PRACTICAL BOUNDARY-ELEMENT MODELING FOR MINE PLANNING

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ABSTRACT

As part of the initial investigation and validation of a new boundary-element formulation for stress modeling in coal mines, the underground stresses and displacements at two multiple-seam coal mines with unique stress problems were modeled and predicted. The new program, LAMODEL, calculates stresses and displacements at the seam level and at requested locations in the overburden or at the surface. Both linear elastic and nonlinear seam materials can be used, and surface effects, multiple seams, and multiple mining steps can be simulated. In order to most efficiently use LAMODEL for accurate stress prediction, the program is first calibrated to the site-specific geomechanics based on previously observed stress conditions at the mine. For this calibration process, a previously mined area is "stress mapped" by quantifying the observed pillar and strata behavior using a numerical rating system. Then, the site-specific mechanical properties in the model are adjusted to provide the best correlation between the predicted stresses and the observed underground stress rating. Once calibrated, the model is then used to predict future stress problems ahead of mining. At the two case study mines, the calibrated models showed good correlation with the observed stresses and also accurately predicted upcoming high stress areas for preventive action by the mines.

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INTRODUCTION

Mine planners have a variety of modeling methods, both empirical and numerical, for analyzing pillar stresses and determining safe pillar sizes for various mine geometries and geologic structures. Empirical methods emphasize the collection and interpretation of case histories of pillar performance. The Analysis of Longwall Pillar Stability (ALPS) and Analysis of Retreat Mining Pillar Stability (ARMPS) programs are two such empirical programs that are derived from large databases of real-world pillar studies and can be used for determining pillar sizes for single-seam longwall and retreat room-and-pillar mining, respectively [Mark 1992; Mark and Chase 1997]. The Virginia Polytechnic Institute and State University, Blacksburg, VA, recently developed a comparable empirical program called Multi-Seam Analysis Package (MSAP) for sizing pillars for multiple-seam situations [Kanniganti 1993]. These empirical programs are closely linked to reality and very user-friendly; for many typical mining geometries, they work extremely well.

However, it is difficult to apply these empirical programs to mining situations beyond the scope of the original empirical database. Therefore, when complicated stress conditions arise from complex single- or multiple-seam mining geometries, numerical modeling techniques such as finite-element, boundary-element, discrete-element, or finite-difference are usually applied. In general, these numerical, or analytical, design methods are derived from the fundamental laws of force, stress, and elasticity. Their primary advantage is that they are very flexible and can quickly analyze the effect of numerous geometric and geologic variables on mine design. Their primary disadvantage is that they require difficult-to-obtain and/or controversial information about material properties, failure criteria, and postfailure mechanics. In this paper, the solid foundation of empirical pillar design and in-mine observation is combined with the flexibility of numerical modeling to provide a practical technique for mine planning in difficult situations.

LAMODEL

In order to analyze the displacements and stresses associated with the extraction of large tabular deposits such as coal, potash, and other thin vein-type deposits, the displacement-discontinuity variation of the boundary-element technique is frequently the method of choice. In the displacement-discontinuity approach, the mining horizon is treated mathematically as a discontinuity in the displacement of the surrounding media. Using this technique, only the planar area of the seam needs to be discretized, or gridded, in order to obtain the stress and displacement solution on the seam. Often, this limited analysis is sufficient, because in many applications only the distributions of stress and convergence on the seam horizon are of interest. Also, by limiting the detailed analysis to only the seam, the displacement-discontinuity method provides considerable computational savings over other techniques that discretize the entire body (such as finite-element, discrete-element, or finite-difference). It is a direct result of this computational efficiency that the displacement-discontinuity method is able to handle large areas of tabular excavations, which is needed in many practical coal mining problems.

A displacement-discontinuity program incorporating a laminated medium was recently developed by the National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory; this new program is called LAMODEL. Traditional displacement-discontinuity programs use a homogeneous isotropic elastic formulation that simulates the overburden as one solid material. In contrast, the LAMODEL program simulates the geologic overburden stratifications as a stack of layers with frictionless interfaces. Specifically, each layer is homogeneous isotropic elastic and has the same elastic modulus, Poisson's ratio, and thickness. This "homogeneous layering" formulation does not require specifying the material properties for each individual layer, yet it still provides a realistic suppleness to the mining overburden that is not possible with the classic homogeneous isotropic elastic overburden model. From our experience, this suppleness provides a more accurate strata response for modeling local deformations, interseam interactions, and/or surface subsidence. The LAMODEL program calculates stresses and displacements at the seam level and at requested locations in the overburden or at the surface. Both linear elastic and nonlinear seam materials can be used. The program also has the ability to analyze (1) the interseam stresses resulting from multiple-seam mining, (2) the effects of topographic relief on pillar stress and gob loading, (3) the stress changes during mining through multiple mining steps, and (4) the surface subsidence.

INITIAL MATERIAL PROPERTY GENERATION

As mentioned earlier, one of the most difficult aspects of using a numerical model is determining the correct (most accurate) material properties for input. After developing numerous displacement-discontinuity models and then comparing their results with field measurements and observations, a fairly streamlined, systematic technique for developing initial material properties was developed. Initially, the critical material properties (coal, gob, and rock mass) are determined using a combination of laboratory research, empirical formulas, and experience. Then, in the calibration process, these initial material properties are systematically adjusted in subsequent runs of the model until the results correspond as closely as possible to field observations. This technique for determining material properties has many similarities to the procedure used by Karabin and Evanto [1999].

First, to address the problem of determining the input coal behavior, the basic coal strengths are derived from the empirical pillar strength formulas, which are solidly based on observed pillar behavior. Specifically, the peak strength of a model coal element is directly determined based on an in situ coal strength and its distance from the edge of the pillar [Heasley 1998] using the stress gradient implied by the Bieniawski pillar strength formula [Mark and Chase 1997]. This peak strength is then implemented using an elastic, perfectly plastic material model [Zipf 1992]. For an initial estimate, an in situ coal strength of 6.2 MPa (900 psi) [Mark and Barton 1997] and an elastic modulus of 2 GPa (300,000 psi) is typically used.

This general procedure for generating the initial coal properties for elements in LAMODEL fulfills a number of practical requirements. It provides LAMODEL pillars with peak strengths that closely follow the empirically proven Mark-Bieniawski pillar strength formula and with stress profiles that closely follow the Bieniawski stress profile. As opposed to a simple elastic material model with no load limit, this procedure using elastic-plastic material allows the pillars to reach a maximum load-carrying capacity and then realistically shed additional load to surrounding areas. Table 1 presents typical elastic-plastic material input values for 3-m (10-ft) coal elements in a 1.8-m (6-ft) seam with a 6.2-MPa (900-psi) in situ coal strength. (Note that the peak stress for the coal elements decreases from the core to the rib of the pillar, which gives the pillar the proper stress profile.)

Second, to address the gob loading and compaction behavior, a combination of laboratory research and modeling experience is used. In the laboratory, Pappas and Mark [1993] found that an exponentially strain-hardening material with a tangent modulus that increases linearly with stress provided a reasonable representation of simulated gob material. This material model is implemented in LAMODEL [Heasley 1998] and is used for the gob modeling. The necessary input for this material is initial modulus, final modulus, and final vertical stress. From experience, these three values are initially set at 6.2 MPa (900 psi), 110 MPa (16,000 psi) and 27.6 MPa (4,000 psi), respectively (see table 1).

