

Topography and Coal Seam Initial Stress Estimation: a Sensitivity Study

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ABSTRACT

Estimation of the initial vertical stress carried in a coal seam is an important first step in virtually all methods of evaluating the required size of pillars in coal mines. Such estimates are a trivial exercise in coal fields overlain by gently undulating topography. The LaModel program is easily and routinely applied in such cases to efficiently estimate mining-induced stresses throughout the coal seam. However, application of LaModel to coal mines operating under rugged topography and/or in tectonically disturbed regions is more difficult. LaModel estimates stresses in a two-step process. Topographic and multi-seam mining effects on in-situ stresses are estimated in an initial step, and then mining-induced stresses are estimated in an independent second step. A LaModel program function has recently been introduced that decouples these two steps, allowing in-situ stresses to be directly entered from a file rather than calculated. One application of this function is to streamline sensitivity studies by avoiding repeated recalculation of in-situ stress. The function also allows importation of in-situ stress estimates developed by other means. There are no constraints on the imported stress field, which may include significant stress perturbations due to topography, faults, etc. Hence, the range of geologic environments that can be examined by LaModel is significantly increased. This study uses the new decoupling function in an exploration of in-situ stress estimation in mountainous terrain. One option is to use the topographic stress estimation feature included within the LaModel program, and the influence of important parameters in this routine is explored. Another option explored is importation of results from a detailed volume element model. Results of this study suggest that the method used to estimate in-situ stress, and the details of its execution, can have a significant impact for mines in mountainous terrain with strong overburden. More generally, decoupling is an efficient and flexible function that should be considered for most design studies.

INTRODUCTION

An estimate of the initial vertical stress field in a flat-lying coal seam is a necessary starting point for analyses of how mining of coal shifts stresses onto pillars and barriers. The simplest estimate of vertical stress is simply the product of the depth at the point of interest and the weight density of the ground. In this work, a stress

estimate developed in this manner is called an “undispersed stress,” because distortions to stress conditions caused by topography or geology are neglected.

Coal mine design methods typically compare estimated loads on pillars and barriers (from a combination of initial and mining-induced stresses) to estimates of strength. These methods include the empirical ALPS (Mark, 1987; Mark, 1992) and ARMPS (Mark, 2010) guidelines published by NIOSH, as well as numerous numerical stress analysis programs, such as boundary element programs like LaModel (Heasley, 2007; Heasley, 2010) and volume element programs, including FLAC3D (Itasca Consulting Group, 2009). Stress analysis programs may also be used to develop load and strength estimates for other mine structures, including stratigraphic bridges or pressure arches that form over the gob.

Topography is attracting increasing attention in analysis of coal pillar stresses. For instance, Mark (2010), in ARMPS 2010, has recognized spreading of stress beneath a ridge. He recommends averaging the maximum depth of cover with the least depth occurring within 200 ft (61 m), inby or outby, of the deepest point. Heasley et al. (2010) report that including actual mined geometry and topography in modeling of ARMPS case studies provides approximately a 10% better delineation between the successes and failures than when this detail is not included. Vandergrift and Conover (2010) take a different approach in their ALPS analysis of a deep coal mine. They use a LaModel analysis to find the greatest vertical stress level, and then divide this value by the weight density to find an “effective” depth value.

The development of an initial vertical stress estimate rests on three main factors. The first is the depth and specific weight of overlying strata. This factor is used in all analyses. The second is an estimate of how undulations in overlying strata might induce related undulations in the initial vertical stress field carried within the coal seam. This factor is often ignored, and properly so, where topography is flat or only slightly undulating. However, it is often considered in more extreme terrain—the main topic of this investigation. The third factor is distortion of the distribution of vertical stress within the seam by various geologic features including faults, stratigraphy, dip of the coal seam, facies changes, etc. These factors are only rarely addressed, as in cases where

unexpected changes in ground behavior, especially bumping, are observed in tectonically disturbed regions (Peperakis, 1958).

In some cases, stress measurements and/or observations may be available to assist in development of an initial stress estimate. However, these are few and far between even in the best cases. As such, the problem of estimating the stress distribution between measurements is typically left to one of the empirical or numerical methods mentioned above. Thus, the following question can be posed: “Does it matter which of these methods is used?” This paper presents a sensitivity study that addresses this question. The study focuses primarily on the LaModel program, as it has the ability to model mining-induced stresses efficiently on the scale of a modern coal mine. LaModel was also utilized in the investigation of the Crandall Canyon collapse (Heasley, 2008a; Heasley, 2009), and its use has been addressed by a recent MSHA Program Information Bulletin (Skiles and Stricklin, 2009). LaModel estimates of initial stresses are explored for a variety of input parameter choices. They are also compared to initial stress estimates used in the ALPS/ARMPS approach and a detailed elastic model developed with the 3D FLAC program. These methods are applied first to a step geometry, and then to the topography over an actual coal mine in mountainous terrain.

