USING GIS AND NUMERICAL MODELING TO ASSESS SUBSIDENCE OVER ABANDONED MINES

by

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Abstract. The U. S. Bureau of Mines (USBM) has been developing techniques to assess surface subsidence over abandoned coal mines. One technique has involved estimation of stress acting on every pillar of an abandoned mine then comparing it to pillar strength and floor bearing capacity. This required computations for several thousand pillars for one mine. Mine maps are digitized and saved as a computer drawing file. Then the tributary area loading each pillar was determined graphically and outlined. Geographic Information System (GIS) software was used to compute the ratio of pillar area to tributary area for each pillar and then divide the average overburden stress by this ratio to compute an estimated pillar stress. Numerical modeling was then used to analyze a two-dimensional cross section of the overburden and mine, and provide an independent estimate of stresses. Based on published data for floor bearing capacity and pillar load capacity, GIS was used to perform a mine-wide classification of pillars according to stress level. An example of this analysis and classification is presented in this paper for an abandoned coal mine in the Illinois Basin. The mine had been operated in the Herrin No. 6 Seam at a depth of 60 m with an average overburden stress of 1.4 MPa. It was found that pillars with estimated stresses greater than 5 MPa correlated with historical subsidence events. Due to the greater detail considered in this approach, it provides a fundamental basis for the assessment of subsidence risk since it incorporates the geometry of mine pillars and entries as well as the ultimate strength of the pillars and floor.

Additional Key Words: pillars, stress, animation, CAD

Introduction

Coal mining was active in Collinsville, Illinois from 1870 to 1964, and the area is underlain by a network of mine openings. Support for the overlying rock is provided by stable pillars and blocks of coal as well as those that may be failing or possibly punching into the underlying claystone. As a result of failures within the abandoned mines, there have been localized mine subsidence occurrences throughout the city. Movement of the overlying rock, and ultimately the surface, has subjected structures, streets, and utilities to strains and stresses that have caused damage. Occurrences of subsidence and damage have been regarded as random events. Current research indicates that this may not be the case and rational assessment of subsidence potential may be possible.

Subsidence characterization over abandoned room-and-pillar mines remains relatively undeveloped due to a lack of understanding about time-dependent rock mass behavior at mine level and within the overburden. The effectiveness of early warning technology inherently requires that the timing and extent of a subsidence event can be anticipated. In the case of important structures located over abandoned mines, it is not adequate to say that subsidence may occur. A means must be provided to indicate if strata movements are occurring (and the rate at which they are occurring)

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beneath these structures so that appropriate measures can be taken to mitigate damage. One component of research being conducted by the USBM has involved monitoring of subsurface movements which are precursors of surface subsidence. This paper concentrates on another component involving the use of historical subsidence data and mine maps to identify areas over abandoned mines with a high likelihood of subsidence occurrence.

The USBM in cooperation with the Illinois Mine Subsidence Insurance Fund (IMSIF), Illinois Abandoned Mined Land Reclamation Council (AMLRC), and Collinsville Community Unit School District No. 10 (CUSD #10), has implemented these techniques to allow proactive land use planning over abandoned mines. This joint project was initiated because of subsidence damage to one school, the Dorris Elementary School (figure 1 and figure 2). It will be replaced by a new building and two sites are being considered. One site is an athletic field adjacent to the existing school. The alternative site is an athletic field adjacent to the Lincoln Elementary School (figure 2). Both sites are undermined so it is a situation in which the school district must assess the relative risk of future subsidence.

The USBM conducted a program of site characterization involving core drilling, downhole camera inspection of mine conditions, monitoring of subsurface movements, and data analysis. This paper focuses on efforts to estimate pillar stresses and correlate occurrences of historical subsidence with pillars that are highly stressed. This effort was undertaken using two independent approaches. The first approach involved GIS analysis of the geometry of pillars and entries to estimate stresses assuming tributary loading on pillars (Whittaker and Reddish, 1989). The second approach involved numerical modeling of a two-dimensional cross section of the abandoned mine and overburden to estimate the distribution of stress.