Table 1.—Typical elastic-plastic coal and strain-hardening gob parameters

COAL ELEMENTS: UPPER MINE		
Element	Peak stress, MPa	Peak strain
A (core)	85.9	0.04152
B	56.1	0.02712
C	38.3	0.01992
D (rib)	11.4	0.00552
GOB ELEMENTS		
Initial modulus, MPa	Final modulus, MPa	Final stress, MPa
6.2	110	27.6

The third critical set of material inputs in LAMODEL is for the overburden and consists of a lamination thickness and an elastic modulus. In LAMODEL, the lamination thickness has a major influence on the stress and displacement distribution at the seam and throughout the overburden. Prior research [Heasley 1998] comparing LAMODEL results with empirical relationships and measured field data shows that for large-scale stress distributions (such as longwall abutments) lamination thicknesses ranging from 15 to 100 m (50 to 300 ft) provide the best match to field measurements. However, when small-scale stress distributions (such as interseam stresses) or overburden displacements (such as subsidence) are of primary concern, then lamination thicknesses ranging from 3 to 15 m (10 to 50 ft) provide the best match to field observations [Karabin and Evanto 1999; Pappas and Mark 1993]. A lamination thickness of 15 m (50 ft) was used for case study 1, and a thickness of 5 m (15 ft) was used for case study 2. In both case studies, an elastic modulus of 20 GPa (3,000,000 psi) was used for the overburden.

STRESS MAPPING

In order to optimally use LAMODEL for accurate stress prediction at a given mine, the program should first be calibrated to the site-specific geomechanics based on previously observed stress conditions at that mine. One of the simplest and easiest methods to "quantify" the stress at a particular mine is to use "stress mapping." The pillar-centric stress mapping technique used here to quantify the observed stress conditions is a slight modification of the stress mapping technique originally developed for mapping areas of high horizontal stress [Mucho and Mark 1994]. For LAMODEL calibration in these case studies, the primary interest is the stress in the pillars; therefore, the primary stress indicator is the pillar rib damage, although other stress-related features, such as roof cracks or floor heave, are also noted during the stress mapping process because they can be useful indicators of stress reactions.

Stress mapping a mine area essentially consists of traveling the rooms and crosscuts in that area and carefully observing the conditions of the pillars, roof, and floor. The observed conditions are assigned a numerical rating and indicated on a map. For the rib damage stress mapping used here, the following numerical rating criteria were applied:

0: Rib still intact with no sloughed coal, original rock dust still in place.
1: Very slight pillar sloughage, some broken coal at base of rib.
2: Slight pillar sloughage, broken coal covers one-third of rib.
3: Significant pillar sloughage, broken coal piled halfway up rib.
4: Severe pillar sloughage, broken coal piled almost to roof.
5: Rib is composed of completely broken coal at the angle of repose, pillar may be failed.

MODEL CALIBRATION

In the model calibration process, the initial material properties are systematically adjusted in subsequent runs of the model until the results correspond as closely as possible to field observations and/or empirical formulas. For the coal properties, the in situ coal strength is adjusted until the pillar stress/failure in the model matches the observed pillar behavior as represented by the stress mapping/rib rating. For the gob properties, the final modulus value is typically adjusted up or down in LAMODEL to increase or decrease the gob stress until the model gob stress matches empirical abutment angle formulas [Mark and Chase 1997] and/or field measurements and observations. For the overburden properties, the lamination thickness is typically adjusted up to provide wider abutment stresses and smaller interseam stresses or adjusted down to provide narrower abutment stresses and greater interseam stresses as dictated by the observed stress mapping.

Once the model is reasonably calibrated and realistic pillar strengths and load distributions have been established, the mechanics-based overburden behavior in the LAMODEL program can be effectively used to accurately analyze the complicated stresses and displacements associated with future complex mining scenarios. The above technique of combining empirical pillar strength and abutment load formulas with in-mine stress mapping and the analytical mechanics of a displacement-discontinuity model capitalizes on the strengths of both the empirical and analytical approaches to pillar design. The empirical formulas and observational calibration base the model on realistic behavior; the analytical mechanics allow the model to accurately consider and analyze the effects of numerous geometric and geologic variables. Using this technique, a displacement-discontinuity model can be the most practical approach for stress analysis and pillar design in complex mining situations such as multiple seams, random pillar layouts, and/or variable topography.

CASE STUDY 1

The first case study location was a multiple-seam, room-and-pillar coal mining situation in eastern Kentucky. At this location, the lower mine had been adversely affected by mining in the upper seam (see figure 1). In particular, the lower mine experienced serious ground control problems when it mined under a barrier pillar between two upper seam gobs ("Model Area" shown in figure 1). At this multiple-seam interaction site, in-mine stress mapping was used to quantify the severity of the multiseam interactions. This stress mapping was also used to calibrate a LAMODEL simulation of the area. The results of this numerical simulation provided predicted stress levels to avoid in future multiple-seam or high-cover mining.

The geology at this location is fairly typical of the southern Appalachian coal basin, with various sedimentary layers of sandstones, siltstones, shales, and numerous coal seams. The topography is very rugged, with various steep ridges and valleys that have a topographic relief of over 600 m (2,000 ft) (see figure 1). The overburden in the study area ranged from 150 to 450 m (500 to 1,500 ft), with an average of about 300 m (1,000 ft). Because of the highly variable topography at this mine, it was critical to include the topographic stress effects in LAMODEL in order to obtain accurate results.

The overlying, or upper, mine operates in the Upper Darby Seam, which typically averages about 2.0 m (6.0 ft) thick. The lower mine operates in the Kellioka Seam, which averages about 1.5 m (4.5 ft) thick in the study area. The interburden between the two seams averages about 14 m (45 ft) and consists of interbedded sandstones and shales. The core logs nearest to the study site indicate about 3.5 to 5 m (10 to 15 ft) of shale directly over the Kellioka Seam. This is then overlain by 7.5 to 10.5 m (25 to 35 ft) of interbedded sandstones and shales, with shale primarily forming the floor of the Upper Darby Seam. Both mines are room-and-pillar drift mines and use continuous miners for coal extraction. In some production sections, depending on local mining conditions, the mines remove the pillars on retreat for full extraction.

In the study area, the lower mine was forced to dogleg around an abandoned, flooded mine in the upper seam (not shown in figure 1). This dogleg forced the lower mine to develop entries under a barrier pillar between two previously mined, upper seam gobs, as shown in the detail of figure 2. Mine management anticipated increased multiple-seam stresses in this area. In an effort to safely control these higher stress levels, the mine located the critical travelway and belt entries