The paper also introduces a new LaModel program feature that allows for independent analysis of initial and mining-induced stresses, and it explores its application in rugged topography and tectonically disturbed regions.

METHODS FOR MODELING TOPOGRAPHY

The accuracy of an in-situ stress estimate depends, in part, on tradeoffs with the level of effort applied. Ignoring the influence of topography can greatly simplify the calculation, which is a definite advantage of tributary area methods. Topography can also be modeled explicitly. Volume element programs, like FLAC3D, explicitly define a topographic surface and model overburden up to this surface.

The boundary element method approach lies somewhere between these approaches. LaModel is typical of such programs, beginning with the assumption that the coal seam lies in an infinite elastic space. In the case of LaModel, this space is simplified to consist of elastic layers of thickness t and elastic modulus E separated by frictionless interfaces. In fact, the fundamental flexibility of the elastic body relies on the product of these variables: E times t . This can be seen in the analytical solution for convergence (s) at the midspan of a slot (Heasley, 1998), given by Equation 1:

$$s = \frac{\gamma H \sqrt{12(1 - \nu^2)}}{Et} \quad (1)$$

where

γ = average density of overburden

H = seam depth

ν = Poisson's ratio of the overburden

Numerical techniques can be used to simulate an infinite half-space or a traction-free surface at the ground level (Heasley, 1998), but specification of a ground surface in this way only impacts mining-induced stresses and does not impact initial in-situ stresses.

Stress estimation in LaModel is a two-step process. In-situ stresses are estimated in an initial step, followed by estimation of mining-induced stresses in a second step. This procedure, in combination with limiting overburden to elastic homogenous behavior and defining elements only on the coal seam (instead of throughout the rock mass volume), creates significant advantages in computational efficiency. Of course, these simplifying assumptions also limit the types of ground behavior that can be modeled (Heasley, 2008b; Larson and Whyatt, 2009a; Larson and Whyatt, 2009b; Larson and Whyatt, 2010).

Since not all coal seams lie under flat topography, LaModel includes options for arriving at non-uniform estimates of initial in-situ stresses on the coal seam. The first option of topography modeling has been included with the LaModel program since its development. This option estimates initial stresses from a grid of “topographic” elements, each of which adjusts loading for the surface elevation at that location. The second option is a new function that allows in-situ seam stress estimates to be directly imported.

LaModel Topographic Loading Option

The topographic loading option in LaModel places a grid of topographic elements on a horizontal plane over the seam. This plane is referred to as the “datum” and can theoretically be placed at any elevation. The default is at the average elevation of the surface over the seam area. Initially, a uniform stress field is applied as if a level ground surface existed at the datum elevation. Topographic elements, acting like footings on the datum surface, then add or subtract loads on the datum to account for differences between local and datum elevations. The load applied by topographic elements to the datum is then propagated down to the seam level using a stress influence function, much like in classic footing solutions (Figure 1). Therefore, in LaModel, the initial in-situ stress on a coal seam element is a combination of the uniform stress field estimated for the datum plus applied stresses integrated from all the topographic elements. The topographic element grid and datum can be generated automatically from AutoCAD drawings of the elevation or overburden contours with tools provided with LaModel, or they can be inputted manually with a text editor. In either case, the topographic data files are text files and can be manually edited.

The influence function F used to propagate the stresses from the overburden datum to the seam is significantly different from the function defining the overburden stiffness in that the product Et does not behave as a single variable. Rather, E and t operate as two independent variables in the stress influence function, shown in Equation 2. Because of this difference between functions, calibration of E and t to mining-induced stress change does not speak to whether the individual values are reasonable for calculation of initial topographic stress variation. In other words, an Et product that is well-calibrated for mining-induced stress calculations (Heasley, 2008b; Larson and Whyatt, 2009a; Larson

