The speed and transparency of this approach are significant advantages. Larson and Whyatt (2012) applied these equations to a deep western coal mine, noting that the LTD was found to be four times that estimated by Equation 1. LTD is easily adjusted by simply inserting a fictitious depth in Equation 1, or by inserting LTD as a constant in Equation 2. However, Larson and Whyatt (2012) also suggest that the extreme equivalent depth of 35,912 ft implied by this LTD is well removed from the underlying case depths ranging from approximately 380 ft to 875 ft (Peng and Chiang, 1984: p. 64). Pillar load estimates derived from this approach are examined later in this paper.

LaModel Calibration

LaModel, a code with a displacement discontinuity formulation in a laminated medium, has been very successful as an evaluation tool for coal mine layouts (Heasley, 1998, 2008; Heasley, 2011; Heasley, et al., 2010). It is a solution for a crack (filled with coal material) in a medium consisting of a series of plates with frictionless, cohesionless interfaces. One of the input parameters is the thickness of these even, repeated plates. The result of such formulation is that the laminated rock mass can be more flexible than a strictly elastic medium, thus enabling LaModel to simulate the surface effects of subsidence reasonably well, but at the cost of accuracy in load distribution (Heasley, 2008).

Heasley and his fellow researchers have provided specific guidance on model calibration (2008, 2009; Heasley, et al., 2010), and Heasley has also provided guidance on adjusting input parameters for site-specific conditions (2012). The basic steps of calibration are (1) calibrate rock mass stiffness to load transfer distance; (2) calibrate gob stiffness to reflect appropriate amount of load through the gob; and (3) calibrate rock mass strength. Larson and Whyatt (2012) demonstrated, with LaModel, a method of calibrating rock mass stiffness to load transfer distance, determined using a 20-psi increase with borehole pressure cells (BPCs) as a threshold. However, for reasons described below, they did not proceed with the rest of the calibration—that is, calibrating gob stiffness and coal strength—which are the last two steps of the calibration process outlined by Heasley.

Larson and Whyatt (2012) calibrated rock mass stiffness to load transfer distance with the LaModel program in a panel-scale model of the mine used in this study, applying the method recommended by Heasley and Heasley et al. (Heasley, 2008, 2009; Heasley, et al., 2010). The initial stage was successful in matching LTD but required an extreme set of overburden properties (*E* = 37,461, 800 psi, *t*= 443.31 ft). Heasley's second step suggests adjusting properties to attain "reasonable" gob loading. While gob loads are difficult to measure, estimates of 20% to 60% are commonly used in pillar design, based on common geometries and calculations using ALPS standards (e.g., Mark, 1990). Unfortunately, the gob load resulting from overburden property calibration was very small. Attempts to increase gob loading through calibration of other model parameters were not successful. The best results obtained are listed in Table 1. Other parameter values resulted in even more unrealistic results. These results show a trade-off between realism in load transfer distance and gob loading. In short, it was not possible to accomplish calibration of gob modulus to both observed load transfer distance and reasonable gob loading at this site.

The Mulsim Alternative

Mulsim is an indirect boundary element method[1] (Crouch and Starfield, 1983). It is based on the analytical solution of a

1 An indirect boundary element method refers to the fact that there is an intermediate step in the solution process—that is, the method first solves for the singularities that satisfy the specified boundary conditions, and then computes the rest of the boundary parameters in terms of these singular solutions.

Table 1. List of LaModel cases with resulting load transfer distance and percent loading through the gob.

Case	Coal modulus, psi	Final gob modulus, psi	[1]Load transfer distance, ft	[2]Percent of load through gob
1	370,000	6,000,000	409	9.94%
2	370,000	4,000,000	1,048	7.90%
3	250,000	4,000,000	566	10.02%
4	250,000	3,000,000	851	8.33%
5	150,000	2,250,000	761	9.96%
6	150,000	2,000000	1,223	9.11%
7	50,000	660,000	635	9.98%
8	50,000	650,000	973	9.80%
9	50,000	500,000	1,788	6.69%

[1]Target load transfer distance was 1,764.2 ft.
[2]Percentage of load through gob according to empirical assumption = 23.1%.