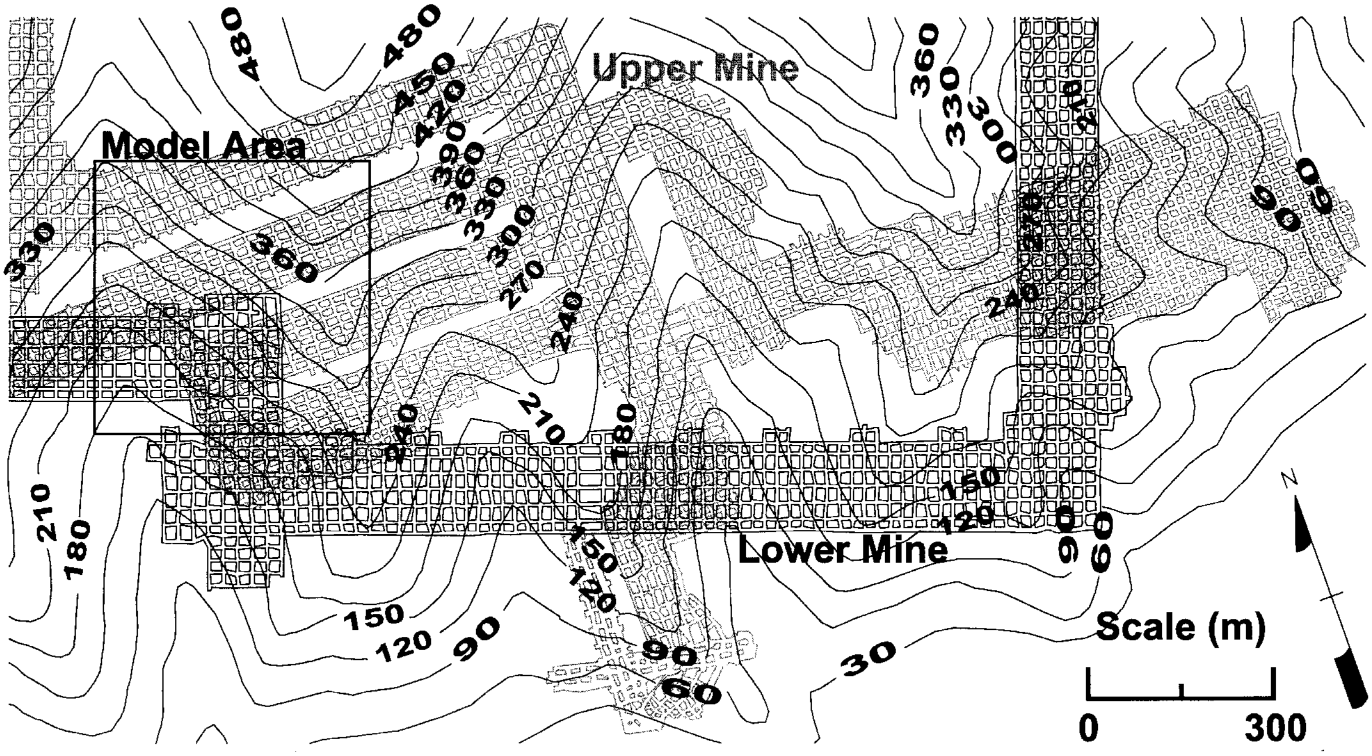

Figure 1.—Mine map for case study 1.

away from the influence of the barrier pillar and used a double row of supplemental cable bolts on 0.6-m (2-ft) centers throughout most of the travel entry under the upper seam mining. With these precautions, the mine was able to safely and efficiently mine the entries under the barrier pillar and surrounding gob. However, throughout the section, the stress effects of the overlying barrier and gob were abundantly visible, and on two occasions (in the northeast corner of the section), the mine was unable to complete crosscuts because of roof instability and poor pillar conditions.

STRESS MAPPING

In order to quantify the stress effects of the barrier pillar and gob zones on the lower seam, a detailed stress mapping of a large portion of overmined area was performed. As previously described, the amount of rib sloughing was noted on a scale of 0 to 5, and any stress-related features such as roof cracking, potting, cutting, or floor heave were also noted. The results of this stress mapping exercise are shown in figure 3*A*. In this figure, the observed condition of the pillar ribs is shown in gray scale by degree of damage; the darker shades signify increased sloughing (or stress). Also, the observed roof cracking, potting, cutting, and floor heave are indicated on the map.

Several useful observations can be made from the detailed stress mapping shown in figure 3*A*. First, the transfer of the abutment stresses from the overlying mine to the area under the barrier pillar and to the area at the ends of the pillared sections can clearly be inferred in the rib conditions of the lower mine pillars. Also, as a corollary to the interseam transfer of the barrier pillar abutment stresses, the lower seam pillars under the gob areas in the upper seam show considerable stress relief. The next major observation pertains to the location and orientation of the roof tension cracks and guttering. Clearly, the tension cracks in the roof of the northeast corner of the section are situated directly under the overlying barrier pillar and are oriented parallel to the axis of this pillar. Also, the observed

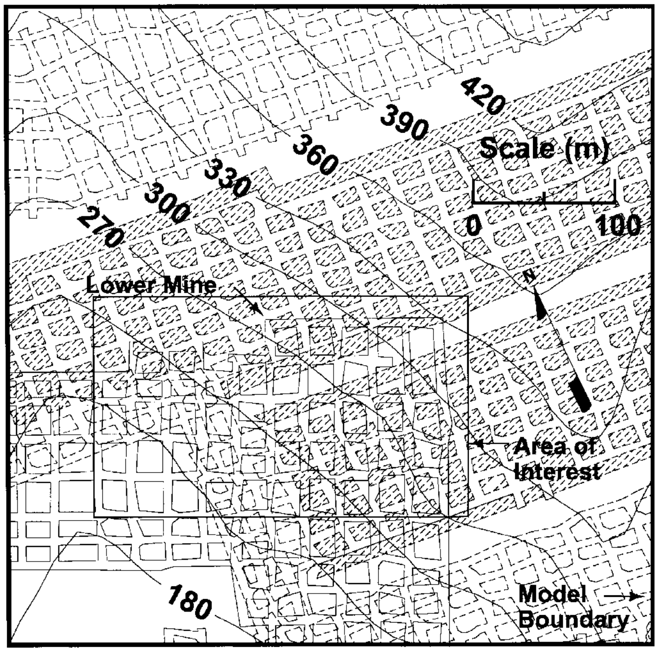

Figure 2.—Enlargement of model area for case study 1.