Geometric and Subsidence Data Collection

The project sites are located in Collinsville (figures 1 and 2) which has been extensively undermined. Historically, the old high school and Dorris Elementary School have been damaged by subsidence. There has been no evidence of subsidence at the Lincoln Elementary School.

Available data which were collected for this projected included: 1) U.S. Geological Survey (USGS) 7.5-minute Collinsville quadrangle map, 2) mine maps, 3) subsidence survey data, 4) drilling logs, 5) structural damage reports, and 6) Madison County plat map and orthophoto overlays. Maps were assembled and digitized for the following mines (ISGS, 1991):
Bullock Mine, operated 1899 - 1946;
Heinz Bluff Mine, operated 1883 - 1907;
Huntley Bluff Mine, operated 1886 - 1887;
Lumaghi Mine No. 1, operated 1883 - 1903;
Donk Bros. Mine No. 1, operated 1900 -1922.

Surface subsidence has been monitored by the IMSIF and the AMLRC (Gibson and Schottel, 1990) in response to occurrences of subsidence damage. Collectively, ninety-eight benchmarks in the area of Dorris School and the old high school have been monitored at various times during the period from February 1984 to August 1994. This monitoring has been performed in response to claims of subsidence damage so it was started after "events" had affected the ground surface. Furthermore, data were collected as a series of nets with local reference systems that were not tied to a common origin.

All surface feature and mine maps were digitized and assembled as a drawing file using computer-aided drafting (CAD) software. This allowed all spatial data to be assembled, viewed, and plotted with a common origin, reference system, and graphical scale. With the survey monuments now tied to a common reference, it was possible to assign global coordinates to each point. A drawing of the Dorris Elementary School with surveyed benchmark locations was obtained from the AMLRC. Drawings and survey elevation measurements of monitored benchmarks and structures in the surrounding area were obtained from the IMSIF. The mine maps and drawings were scanned using DeskScan II, then digitized using AutoCAD and assigned to different drawing layers. The historical survey data from both AMLRC and IMSIF were entered into a spreadsheet.

The digitized base map was created using section corners and road intersections as control points for positional accuracy of the mine and subdivision drawing layers. This made it possible to register the map with USGS 7.5 minute Collinsville quadrangle digital line graph (DLG) features and the Universal Transverse Mercator (UTM) projection coordinate system. Road alignments, property boundaries, and the addition of cultural features (baseball field, power poles, fences) for the two school sites were entered from overlay maps obtained

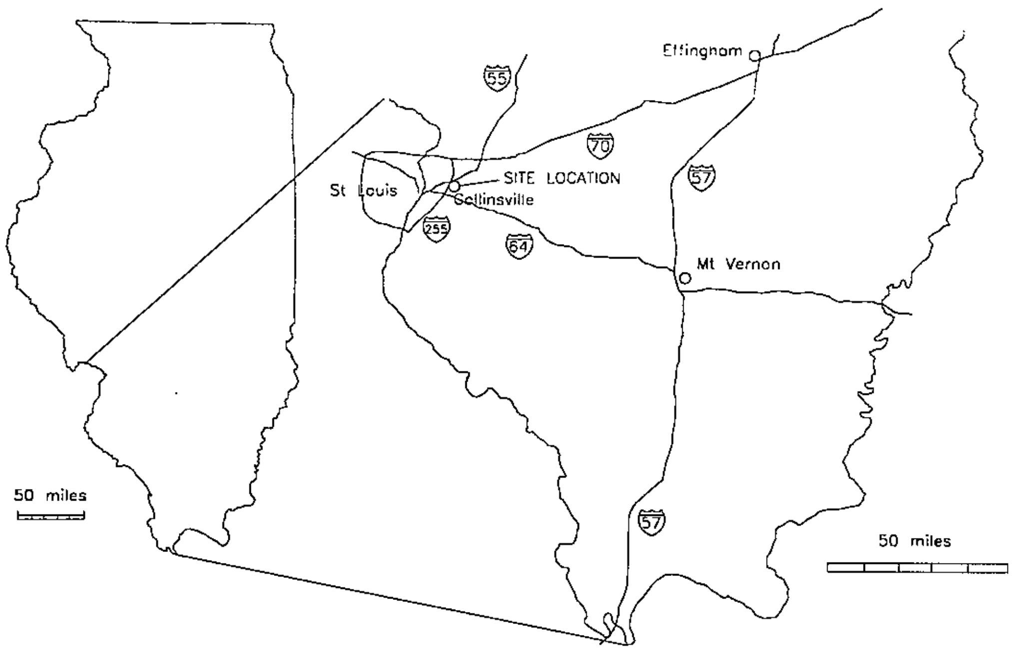

Figure 1.-Site location in Illinois.