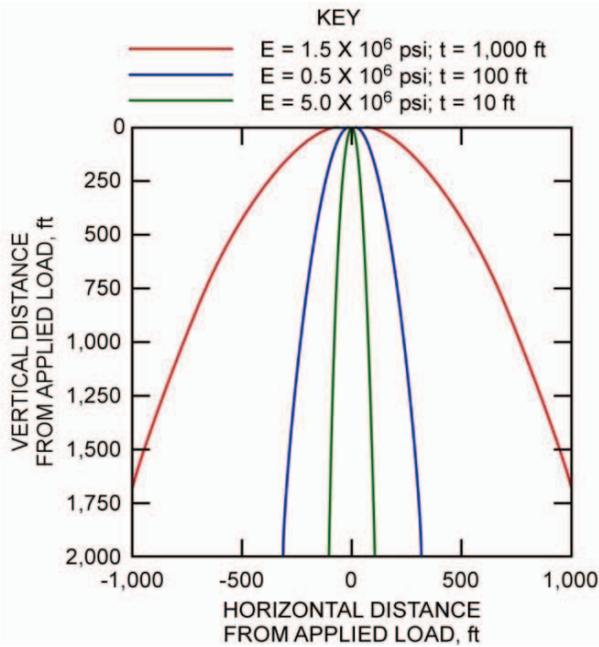


Figure 1. Plot showing the extent that vertical stress spreads beneath a topographic load in LaModel. Thick laminations spread loading widely (red) while thinner laminations narrow the area of influence (blue and green lines). Note that the product of elastic modulus and lamination thickness is identical for the blue and green curves.

and Whyatt, 2009b; Larson and Whyatt, 2010) may not provide the most accurate estimate of topographic loading.

$$F = \frac{E}{8\pi Z^2} \left(\frac{12(1 - \nu^2)}{t^2} \right) \times \left(\frac{X^2 + Y^2}{4|Z|} \right) e^{-\sqrt{\frac{12(1-\nu^2)}{t^2}} \left(\frac{X^2 + Y^2}{4|Z|} \right)} \quad (2)$$

where

X, Y, Z = distances between source and influenced point in coordinate directions.

Topographic elements apply pressure that spreads out with depth (Figure 1), much like in a footing solution. The amount of spreading is dependent on overburden properties, especially the thickness of laminations in the overburden. Thinner overburden layers tend to concentrate the pressure and limit spreading of the loads. The amount of spreading also varies with the distance, or depth, between datum and seam. The influence of datum elevation will be further examined later in this paper.

LaModel In-Situ Stress Import Option

LaModel saves the results of its in-situ stress calculation in an array that is used in subsequent calculation of mining-induced stresses. Recently, a new functionality was added to the LaModel program allowing for input and output of this array from a file. If the program detects the file, it will import in-situ stress information rather than computing it. This new function streamlines sensitivity studies where initial in-situ stress conditions are held constant,

especially for a sensitivity study for a single-seam case. Since the pre-calculated overburden stress file can be edited by the LaModel user, it can also introduce in-situ stress estimates developed by other methods. Suitable methods for generating this estimate might include other modeling methods, stress measurements, and/or stresses inferred from seismicity, faulting, etc.

This feature is possible in LaModel because, as discussed previously, the in-situ stress calculation is separated from the calculation of mining-induced stresses. The in-situ seam stresses are calculated in an initial step and saved for later use in a second step that estimates the mining-induced stresses. Because of this separation, topography is not considered after the initial overburden stress calculation, and thus it is not “linked” to further calculations. The geometry influencing overburden stiffness is defined either as an infinite laminated space or as an infinite laminated half-space whose surface is specified independently of the datum elevation. This design is distinctly different from volume element programs such as FLAC3D, where all physical and geometrical properties of the ground explicitly influence all elements of model response, including stiffness of the overburden.

By comparison, FLAC3D provides for considerably more complex/comprehensive modeling of topography and lithology within the overburden. There is also the possibility of introducing faults and residual stresses Whyatt (2000) within FLAC3D. In the context of western coal mines, both of these features are potentially important. For example, Horst and Graben fault systems at the Sunnyside Mine in Utah have been associated with variations in measured stresses and coal bump activity (Peperakis, 1958; Osterwald et al., 1993). Also, the presence of intrusive bodies in close proximity to coal seams, as has been observed in western Colorado, may result in complex residual stress systems (Robeck, 2005).

However, the sophistication of some volume element approaches can easily outrun the accuracy of stress measurements and the detail available in geologic mapping of the terrain in question. That is, the uncertainty inherent in model inputs limits the detail that can be justified. Still, the ability to test the performance of a given mine design against a broad range of possible in-situ stress conditions can be a definite advantage. The cost of this sophistication is a significant increase in effort and computation time.

The new topographic stress import feature in LaModel opens up new opportunities for hybrid analyses. For example, a relatively large-scale volume element model, which may be poorly suited for modeling detailed mining progress, can be used to calculate the influences of topography, faults, etc. Then, the results of this initial in-situ stress modeling exercise can be implemented as initial conditions in LaModel for detailed modeling of mining-induced stresses. Alternatively, using only LaModel, the topographic stress import feature allows the topographic stress to be calculated with a different set of parameters than are used for the mining-induced stress calculation. This new stress import feature greatly expands the options available to the analyst.

IDEALIZED TOPOGRAPHY SENSITIVITY STUDY

A sensitivity study was designed with two aims in mind. The first aim was to evaluate how parameters, including datum location and overburden properties, influence the estimated distribution of

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vertical stress on the coal seam. The second was to examine how the numerical accuracy of the program varied—that is, the degree to which variations in initial stress estimates are due to changes in overburden properties, and the degree to which they might be influenced by poor solution accuracy.