constant displacement discontinuity over a specific line segment in an infinite elastic medium. Mulsim differs from LaModel fundamentally in that the overburden equations derive from an elastic medium without laminations. The three-dimensional formulation can be traced to Sinha (1979), who drew on the work of Crouch (1976) and Salamon (1963, 1964a, 1964b). It was further developed by Beckett and Madrid (1986, 1988) as Mulsim/BM, which expanded the number of materials to 26, included gob elements and structural elements such as packwalls and cribs, and included fine grids for an area of interest. Zipf (1992a, 1992b) added nonlinear elements, multiple mining steps, and energy release and strain energy computations into a version he called Mulsim/NL. Maleki (see Maleki, et al., 2003) added the ability to include effects of topography and added other enhancements in a proprietary version of the code that he called MULSIMTI. The authors received the source code of Mulsim/NL from Dr. Zipf and expanded it to handle larger problems (450 x 450 coarse elements and 2000 x 2000 fine elements within those coarse elements) and up to 52 in-seam materials for the purpose of this study, calling it Mulsim/Large. In this paper, the code is typically referred to as Mulsim for brevity. It is potentially a good predictor of mining-induced stress redistribution where the overburden has strong, stiff members, as is frequently the case in the western United States. (Larson and Whyatt, 2009).

Table 2 lists features of LaModel and the current NIOSH version of Mulsim. There are some important differences in capabilities that may influence which tool to use. One not listed is the comparative computational time required. In the size of problem modeled for this paper, Mulsim/Large took 400 to 500 times longer to complete computations. Computation time with Mulsim/Large can be reduced by minimizing the number of coarse blocks that become fine elements.

Constructing inputs and handling outputs for a large number of excavations for both LaModel and Mulsim can be a challenge. Heasley's LamPre 3.0 (2010) is a very useful tool, but it handles a maximum of 20 mining steps, even though LaModel 3.0 can handle 200 mining steps. Some practical methods learned by the authors for constructing input files for a large number of mining steps for both LaModel and Mulsim are described in the Appendix.

APPLICATION OF MULSIM

An equivalent Mulsim model was constructed for this same deep western mine. LaModel inputs were converted to Mulsim format, maintaining as many details as possible, including meshing of the coal seam. The overburden model was the exception. Mulsim overburden properties were estimated as a thickness-weighted average of estimated elastic parameters of each member. A stratigraphic column representative of the area (Robeck, 2005; see his Figure 3) was idealized further as shown in Figure 2. Estimated properties for each type of strata are listed in Table 3. Properties are in line with ranges reported by several authors (Farmer, 1968; Vutukuri, Lama, and Saluja, 1974; Lama and Vutukuri, 1978a, 1978b, 1978c; Pariseau, 2012). The seam mined was the DU Seam. Drilling experience suggests this seam is a somewhat softer and weaker than other seams in the column. Initial models examining load transfer distance used an elastic coal model. Later models used the Mark-Bieniawski pillar model (Mark and Chase, 1997) with 900 psi coal, also in accord with LaModel runs. The gob modulus was determined with the default procedure in LamPre (Heasley, 2008, 2009; Heasley, et al., 2010), as it was for both programs.

Model-estimated load transfer distances were determined using the 20-psi-stress-increase threshold that Larson and Whyatt (2012) used with BPC measurements. The Mark-Bieniawski coal strength model produced an average load transfer distance estimate of 1,845.0 ft, which is 4.5% above the measured average, but this average ignores BPC locations affected by yielded elements in which there was no stress increase resulting from panel mining. The average load transfer distance determined with this model was, thus, artificially high at 1,845.0 ft, but just 4.5% above the measured average of 1,764.2 ft. Using an elastic model to minimize anomalies caused by yielding elements, initial model results, without further calibration, produced an average model-estimated load transfer distance that was 1,628.2ft, just 7.7% below the measured average. This load transfer distance result stands in stark contrast to initial LaModel results, which were roughly 75% below the measured average. The initial Mulsim model was used, unaltered, as a basis for subsequent analyses.