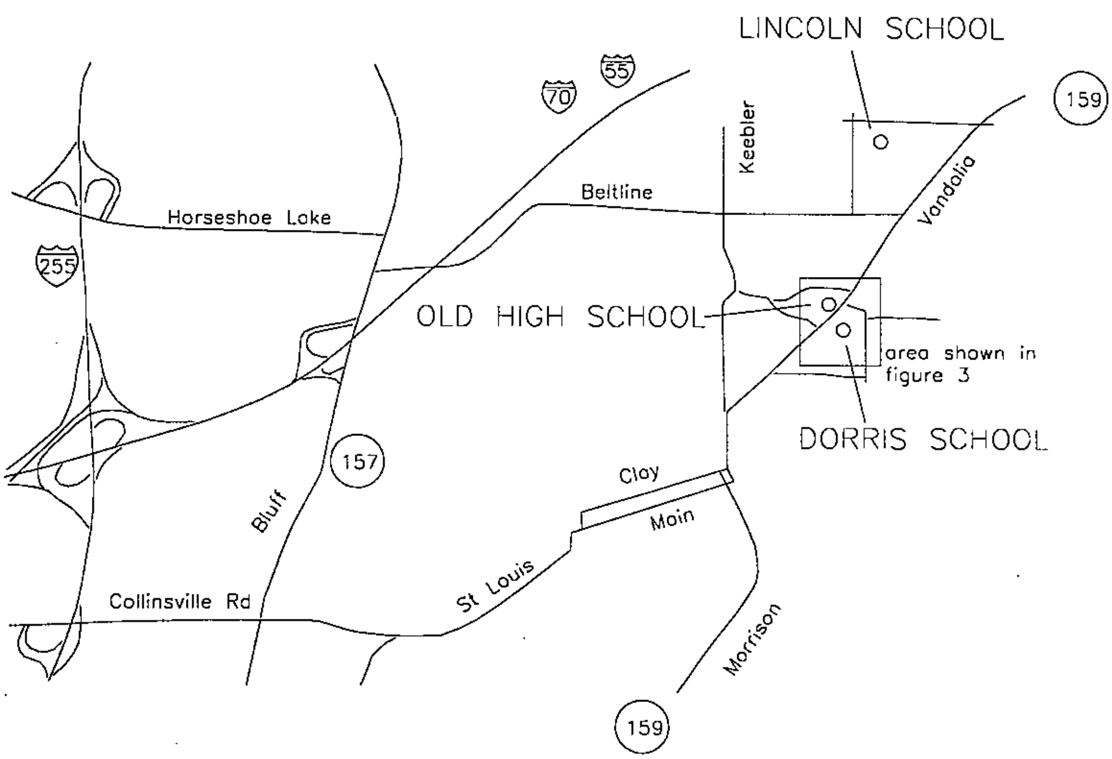

Figure 2.-Site location in Collinsville, Illinois.

from the Madison County Maps and Plats Department. These maps display property boundaries as an overlay with aerial photography at a scale of 1:1200 (1 in.= 100 ft).

Map scale errors may have been introduced or compounded as a result of scanning or digitizing copies of the maps used for data entry. USBM researchers recognize that accuracy of the base maps is an approximation and therefore use the maps to assess general tendency correlations between structural damage and ground surface curvatures (Triplett et al, 1992), and as a tool for display of spatial analyses. However, the elevations of subsidence monitoring points used to build the research database were measured using modern survey techniques with a precision of ±1.5 mm (±0.005 ft).