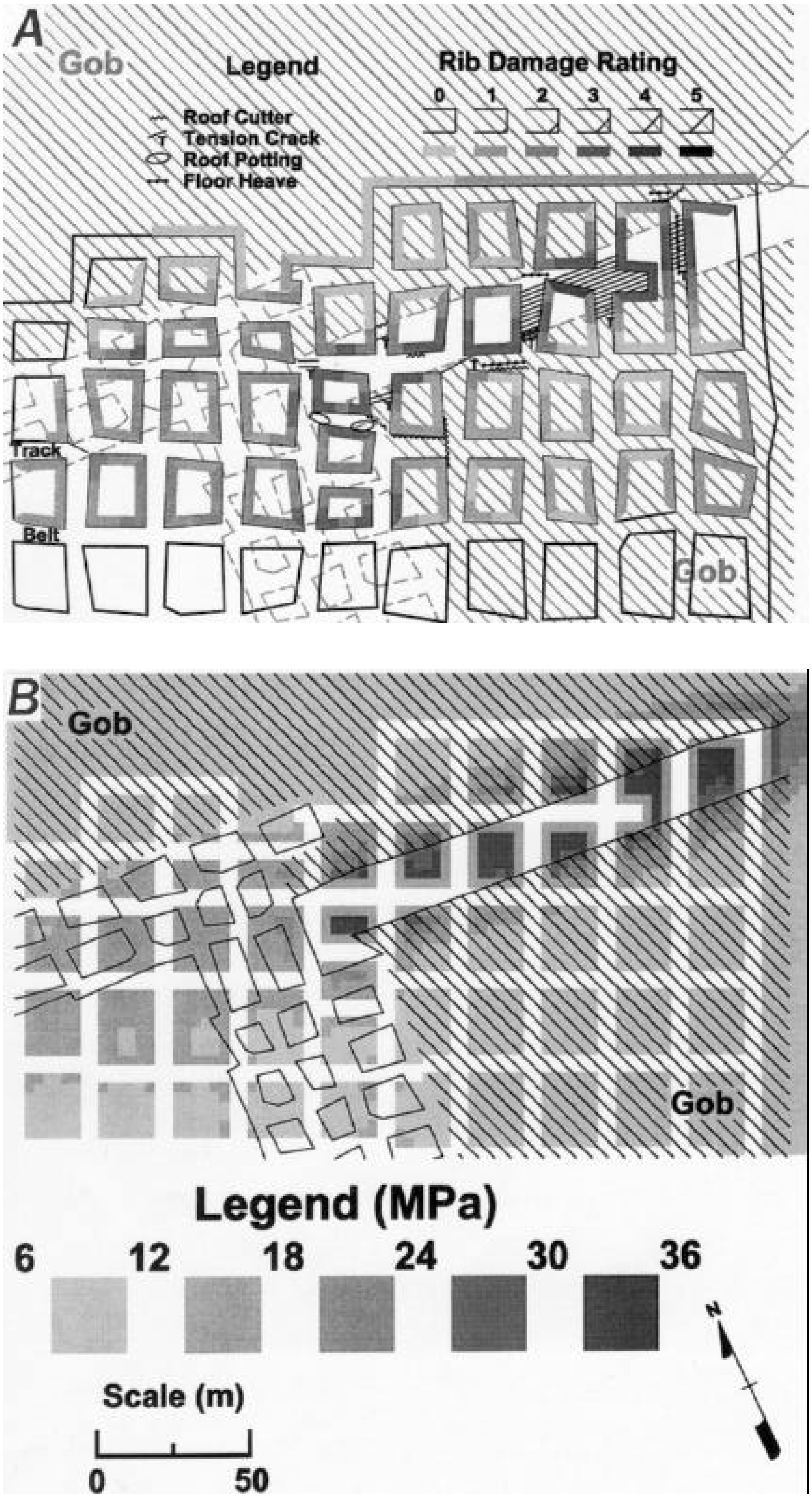

Figure 3.—Comparison between (*A*) in-mine stress mapping and (*B*) LAMODEL calculated stresses for mine 1.

compressional roof cutters are located at the edge of, or adjacent to, the overlying abutment zones and oriented parallel to these zones. This location and orientation of the tension and compression suggest that the lower mine roof is behaving like a beam that is bending into the relatively soft coal seam under the load of the barrier pillar in the upper seam. This beam scenario correctly accounts for the tension directly under the applied load and the compression adjacent to the applied load.

MODEL DESIGN

For the LAMODEL simulation of this area, the seams were discretized with 3-m (10-ft) elements in a 150-by-150 grid with the model boundary, as shown in figure 2. Symmetrical seam boundary conditions were set on all four sides, and no free-surface effects were included. The interburden was set at 14 m (45 ft), and the rock mass was simulated with a modulus of 20 GPa (3,000,000 psi) and 15-m (50-ft) thick laminations. An elastic, perfectly-plastic material was used for the coal in both seams, and the peak strength of the coal was determined from the Mark-Bieniawski pillar strength formula, as in appendix C of Heasley [1998]. Table 2 presents the coal and gob input values used in LAMODEL for this particular case study.

Also, because of the high topographic relief at the site, the topography was discretized with 15-m (50-ft) elements for an area extending 300 m (1,000 ft) beyond the limits of the displacement-discontinuity grids. The importance of including the topographic stress effects in the model is evident in figure 4, which shows the topographic stress at the level of the lower mine. It is interesting to note in this figure the amount to which the topographic stress is "smoothed" with depth compared to the original topography. Also, it is evident that the overburden stress changes about 3 MPa (450 psi) in traversing from the southwest to the northeast corner of the pillars in the study area. This difference in overburden stress could very well account for the increased mining difficulties at the northeast corner of the section.

MODEL CALIBRATION AND ANALYSIS

Very little work was required for calibrating the LAMODEL simulation to the observed stress mapping. In both seams, the original Mark-Bieniawski pillars strengths and the initial overburden modulus and lamination thickness provided a good fit to the observed pillar behavior (see figure 3). The only parameter that was ultimately manipulated was the modulus of the gob material (see table 2). This modulus was adjusted to provide a peak gob stress in the range of 40% to 60% of in situ stress, a reasonable range for a 90-m (300-ft) wide gob in 300 m (1,000 ft) of cover [Mark and Chase 1997]. A number of variations in pillar strength, overburden modulus, and lamination thickness were investigated, and the simulation results varied a little. However, the initial parameter values with the adjusted gob modulus provided a reasonably optimum fit to the observational stress mapping.

Table 2.—Coal and gob parameters for case study 1

COAL ELEMENTS: UPPER MINE		
Element	Peak stress, MPa	Peak strain
A (core)	85.9	0.04152
B	56.1	0.02712
C	38.3	0.01992
D (rib)	11.4	0.00552
COAL ELEMENTS: LOWER MINE		
Element	Peak stress, MPa	Peak strain
A (core)	113.2	0.05472
B	73.5	0.03552
C	53.6	0.02592
D (rib)	13.9	0.00672
GOB ELEMENTS		
Initial modulus, MPa	Final modulus, MPa	Final stress, MPa
6.2	110	27.6

The calculated pillar stresses from the final calibrated LAMODEL run are shown in figure 3*B*. These modeled stresses correlate extremely well with the stress mapping in figure 3*A*. The high stresses under the barrier pillar are evident in the model results; the area of stress relief under the gob is also shown. Even the intermediate stress levels under the overlying pillars and solid coal in the southwest corner of the model closely match the observed pillar stress mapping. A few more details of the modeled stress output are shown in figure 5, where the isolated single-seam stress and just the interseam stress are displayed. In this figure, the effect of the overlying barrier pillar can be clearly seen. In particular, the maximum single-seam stress on the pillars (figure 5*A*) of around 15 MPa (2,200 psi) is seen to increase to over 36 MPa (5,200 psi) with the addition of the barrier pillar stress (figures 5*B* and 5*C*). Also, it is interesting to note the increased abutment stress in the northeast corner of the section (figure 5*C*), presumably due to the increasing overburden and the increasing distance from the upper panel boundaries. A stress relief of about 7 MPa (1,000 psi) under the gob areas is also shown in figure 5*C*.

For the mine management, this stress modeling using LAMODEL, in conjunction with good in-seam correlations with stress mapping, provided valuable background information for future multiple-seam mine planning. In this case study, a calculated multiseam stress concentration of about 15 MPa (2,200 psi) with pillar stresses of 35 MPa (5,200 psi) at this site caused sufficient roof instability to prohibit the mine from driving two crosscuts. Therefore, it seems that the 15-MPa stress concentration (35-MPa pillar stress) is close to an upper limit for successful entry development at this mine. The mine can use this calculated limit in conjunction with future modeling in order to lay out future room-and-pillar panels influenced by overlying workings.