Models were also compared by the portion of undermined overburden weight carried by the gob. These results are summarized in Table 4. The Mulsim result has an effective β (for this panel width and depth) of 13.2°, which contrasts with the empirical database standard of 21°. However, this effective β is within the range reported by Tulu and Heasley (2012). While the correct proportion carried by the gob is difficult to know, values in the 20% to 60% range are credible. By comparison, the range in the table, with the exception of the calibrated LaModel result, are from 23.1% to 47.1%. A value of close to zero would require little or no caving, which, if true, would be evident through observation. With this exception, it is difficult to discount any of these results as unrealistic.

Table 2. Feature comparison of LaModel and Mulsim/Large.

Feature	LaModel	Mulsim/Large
Infinite elastic solid?	Yes	Yes
Laminations?	Yes	No
Effects of stress components other than vertical?	No	Yes
Number of seams possible to include	4	4
Dipping seam?	No	Yes
Coarse elements?	No	Yes
Symmetry capability at boundary?	Yes	No
Fixed capability at boundary?	Yes	Yes
Topography datum?	Yes	No
Maximum number of coarse elements in x and y directions	NA	450
Maximum number of fine elements in x and y directions	2,000	2,000
Maximum number of in-seam materials	52	52
Maximum number of excavations	200	Unlimited

Table 3. Properties of the principal stratigraphic units assumed for components in Figure 2 for interbedded units, proportions of each material were estimated to determine properties. Idealized members and their properties were used, in turn, to determine initial properties for input into LaModel and Mulsim.

Property	Sandstone	Siltstone	Shale	DU seam	Other seams
Young's modulus, million psi	4.000	2.000	1.500	0.3700	0.4000
Poisson's ratio	0.2300	0.2500	0.3500	0.3500	0.3300
Density, lb/ft^3	162.0	162.0	162.0	80.00	85.00
Unconfined compressive strength, psi	1,400	8,000	4,000	900.0	1200
Friction angle, degrees	35.00	30.00	30.00	35.00	35.00
Dilation angle, degrees	5.000	5.000	5.000	5.000	5.000
Tensile strength, psi	1,400	800.0	400.0	90.00	120.0

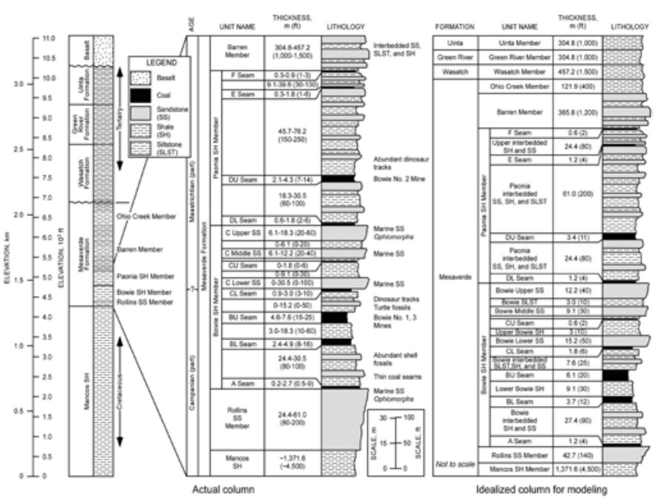

Figure 2. Generalized stratigraphic column in the area of the case study. Idealized column for case study was based on this column. (Figure after Robeck, 2005.).

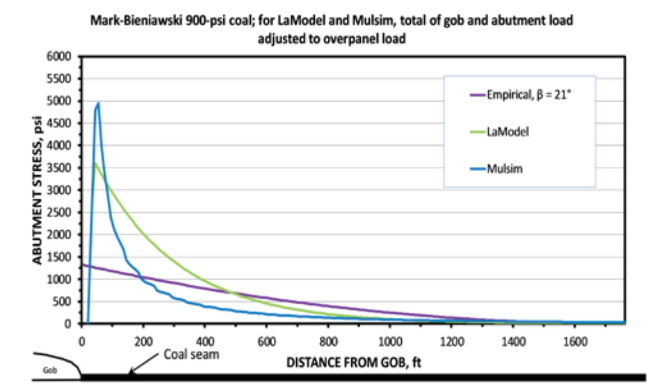

Figure 3. Abutment stress (stress increase above the pre-mining stress on the abutment) profile of case study with no gate roads. Total of abutment load and gob load = overpanel weight for all three methods. Gob load proportion is as reported in Table 4.