LaModel results were compared to the undispersed stress level (weight density multiplied by immediate depth), which is used in ALPS and ARMPS, and the results of an elastic volume element model. Variation of stress is influenced by overburden geology and tectonic regime of a particular site. As such, a “right answer” exists for a particular site. The study did not evaluate the plausibility of each result, but rather sought to evaluate the range of results generated by a reasonable range of overburden properties. However, some checks are possible. For example, the full weight of overburden, overall, should be supported by the coal seam, regardless of its distribution. Likewise, coal seam stress beneath a long expanse of level ground should approach the undispersed stress value. These properties serve as checks on results and are particularly easy to implement for idealized geometries. Nevertheless, since all solution schemes are approximate, some deviation is expected. The amount of deviation is an indication of the numerical accuracy of a particular solution. Numerical accuracy by itself, however, does not establish that a solution is plausible for a particular site.

The sensitivity study first examined vertical stress estimates for an idealized geometry including periodic jumps in elevation (“cliffs”) between regions of different surface elevation, all above a flat-lying coal seam (Figure 2). This periodic shift model was designed as an extreme ridge and valley geometry. Model results were examined in the middle of the periodic cycles, as indicated. The LaModel surface modeling mesh was extended 2,000 ft (609.6 m) beyond the symmetric seam model in the direction perpendicular to the paper.

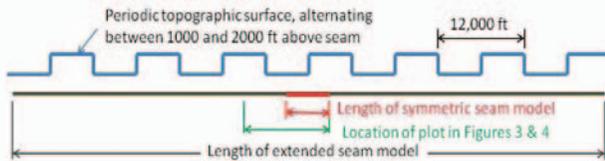


Figure 2. Setup of periodic topography experiment with LaModel showing the length and positioning of the extended periodic seam models. Location of profiles in Figures 3 and 4 are shown.

A variety of LaModel runs were conducted with datum elevations of 1,000 ft (304.8 m), 1,500 ft (457.2 m) (the average depth), and 2,000 ft (609.6 m); and lamination thicknesses of 50 ft (15.2 m), 250 ft (76.2 m), and 1,000 ft (304.8 m). The material density specified (158.4 lb/ft³ (2537.3 kg/m³)) produces an average seam stress of 1,650 psi (11.4 MPa), with minimum and maximum undispersed stresses of 1,100 psi (7.6 MPa) and 2,200 psi (15.2 MPa), respectively. Other parameter values for this model are summarized in Table 1.

Care was taken to minimize the contribution of other factors in the LaModel results. For example, only results near the middle of the model were examined, at least 33,000 ft (10,058.4 m) from the left and right ends of the topographic grid. In the direction

perpendicular to the paper in Figure 2, the topographic grid was extended 2,000 ft (609.6 m) beyond the seam grid. Since the influence function indicated in Figure 1 extends about 1,200 ft (365.8 m) for a lamination thickness of 1,000 ft (304.8 m) at the Young’s modulus used, topographic overlap was sufficient in this case. Second, since displacements will be small when lamination thicknesses are 1,000 ft (304.8 m), the equilibrium threshold was lowered two orders of magnitude below the default.

Results for datum variation, using a constant lamination thickness of 1,000 ft (304.8 m), are illustrated in Figure 3. The most evident result is that LaModel smooths the abrupt change in stress at the “cliff” faces, as one would expect. A second feature illustrated by the figure is that moving the datum up and down causes a corresponding offset of the stress curve and the average stress felt by the coal seam. Finally, the curves for the highest and lowest datum elevations provide the best fits to the undispersed stress level in the middle of ground segments at the datum elevation. Results are compared to a similar half-cycle elastic FLAC3D model (labeled as “Length of symmetric seam model” in Figure 2), with the bottom boundary set 3,000 ft (914.4 m) below the coal seam. FLAC3D results are in the middle of this set of curves, tending towards the highest datum result beneath high elevations and the lowest beneath lower elevations.

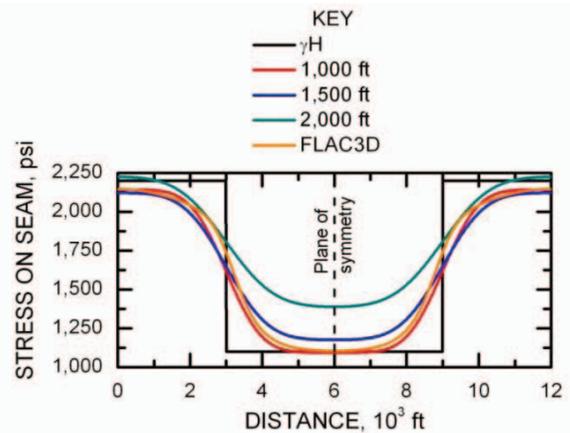


Figure 3. Stress-on-seam profiles showing influence of topography and of the topographic datum chosen for 1,000 ft lamination thickness. Stress-on-seam profile calculated by FLAC3D is also shown.