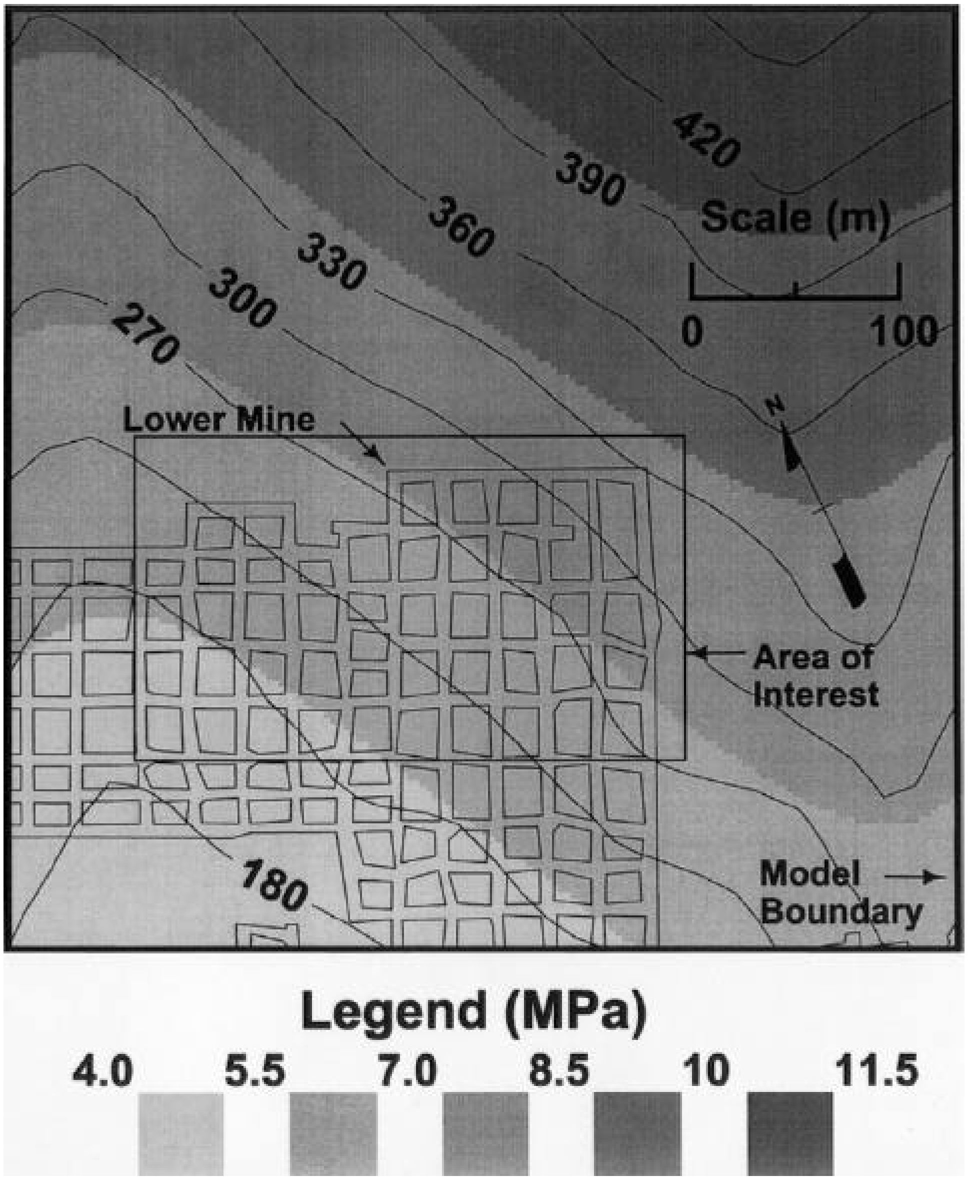

Figure 4.—Calculated topographic stress for case study 1.

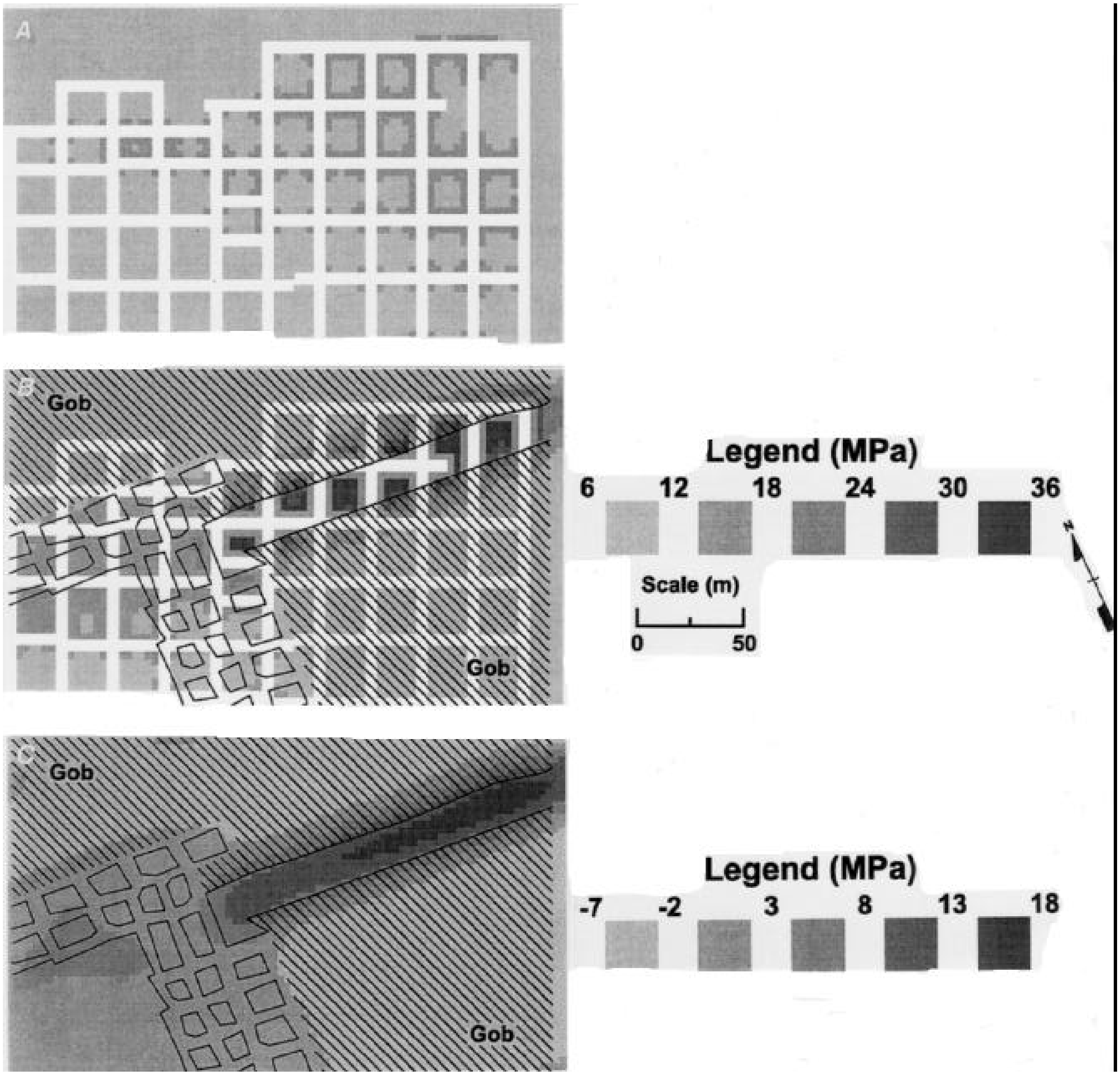

Figure 5.—The LAMODEL stress output for case study 1. *A*, Single-seam stress; *B*, multiple-seam stress; *C*, additional stress from upper seam.