ABUTMENT STRESS DISTRIBUTION

The primary goal of all of these models is to estimate loading of abutments and gate road pillars surrounding a longwall panel. The solid abutment case is a good starting point as it is the simplest. The panel geometry in this case was simplified by neglecting gate

Table 4. Gob loading for various models.

Model	Gob load, % of overpanel weight[1]
Empirical	23.1
LaModel, default parameters	47.1
LaModel, calibrated rock mass stiffness	0.28
Mulsim, Mark-Bieniawski 900-psi	36.7
[1]Total overburden weight for LaModel differed from the rest because it accounted for topography.	

roads and crosscuts, which were replaced by solid coal. Results for a vertical cross-section from mid-panel (i.e., halfway down the length of the panel) are plotted in Figure 3. Such plots are a convenient way to consider loading of pillars of various widths. The area under each of these curves is affected by various levels of gob loading. Recall that the calibrated LaModel result has virtually no gob load.

A better comparison might be made by adjusting results to reflect identical amounts of gob loading. Then, these results will vary in the distribution of loading, not the amount. Such a result is plotted in Figure 4, using the empirical estimate of gob loading as a standard. The largest impact is a reduction in near-gob abutment stress for LaModel. The curves in Figure 4 are very similar in shape to those in Figure 5, which was published by Heasley (2000, see his Figure 3). The single difference is that load transfer distance for the present case study is approximately nine times that in Heasley's figure. Notably, the peak stresses in the present study are also smaller than in Heasley's figure, due to the large difference in load transfer distance.

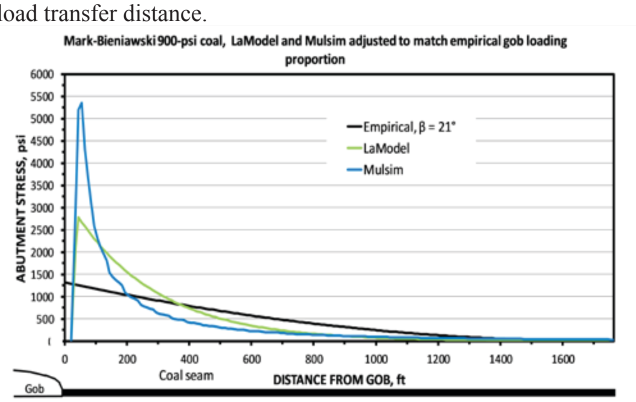

Figure 4. Abutment stress-increase profiles for case study with no gate roads. Loading for LaModel and Mulsim have been adjusted with respect to that in Figure 3 so that gob loading is equivalent to that of the empirical case with β = 21°.

PILLAR LOAD ESTIMATES

Re-introduction of actual mine pillars in the mesh allows us to estimate loads on pillars at this mine, and assess how these estimates vary with method. The Mulsim result is taken to be the standard for this comparison, as it appears to best describe ground response. Thus, the areas under the curves in Figure 6

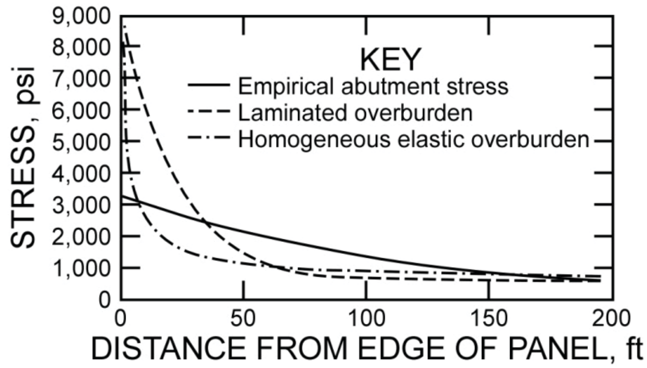

Figure 5. Comparison of the longwall abutment stress computed from the homogeneous elastic model, the laminated model, and the empirical formula. (Figure after Heasley, 2000.).

are somewhat less than those in Figure 4 of the previous section. Figure 6 shows the abutment stress profiles for all three methods after such adjustments. The relative lack of stress concentration around gate roads in the LaModel curve is a result of its very high overburden stiffness.