Resulting stress estimates are presented in Table 2. As expected, all of these runs contain some level of error, in that all numerical methods provide an approximate rather than exact solution. FLAC3D and the average datum best account for carrying of overburden load by vertical stress on the coal seam. Local results, computed beneath the middle of the high (“ridge”) and low (“valley”) segments tell an interesting story. In these cases, the LaModel results closest to the undispersed stress level are provided by a datum at the local elevation, despite the greater error in average stress. This is termed a “variation” rather than an error because there is likely a small geometric component to the difference, especially for thicker laminations, as illustrated by the FLAC3D result.

Table 1. Parameter values for periodic topography experiment.

Input	Value	Input	Value
Average overburden depth, ft	1,500	No. of seam grid zones, x-direction	600
Grid spacing, ft	10	No. of seam grid zones, y-direction	20
Rock Poisson's ratio	0.25	Lamination thickness, ft	Varied
Rock Young's modulus, psi	3,000,000	Stress gradation, psi/ft	1.1
Coal Poisson's ratio	0.33	Spacing of topographic points, ft	50
Coal Young's modulus, psi	370,000	Over-relaxation factor	1.35
Seam thickness, ft	10	Equilibrium tolerance	0.0000001

Table 2. Stress estimates for the periodic model with 1,000-ft laminations.

Datum	Avg Stress (psi)	Error	Max Stress (psi)	Variation	Min Stress (psi)	Variation
1,000 ft	1,619	1.9%	2,143	2.6%	1,094	0.5%
1,500 ft	1,650	0.0%	2,123	3.5%	1,177	7.0%
2,000 ft	1,808	9.5%	2,225	1.1%	1,390	26.4%
FLAC3D	1,647	0.2%	2,147	2.4%	1,105	0.5%

Variations in these results arise entirely from the numerical methods used to implement a model of overburden behavior. That is, the definition of the datum controls how the solver attempts to implement the overburden model for a particular topography.

This exercise provides some guidance for the analyst. First, placing the datum at the average elevation of the ground above the coal seam will likely provide the best overall results. However, if a particular region of the model is of special concern, especially under a ridge or valley, the best local results can be obtained by placing the datum at a similar elevation. Moreover, it is useful to determine whether the initial stress estimate is sensitive to a change in datum, particularly when larger lamination thicknesses are used. Finally, it is always useful to investigate whether the initial seam stresses account for the full weight of overburden.

Additional runs were used to evaluate the influence of changes in overburden properties for particular datum elevations. These results are summarized in Figure 4, where estimates for various thicknesses and the FLAC3D elastic model are plotted for each datum. Plotting results in this way shows the relative spreading of stress in these solutions as well as the influence of the datum elevation used. The elastic result provides the most smoothing, while the degree of smoothing provided by LaModel varies. The thickest laminations provide spreading of stresses similar to the elastic model, while very thin laminations provide very little spreading, approaching the undispersed stress, or γH , line.

The average stress on the seam is summarized in Table 3 for each run. The most striking result is the change in smoothing of vertical seam stresses around the elevation jumps. The models using 1,000-ft (304.8-m) -thick laminations roughly follow the elastic FLAC3D results. Results for smaller thicknesses converge on the undispersed stress curve, which would be a bound for very small lamination thicknesses. Thus, the range of LaModel initial stress solutions lies between that generated by FLAC3D and the undispersed stress level. Finally, numerical accuracy appears best

for thinner laminations. This is not surprising, since the program is optimized for use with thicknesses reasonably close to its default value of 50 ft (15.2 m).

REAL TOPOGRAPHY SENSITIVITY STUDY

The topography over a real coal mine, in this case an operating coal mine in mountainous terrain, better shows the practical use of these methods. While the topography at this site is considerably more rugged than is typical for coal mines, it should demonstrate whether the considerations explored in this paper might be significant for at least some coal mines. As such, this portion of the study examined whether the conclusions reached for idealized geometries are significant for plausible design calculations.

Volume Element Model

A detailed volume element model was constructed with the FLAC3D program (Figure 5). The model mountain was constructed one column of elements at a time. Major strata were modeled discretely and were assumed to behave elastically. The sides and bottom of the model were given symmetric boundary conditions and loading was supplied by gravity alone. The initial vertical stress on the seam, illustrated in Figure 6A, was formatted into an initial stress file that was read by the LaModel program.