CASE STUDY 2

The second study site was a longwall mine located in Greene County, PA, and operating in the Sewickley Seam. This mine is underlain by an abandoned room-and-pillar operation in the Pittsburgh Seam. The primary problem at this site was the transfer of multiple-seam stress from the lower mine. Yielding of smaller pillars and the subsequent transfer of their load to larger pillars in the lower seam apparently caused increases in vertical stress in the upper seam that were noticed during development of the headgate entries (see figure 6). Severe pillar spalling and poor roof conditions were experienced when mining the headgate over these large pillars in the lower seam (figure 7). Mine management was concerned that these underlying abutment pillar stresses would continue to be a problem farther inby in the headgate and also in the longwall panel because there were several areas in the lower seam where similar pillar conditions seemed to exist.

In the study area, the overburden above the Sewickley Seam ranges from 150 to 280 m (500 to 910 ft) and consists predominantly of interbedded shales and sandstones. The interburden between the Sewickley and Pittsburgh Seams ranges from 27 to 30 m (90 to 100 ft) thick and consists of interbedded shales and limestones. The average mining heights of the Sewickley and Pittsburgh Seams are 1.5 m (5 ft) and 1.8 m (6 ft), respectively. The immediate roof of the Sewickley Seam is composed of a jointed dark sandy shale that ranges from 3 to 4.5 m (10 to 15 ft) thick and is overlain by a competent limey shale. The immediate floor of the Sewickley Seam is composed of a 1.2-m (4-ft) thick dark limey shale underlain by a competent limestone unit.

STRESS MAPPING

Figure 6 shows the overlay of the lower seam workings on the upper seam longwall panel and the area of the headgate where the stress mapping and model calibration were conducted. As described earlier, the process of calibration involved the use of stress mapping to assign a rating from 0 to 5 based on the observed pillar rib conditions. The first 600 m (2,000 ft) of the headgate entries, where problems first occurred (see figure 6), were traversed and assigned rating numbers based on the observed conditions. Figure 7*A* shows the rib damage rating assigned to each rib in this area of the headgate.

MODEL DESIGN AND CALIBRATION

Once the stress mapping was complete, LAMODEL calibration was initiated. For calibration purposes, the "Stress Mapped Area" shown in figure 6 was discretized with 3-m (10-ft) elements with a 90-by-200 grid. Symmetrical boundary conditions were set on all four sides, and no free-surface effects were included. The interburden was set at 27 m (90 ft), and the rock mass was simulated with a modulus of 20 GPa (3,000,000 psi) and 5-m (15-ft) thick laminations. The overburden above the lower mine in this area ranged from 180 to 300 m (600 to 1,000 ft). Due to this variable topography, the topographic stress effects were included in LAMODEL in order to obtain accurate overburden stress results.

Based on the observed stress mapping, model calibration was conducted under the assumption that the smaller pillars (<10.5 m (<35 ft) wide) in the lower mine had essentially yielded and transferred their load to nearby larger pillars. Therefore, in the first step of the calibration process, the coal strength in the lower mine model was adjusted until the pillars showed this observed behavior. Initially, using the elastic-plastic implementation of the Bieniawski formula, as previously explained, an in situ coal strength of 6.2 MPa (900 psi) was used to calculated peak stress and strain values for each coal element, and the initial calibration model was run. In this initial model, the coal in the lower mine was too strong and did not show the desired yielding in the smaller pillars. Therefore, in order to obtain the desired small pillar yielding and subsequent stress transfer to the larger pillars, the in situ coal strength in the lower seam was gradually decreased to 4.2 MPa (600 psi).

With the in situ coal strength of 4.2 MPa (600 psi) in the lower seam and the original coal strength of 6.2 MPa (900 psi) in the upper seam, the model correlated very well with the rib damage rating from the stress mapping. The rib damage rating is in gray scale in figure 7*A*; the results from the model are in a comparative gray-scale plot in figure 7*B*. Clearly, the model pillars with high rib stress correlate well with the pillars with high damage ratings. It can be observed in figure 6 that these high rib stresses occur over the large pillars located in the lower mine in conjunction with overburden that exceeds 250 m (870 ft). The final coal and gob properties used in LAMODEL for the upper and the lower mine are presented in table 3.

Table 3.—Coal and gob parameters for case study 2

COAL ELEMENTS: UPPER MINE		
Element	Peak stress, MPa	Peak strain
A (core)	102.3	0.04944
B	66.5	0.03216
C	48.7	0.02352
D (rib)	12.9	0.00624
COAL ELEMENTS: LOWER MINE		
Element	Peak stress, MPa	Peak strain
A (core)	56.8	0.02747
B	36.9	0.01787
C	27.0	0.01307
D (rib)	7.2	0.00347
GOB ELEMENTS		
Initial modulus, MPa	Final modulus, MPa	Final stress, MPa
6.2	138	27.6