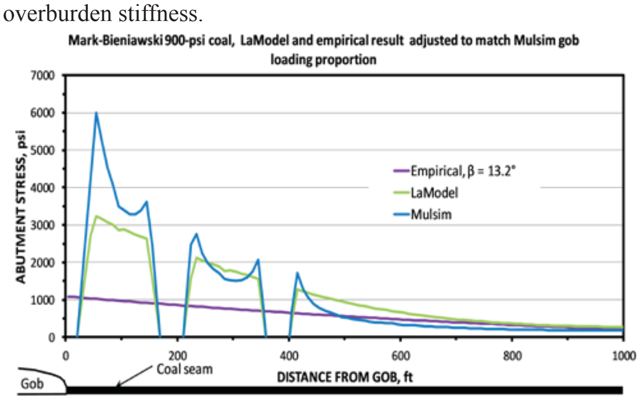

Figure 6. Abutment stress vs. distance from gob for empirical method, LaModel, and Mulsim modeling for the current case study. Empirical method and LaModel total loads remain unchanged, but the gob load proportion of the empirical calculation and LaModel have been adjusted to match that of Mulsim. The angle β matching that abutment load for the empirical curve is 13.2°.

Proportional total pillar load estimates for each method are listed in Table 5, again using the Mulsim result as the standard. While some pillar load estimates are within 5–10%, they are mixed with results that are off by 30% to 65%. Clearly, an error on the order of 50% in estimation of loading is significant.

DISCUSSION AND CONCLUSIONS

Estimation of pillar loads in longwall mines necessarily begins with a choice of analysis method. Larson and Whyatt (2009) showed that choice of method, including the empirical, LaModel, and Mulsim methods examined here, had a significant impact for a hypothetical deep coal mine in strong strata. Given the hypothetical nature of the case, that analysis was based on estimates of overburden properties. This analysis goes a step further—examining consequences in an actual deep longwall coal mine

Table 5. Load on pillars by method, normalized to that of Mulsim.

Pillar	Normalized load on pillar			
	Mulsim	LaModel with 0.28% gob load	LaModel with 36.7%gob load	Empirical with 36.7%gob load
Pillar 1	1.000	1.128	0.716	0.424
Pillar 2	1.000	1.655	1.051	0.777
Note: Pillar 1 is closest to the gob.				

from which observations and measurements of ground response to mining are available. Larson and Whyatt (2012) used this field information to calibrate the empirical method and LaModel to measurements of load transfer distance. This distance was four times that expected from an empirical method (Peng and Chiang, 1984). This result demonstrated that this site is dissimilar from cases underlying the empirical approach. It also required dramatic stiffening of overburden properties in the LaModel analysis—a stiffening that precluded development of gob loading. These results suggested that a different analysis method was needed.

This paper re-introduces the elastic boundary element method for analysis of mining-induced stress around a longwall coal mine. This application is not new (Beckett and Madrid, 1986, 1988; Zipf, 1992a, 1992b), but has been scarce in recent literature. This study revived the Mulsim/NL program that implements this method. The program was expanded to handle LaModel-size meshes in a version dubbed Mulsim/Large. Fortunately, the expanded version of Mulsim used here is well suited to run in parallel with LaModel. An appendix to this paper describes how LaModel input files can be modified for use is such parallel analyses.

Properties for the elastic, homogeneous overburden model in Mulsim were estimated as a thickness-weighted average of typical published elastic properties for each major stratum. These properties, along with a commonly used pillar strength equation and coal properties, produced the measured load transfer distance and reasonable gob loading without further calibration. As such, this method appears to be well suited for deep western coal mines like the case examined here.

Given the number of input parameters required for all of these methods, it is not surprising that LaModel and the empirical approach could be adjusted further to incorporate similar gob loads. This was accomplished by scaling abutment stresses to reflect a desired partitioning of undermined overburden weight to gob and abutment. However, this extraordinary measure failed to synchronize gate road pillar loading. These adjusted results differed from the Mulsim estimates significantly (as large as 65% in this study). These results demonstrate that, for this particular case, the choice of analysis method impacts results in ways that cannot be removed by calibration of input parameters and adjustment of gob loading. That is, the initial choice of analysis method is constraining the possible range of results at this site.