Initial survey data were used to establish baseline elevations and subsequent surveys were used to calculate vertical displacement. Subsidence contours for each date were generated using a statistical technique known as kriging available within SURFER for Windows. The subsidence contour lines were then imported into AutoCAD and contours for each date were placed on separate layers. Figure 3 displays the last date of survey measurements available overlaid on the mine map. The first contour represents 0.05 m (0.16 ft) of subsidence and the contour interval is 0.025 m (0.08 ft).

Analysis of Subsidence Occurrences

By selectively activating different drawing layers, it was possible to generate a series of slides showing subsidence contours for each date that measurements were made overlaid with the mine geometry. The slides were compiled as an animation to enhance the changes in subsidence contours as a function of time. The animations allowed an assessment of subsidence activity and its relation to underlying mine geometry. This was critical since mine level changes are the cause of subsidence and time is a major factor when considering subsidence over abandoned mines. With this visual aid it was possible to qualitatively assess: 1) the rate of surface subsidence, 2) the rate of lateral progression, and 3) the correlation with mine geometry.

Based on the computed subsidence contours, it was hypothesized that the extent of pillars associated with subsidence for each date must be within the limits of the contours. This hypothesis is based on experience (Hunt, 1980) and the conventionally accepted geometrical relationship between subsurface openings and surface subsidence (Whittaker and Reddish, 1989; Kratzch, 1983). The expansion of surface subsidence bowls can be attributed to increasing mine level span widths. The plot in figure 3 illustrates how the bowl width is controlled by the position of pillars at mine level. However, the bowl depth (i.e., maximum subsidence) is controlled by several factors including the magnitude of convergence at mine level and the overburden stratigraphy.

Estimation of Pillar Stresses

In figure 3, it can be seen that the length and width of pillars are on the order of 20 m (64 ft) by 6 m (18 ft) beneath the Dorris School (center bowl). By contrast, they are 17 m (57 ft) by 13 m (43 ft) beneath the old high school (northernmost bowl). Also note the entry widths are different so the pillar stresses must be different. Assume that each pillar supports a column of overburden extending from the mine to the surface and that the column boundaries are the midpoint of entries between adjacent pillars (table 1) (Whittaker and Reddish, 1989). The weight of this column can be computed by assuming that the overburden has a unit weight of 20.3 KN/m^3 (144 lbs/ft^3).

It is estimated that the pillars beneath Dorris were subjected to a stress of 5.8 MPa (840 psi) compared with 2.4 MPa (345 psi) beneath the high school. The capacity of pillars to support this stress is not only controlled by the pillar strength (e.g., 10 MPa) but also floor bearing capacity (e.g., 5 MPa) (Pula et al, 1990). In the case of pillar crushing, convergence could occur rapidly at mine level with rapid subsidence at the surface. In the case of pillars punching into the floor, convergence may be long term. In summary, the difference in maximum subsidence for the three bowls in figure 3 can be attributed to different stress conditions, support capacities, and failure mechanisms.

GIS Analysis of Pillar Stresses

Since the hypothesis of tributary area loading on pillars is based almost exclusively on geometry, this type of analysis lends itself to the use of GIS software to estimate the distribution of pillar stress on a mine-wide scale. The AutoCAD drawing

Figure 3.-Estimated subsidence contours with hypothetical associated pillars shaded, minimum contour is 0.05 m, contour interval is 0.025 m; see figure 4 for location.

Table 1.-Estimation of Pillar Stresses

	Old High School	Dorris School
Pillar Dimensions		
length....................	17 m	20 m
width......................	13 m	6 m
area........................	221 m^2	120 m^2
Overburden Supported		
length....................	22 m	26 m
width....................	20 m	22 m
area.......................	440 m^2	572 m^2
volume..................	26,400 m^3	34,320 m^3
weight..................	537 MN	698 MN
Pillar stress	2.4 MPa	5.8 MPa

Table 2.-Material Properties

	Density kg/m3	Bulk Modulus MPa	Shear Modulus MPa	Constitutive Law	Friction Angle Degrees	Cohesive Strength MPa	Tensile Strength MPa
Soil	2090	330	200	Mohr-Coulomb	30	0.03	0
Rock Mass	2410	630 to 7370	380 to 4420	Mohr-Coulomb	31	2.6	1.0