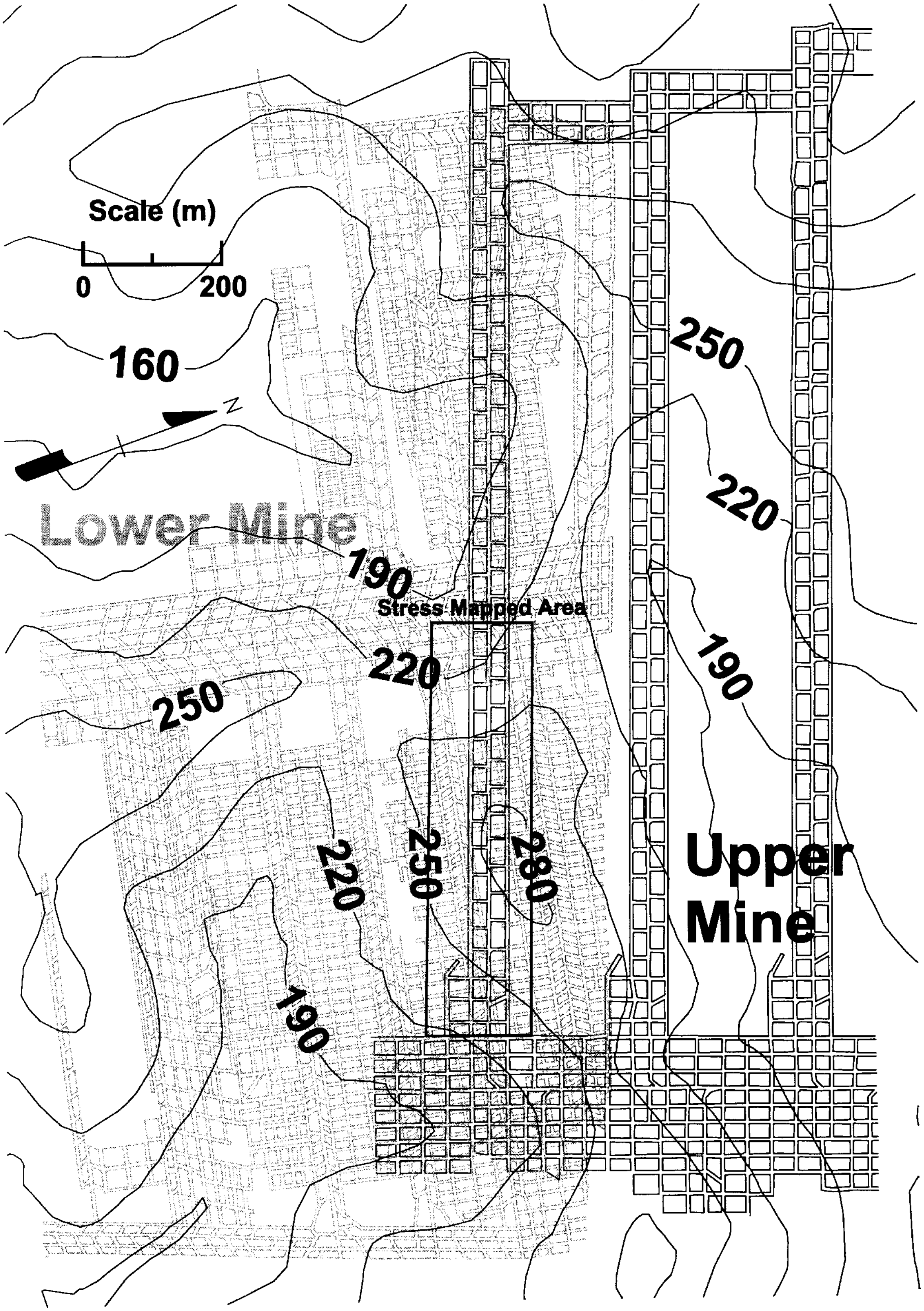

Figure 6.—Mine map for case study 2.

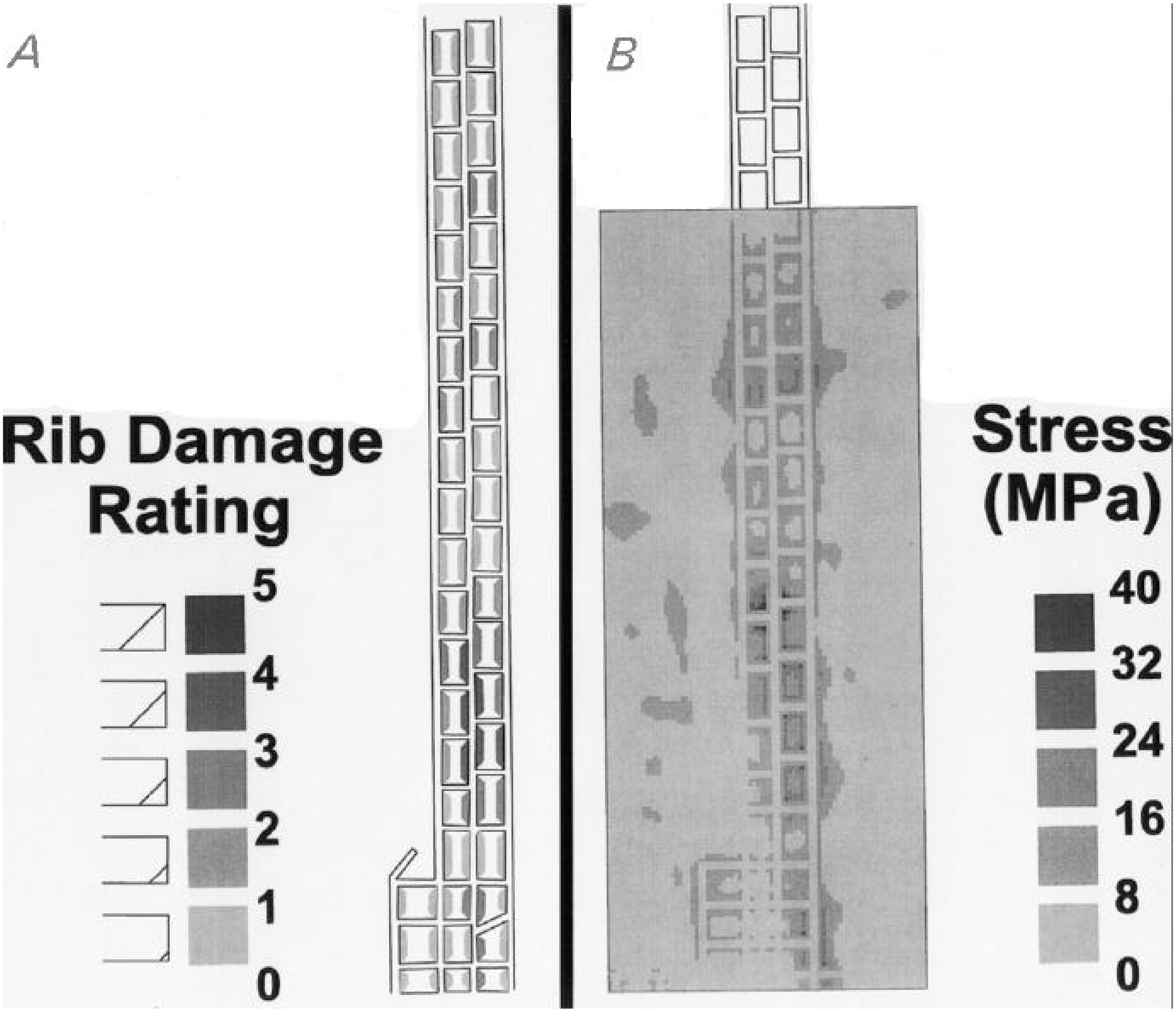

Figure 7.—Comparison between in-mine stress mapping and LAMODEL calculated stresses. *A*, rib damage rating; *B*, stress (MPa).

STRESS PREDICTION FOR MINE PLANNING

With material properties calibrated from observed stress conditions in the mine, additional LAMODEL analyzes were created and run in order to predict areas of potential problems within the remaining headgate and the future longwall panel. Figure 8 shows two areas of the headgate and longwall panel that were modeled using optimized properties from the calibration process. These gray-scale plots show the interseam stress, which is the additional stress on the upper mine due to the lower seam mining. In this figure, zone 1 covers the upper (inby) part of the headgate panel and the first 365 m (1,200 ft) of the longwall panel; zone 2 covers the lower part of the headgate (where the stress problems were first noticed) and the last (outby) 330 m (1,100 ft) of the longwall panel. In these two zones, the lower mine pillar conditions and the overburden depths appeared similar; therefore, the poor pillar conditions encountered in zone 2 were expected in zone 1.