LaModel

In addition to the volume element model, terrain was also modeled with the LaModel program. The small dip of the coal seam was neglected, and the datum was set at the average depth of the coal seam below the surface, including areas where the seam has been eroded. Topography was extended symmetrically at all boundaries, as was the coal seam, to avoid boundary effects and provide a better measure of how much overburden weight is accounted for by seam stress. Results are illustrated in Figure 6B–D with increasing lamination thicknesses of 50 ft (15.2 m),

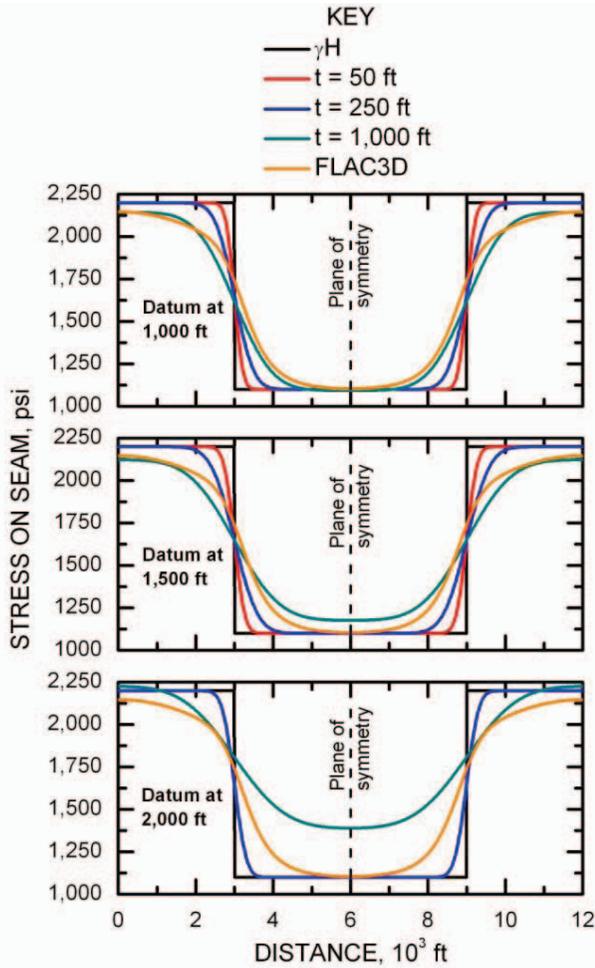


Figure 4. Stress-on-seam profiles showing influence of lamination thickness for each datum used in Figure 3. Average stresses are listed in Table 3.

Table 3. Average stress on seam of periodic topography model for various topographic datum locations and lamination thickness.

Datum location, ft	Average Stress on Seam, psi		
	t = 50 ft	t = 250 ft	t = 1,000 ft
1,000	1,650	1,650	1,619
1,500	1,650	1,650	1,650
2,000	1,650	1,650	1,808

250 ft (76.2 m), and 1,000 ft (304.8 m), respectively. The 50-ft (15.2-m) -thick lamination results closely follow the topography contours with some additional “choppiness” due to the point loading character of overburden elements. Increasing thickness (Figures 6C and 6D) shows an increased smoothing of stress intensity on the coal seam, with the 1,000-ft (304.8-m) lamination thickness plot closely resembling the volume element result of Figure 6A.

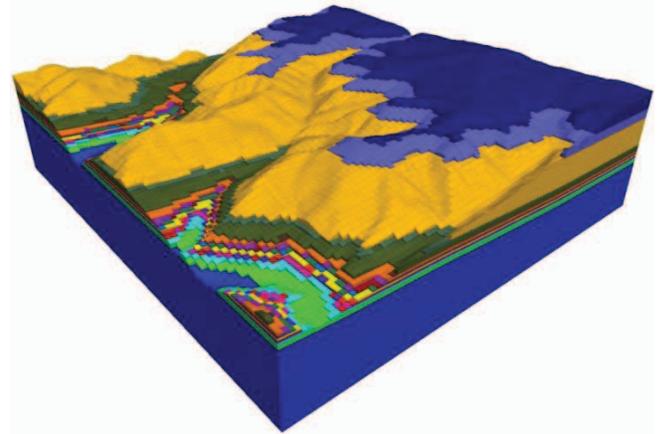


Figure 5. Volume element mesh constructed for modeling of overburden loading of coal seam. Each color represents a different stratigraphic member.

Stress estimates can also be compared in a vertical section through a ridge, as illustrated in Figure 6D. The datum was placed at the default location (the average elevation), close to surface elevations in the region of interest. Coal seam initial vertical stress estimates developed with FLAC3D and LaModel along this section are illustrated in Figure 7. These stresses show little variation along topographic slopes but vary more widely at ridges and valleys. The values of stress estimates beneath the ridge are given in Table 4, which also presents the range of results. Results show that the range can approach a level (19%) where the choice of estimation method can have a significant impact on the “worst-case” stress level.