More generally, these results suggest that the analyst should consider the strong simplifying assumptions underlying boundary element programs like LaModel and Mulsim and, for empirical methods, ground characteristics at underlying case studies. Gross mismatches between assumptions and site ground response are likely to be revealed during calibration when ground properties are assigned extraordinary values. An obvious need for additional adjustment of gob loading or other results outside the analysis method also suggests a mismatch. In such cases, we recommend that the analyst consider alternative methods of estimating the distribution of mining-induced stress.

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APPENDIX: PRACTICAL METHODS FOR CONSTRUCTING INPUT FILES FOR LAMODEL AND MULSIM

Constructing a complicated sequence of excavations for LaModel or Mulsim can be challenging. Heasley's LamPre 3.0 (2010) uses a utility that interfaces with AutoCAD to create a model grid based on excavations indicated in the AutoCAD mine layout map. However, the user still needs to create the excavation sequences. It is not practical to have an AutoCAD map for all excavations desired, especially on a panel scale when many excavations are necessary to track load transfer distance. The authors constructed the excavations another way by superimposing the LaModel grid, consisting of drawn lines between elements, onto the AutoCAD map of the mine layout and constructing the mining layout on a series of sheets of a spreadsheet. Such a grid enabled the authors to determine the basic mine layout with codes for gob, excavation, and elastic material for the remaining coal. Excavation sequences were easily constructed on other mining steps by copying the material codes from the previous mining step to a new sheet and moving the face with copy and paste techniques. While LamPre has such copy and paste capabilities, the authors found this function to be easier to perform with Microsoft Excel, even though it ultimately required copying to a text editor and using the “Find and Replace” feature to remove all of the tabs. The material codes for each mining step were then imported into a single excavation LaModel input file to take advantage of Heasley’s utility in LamPre to impose yield material codes. This was done separately for each mining step because LamPre has a limit of handling 20 mining steps. These sets of material codes with yield rings were then imported back into appropriate sheets of the spreadsheet to keep a record of the mining-step sequence.

Because Mulsim does not have the option of symmetry on model boundaries, it is absolutely necessary to add coarse elements around the area of interest. In this case, the authors added rings of 20 such elements. Moreover, the fine-element grid used in the LaModel mesh was large enough that Muslim computational time was prohibitively excessive. To reduce computation time, the authors took the 640 x 1370 LaModel grid for each excavation and reduced it to 410 x 980, taking it from 66 to 475 in the x direction and 181 to 1160 in the y direction. Outside of this fine-mesh boundary, a Visual Basic macro was used to convert each of the 5 x 5 fine groups into an average material strength for a replacement coarse element. This was best accomplished using the Mark-Bieniawski strength criterion for interpolation because it is linear. A coarse material code closest to the average strength of the 5 x 5 unit was selected. Another macro wrote the fine mesh and coarse mesh to separate .txt files, in the format required by Mulsim.

Because there was no pre- or post-processor available for Mulsim, material codes were plotted as contour plots, using the “Set as Categorical” feature in the analysis and graphing software OriginPro[2] to assign material codes to contour numbers. This capability permitted another visual check of the placement of material codes.

LaModel took just under 27 hours to complete all mining steps. However, one mining step involving gob in Mulsim required 24 to 38 hours on state-of-the-art workstations and up to 48 hours on blade servers made available to the authors.[3] As a test, the results of a sequence of 10 mining steps were compared to the results of individual mining steps that each started from the pre-mining state. The differences were insignificant, owing to the monotonic nature of the mining sequence. Therefore, 185 mining steps of the mining sequence were divided into separate models that could be run in parallel. All mining steps for a model were run and completed within four days, with two sets of parallel models with 18 processors having a total of 104 cores. Assembly of the Mulsim input files was done quickly with the aid of DOS batch files.

2 Mention of any specific product name does not imply endorsement by NIOSH.
3 These time ranges reflect the condition of running one model per core—thus each core on a workstation ran one model at the same time.