However, when comparing the interseam stress between these two zones as shown in figure 8, it is obvious that the stress in zone 2 is considerably greater than that in zone 1. Closer investigation reveals two primary reasons for this. First, the maximum depth over the gate roads and panel in zone 2 is over 280 m (920 ft); in zone 2, the maximum depth is just over 250 m (870 ft). Second, when examining the model output for the lower mine, there seems to be less pillar yielding in zone 1 than in zone 2. In figure 6, it can be seen that the smaller pillars in zone 1 are dispersed among larger pillars and have widths >12 m (>40 ft), whereas in zone 2, there is a large area of pillars with widths <10.5 m (<35 ft). The larger, more dispersed small

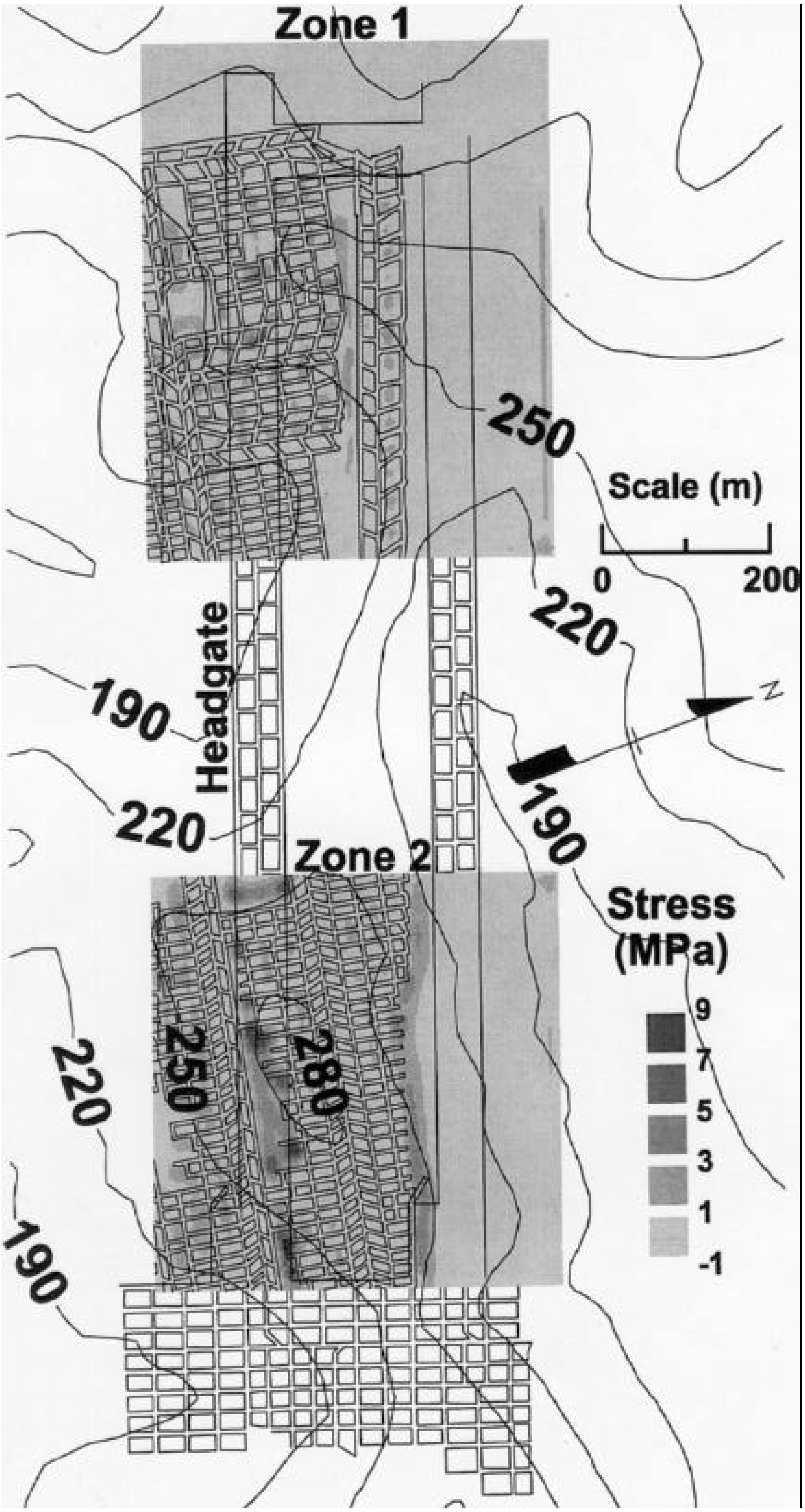

Figure 8.—Interseam stress for zones 1 and 2.

pillars in zone 1 suffer less pillar yielding and therefore cause less load transfer (or interseam stress) on the upper mine (see figure 8). During headgate development in zone 1, no pillar problems were encountered. Thus, the calibrated model successfully predicted the reduced stress conditions in the headgate of zone 1.

The mine management was also concerned about the multiple-seam stresses adversely affecting the retreating longwall panel. In particular, a large, irregularly shaped barrier pillar in the lower mine is superimposed under the center line of the initial half of the longwall panel in zone 1 (see figure 8). However, the interseam stress calculated by the model from this barrier pillar reaches only about 3 MPa (450 psi). When the panel was mined, this slightly increased face stress presented very little problem. Some slight spalling was present on the face during the extraction, but overall face conditions were generally good and no severe ground control problems were evident.

However, in the lower part of the panel near the headgate location where poor ground conditions were first encountered (see zone 2, figure 8), an area of interseam stress up to 9 MPa (1,300 psi) is evident in the panel. Because of the underlying barrier pillar, the mine anticipated difficult face conditions in this area. Indeed, when the longwall face reached this area, ground control problems that included severe face spalling and poor roof condition in the headgate entries were encountered. In fact, the stress interaction with the lower seam was severe enough to stop the longwall face about 15 m (50 ft) short of the longwall recovery chute and make recovery of the supports difficult.

When comparing conditions in zone 1 with those of zone 2, there seems to be a very fine line in the occurrence of ground control problems in the upper seam depending on the overburden depth and the pillar size in the lower seam. Problems were more likely to occur when the depth of cover over the Sewickley Seam exceeded 250 m (820 ft) and when large areas of narrow pillars (<10.5 m (<35 ft) wide) in the lower seam were located adjacent to a larger barrier pillar. These conditions caused yielding of the narrow pillars and the shedding of their load to the adjacent larger pillar. This concentrated abutment stress was then transferred to the upper mine, resulting in poor ground conditions in areas of the headgate entry and longwall panel. Throughout this case study, the calibrated LAMODEL program successfully predicted the high stress areas in advance of mining.

CONCLUSIONS

The primary purpose of the case studies presented in this paper was to validate the new LAMODEL boundary-element program and investigate its utility for stress modeling in mine planning. Based on the comparisons between the stress mapping and the model results for the two case studies, it seems that the LAMODEL program can be calibrated to produce good correlations with the observed stresses. In addition, once realistic pillar strengths and load distributions were established by calibration, the mechanics-based overburden behavior in LAMODEL effectively analyzed the complicated stresses and displacements associated with the complex multiple-seam mining scenarios and successfully predicted upcoming high stress conditions in advance of mining for preventive action by mine management. In case study 1, a calculated multiseam stress concentration of around 15 MPa (2,200 psi) with pillar stresses of 35 MPa (5,200 psi) seemed to be an upper limit for successful entry development at this mine. Similarly, in case study 2, a calculated multiple-seam stress concentration of 9 MPa (1,300 psi) produced severe face spalling and poor roof conditions in the headgate entries, whereas a 3-MPa (450-psi) stress concentration was barely noticeable.

A secondary goal was to present a fairly streamlined, systematic methodology for developing initial material properties and then calibrating these properties to field observations. Initially, the critical material properties (coal, gob, and rock mass) are developed using a combination of laboratory research, empirical formulas, and experience. Then, in the calibration process, a previously mined area is "stress mapped" by quantifying the observed pillar and strata behavior using a simple numerical rating system. Finally, the initial material properties are systematically adjusted in subsequent runs of the model until the results provide the best correlation between the predicted stresses and the observed underground stress rating. This methodology of combining empirical pillar strength and abutment load formulas with in-mine stress mapping and the analytical mechanics of a displacement-discontinuity model capitalizes on the strengths of both the empirical and analytical approaches to pillar design to provide a practical technique for mine planning in difficult situations.

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