Finally, the accuracy of LaModel results for thick laminations was reviewed as if such strata were the preferred overburden model, as might be the case if thick, massive sandstone strata were present in the overburden. In actual fact, this model was chosen because thicker strata cases appear to be more challenging for LaModel computations, and the authors were interested in exploring how LaModel might perform for uncommon, but allowed, input.

This review was based on insight developed from the ideal model considered in the first part of the paper. First, the average coal seam stress was compared to total overburden weight. For this true topography model, deviation from total overburden weight was well below 1%, suggesting a reasonably accurate solution. Second, the run was repeated with the datum moved downward to 1,100 ft (335.3 m) above the seam. Differences appear to be reasonably small except for the “preferred” 1,000-ft (304.8-m) thickness, for which the variation is as much as 100 psi (0.69 MPa), or roughly 5%, in places. As such, it appears that small strata thickness models are relatively insensitive to reasonable variations in datum location. Further, some care may be required in using thicker layers, as in the “preferred” model with a thickness of 1,000 ft. In this case, use of a volume element model might be advantageous.

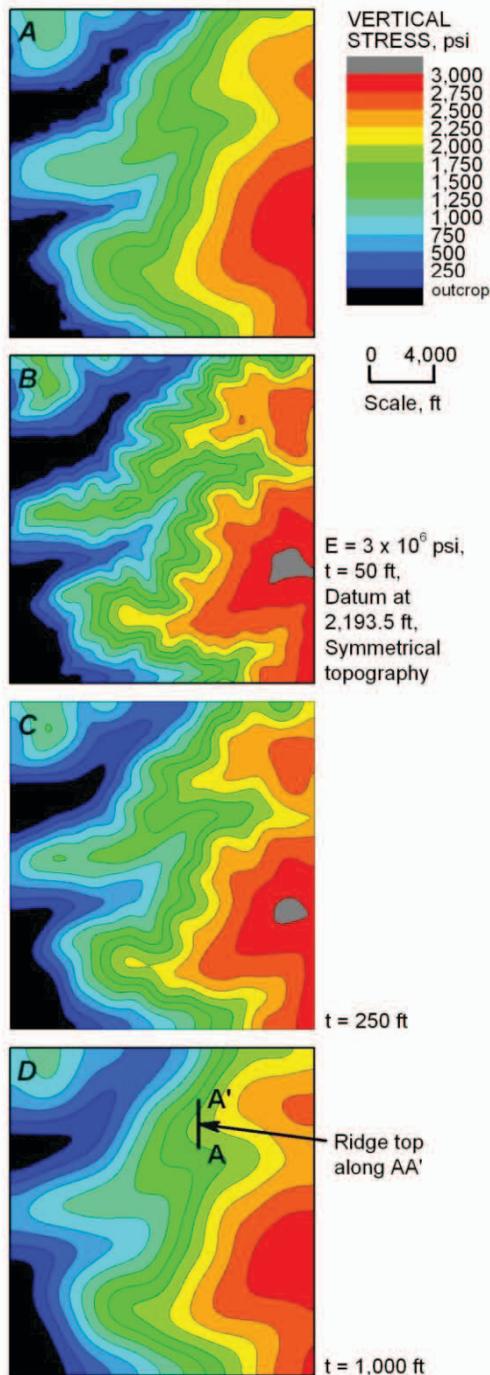


Figure 6. Contours of vertical stress on the coal seam: A, calculated with the mesh of Figure 5 with FLAC3D; B, calculated with LaModel, $t=50$ ft; C, calculated with LaModel, $t = 250$ ft; and D, calculated with LaModel, $t=1,000$ ft. Stress profile locations are illustrated in D, along A-A'.

DISCUSSION AND CONCLUSIONS

An estimate of the initial vertical stress field in a flat-lying coal seam is a necessary starting point for analyses of how mining of coal shifts stresses onto pillars and barriers. Such estimates are a simple exercise in coal fields overlain by gently undulating topography. However, the problem is more difficult for coal mines

operating under rugged topography and/or in tectonically disturbed regions—often under stiff overlying strata. The ability of LaModel (and similar boundary element programs) to efficiently model mining-induced stresses in large areas spanning multiple coal panels makes it an attractive candidate for conducting analyses of large mining areas.

LaModel has a valuable additional ability to incorporate variations in overburden stress through a mine, which makes it an attractive candidate for mines under variable and even rugged topography. LaModel accommodates the effect of topography on loading with a second type of influence function. This function alters coal seam in-situ stress to account for differences between local surface elevation and the average or “datum” elevation. This influence function differs from that used for mining-induced stress calculations in how it incorporates overburden properties of lamination modulus and thickness. Whereas the product of overburden modulus and lamination acts as a single variable for the mining-induced stress influence function, this is not true for the overburden influence function, where each variable has an independent influence. This is an important distinction that should be considered when assigning properties for in-situ stress calculations.

The spreading of coal seam stress away from ridgelines and into areas beneath valleys is strongly dependent on the lamination thickness chosen, irrespective of overburden elastic modulus. As the lamination thickness becomes thinner, it generates less and less spreading of stress, approaching the undispersed stress assumption (no spreading). Similarly, spreading of stress increases as laminations are thickened, eventually approaching that of an elastic solution. Spreading of the overburden stress also depends on location of the datum elevation used by LaModel, but less strongly. Increased spread may require tightening of convergence criteria. Also, it is important to recognize that the location of the datum elevation has no impact on overburden stiffness, as it would in a volume element model.

In this paper, an idealized topographic model with step geometry was used to evaluate LaModel topographic stress modeling and its sensitivity to a number of parameters. In this evaluation, errors as large as 25% (as demonstrated in Table 2) resulted for idealized model geometry with a combination of poor datum choice and thick lamination thickness. While both factors were taken to an extreme (lamination thicknesses used in LaModel are typically less than 500 ft (152.4 m)), this case suggests that care should be taken to assess solution accuracy for thicker lamination cases.

The idealized model runs provide some simple guidance for setting the datum variable and assessing solution accuracy. This guidance is most pertinent for regions in rugged topography with thick, competent overburden strata. First, placing the datum at the average elevation of the ground above the coal seam will likely provide the best overall results. However, if a particular region of the model is of special concern, especially under a ridge or valley, the best local results can be obtained by placing the datum at a similar elevation. Moreover, it is useful to determine if the initial stress estimate is sensitive to a change in datum, especially for thicker laminations. Finally, it is always useful to investigate whether the initial seam stresses account for the full weight of overburden. This check may also help to identify errors in convergence accuracy and topographic grid geometry.

Table 4. Undispersed stress and LaModel stress estimates at four locations in Figure 7.

Position	Undispersed Stress, psi (γH)	LaModel runs				FLAC3D Elastic Model, psi	Range (% of γH)
		Highest Stress, psi	t, ft	Lowest Stress, psi	t, ft		
Ridge top along AA'	2,247	2,192	50	1,822	1,000	1,819	428 (19%)

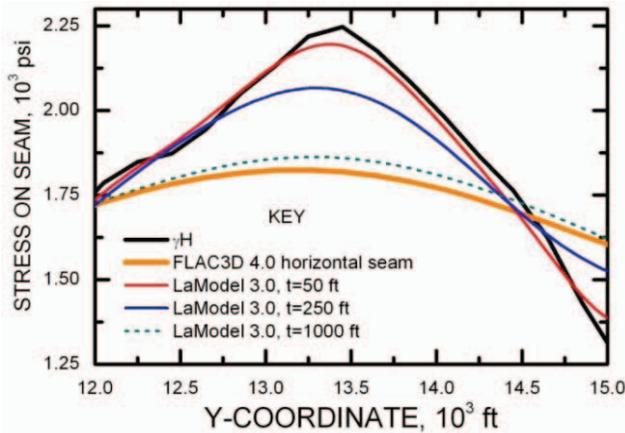


Figure 7. Stress profiles along section A-A' in Figure 6D.

This guidance provided by the idealized model runs was applied to the topography above an operating coal mine to test its relevance to a “real-world” case, although this case involves unusually rugged terrain for a coal mine. The datum selected was the average for the model area and happened to lie close to the surface in the region of interest. In this case, the range of stress levels under ridges varied by 5–10% among various choices of analysis method and overburden properties. The runs were checked according to the criteria summarized above. Results checked well, with the exception that the 1,000-ft (304.8-m) lamination model showed some sensitivity to datum location. This last case might be a good candidate for estimating stress with an elastic volume element method, then importing the results for computation of mining-induced stress.

Finally, it should be understood that this study does not address whether any resulting initial stress estimate is appropriate for a given site. Such a judgment requires specific site information. This is especially pertinent for tectonically disturbed regions where faults and other features perturb the in-situ stress field. In these cases, the new capability to import initial stresses from other sources should prove to be invaluable. This capability also provides an opportunity to decouple overburden properties between initial and mining-induced stress calculations. That is, the set of overburden properties used to estimate in-situ stress levels developed over geologic time need not be the same as that used to model short-term response of the ground to mining. If nothing else, decoupling initial stress estimations from mining-induced stress analysis provides for efficiency in conducting sensitivity studies. Generally, the analyst should find considerable advantage in this new feature.

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