Table 3.- Horizontal Joint Properties

Normal Stiffness MPa/m	Shear Stiffness MPa/m	Slip Criterion	Friction Angle Degrees	Cohesive Strength MPa
30000	1500	Coulomb	15	0

was converted to GIS coverages using ArcCAD. ArcCAD is a bridge between CAD and GIS integrating the editing and graphical tools from AutoCAD with the topological and analytical tools of a GIS program. A user can toggle between AutoCAD and ArcCAD user interfaces, as well as being able to call upon third-party extensions available to AutoCAD. ArcCAD allows simple conversion of the graphical "entities" of the AutoCAD drawings to GIS "features" without requiring additional data input. ArcCAD is a vector-based GIS that enables the coordinates of the CAD graphical representation to be related to real-world coordinates and map projections. A GIS allows integration of data and maps of disparate scales and sources into one set of geographically referenced data files and establishes topology (relationships) between the geographically referenced features.

The tributary area polygon surrounding each pillar was defined by the centerline of the entries surrounding each pillar. This tributary area network was created using AutoCAD then converted to a GIS POLYGON coverage. Since POLYGON coverages automatically calculate area measurements and are accessible in the database, a ratio between the tributary area and pillar area was calculated by merging the two POLYGON coverages. The tributary area/pillar area ratio was multiplied by an estimated overburden unit weight (20.3 KN/m^3 = 144 lbs/ft^3) to compute pillar stress. Computations were required for several hundred to several thousand pillars for each of the four mines shown in figure 4 which encompassed the entire study area. GIS was then used to classify the mine pillars into four levels of stress:

Class	Stress Level
1	< 3 MPa
2	3 - 4.99 MPa
3	5 - 5.99 MPa
4	>6 MPa

Figure 5 displays pillars below Dorris School. The class 3 stress level is consistent with statistical values for bearing capacity of weak floor strata in the Illinois Basin (Pula et al, 1990).

Numerical Modeling of Pillar Stresses

Numerical modeling was done to provide an independent assessment of the GIS analysis. The methodology was patterned after guidelines outlined by Starfield and Cundall (1988) who encouraged researchers to remember that the focus of numerical analysis should be on gaining an understanding of the mechanisms that characterize the system and not on obtaining unique numeric values for specific parameters. Hart and Cundall (1992) go on to explain that this is accomplished by using the computer model as a laboratory to perform experiments on the system. This can result in an improved understanding of mechanisms, knowledge of parameter dependence, and a means by which to check theories or hypotheses. Ultimately, the new knowledge may lead to new theories or simple conceptual models that can be used in design (Hart and Cundall, 1992). In the present study, the numerical analysis increased understanding of stress levels and the distribution of stresses acting on pillars in the abandoned mines.

The Universal Distinct Element Code (UDEC) (Itasca, 1992) was used to perform desk top experiments and identify parameters that significantly influence model behavior. The computer code allows internal deformation of discrete blocks and also allows large displacements and separations along discontinuities. UDEC utilizes the distinct-element method which is a particular type of numerical model that explicitly incorporates contacts between deformable blocks and explicit time-stepping solution of the equations of motion (Cundall and Strack, 1979). Output in the form of displacements, velocities, and stress distributions can be compiled into movies that make it possible to visualize the influence of various parameters on rock mass response.

Stratigraphy

The distinct element model is composed of deformable blocks separated by discontinuities. Since it is hypothesized that overburden response is affected by the location and character of discontinuities within the rock mass, Bureau researchers used the modified Rock Mass Rating (RMR) system (Bieniawski, 1989) to systematically define the location of horizontal discontinuities in the model. A commercially-available spreadsheet program was used to calculate a RMR for each lithologic bed based on drill core logs and engineering property tests. The RMR was then used to calculate a deformation modulus and bending stiffness for each lithologic bed (figure 6). Large contrasts in the bending stiffness between adjacent lithologic beds have been shown to correlate with measured horizontal shear displacements (Siekmeier et al, 1992). Thus the locations of these large contrasts in bending stiffness were used to define

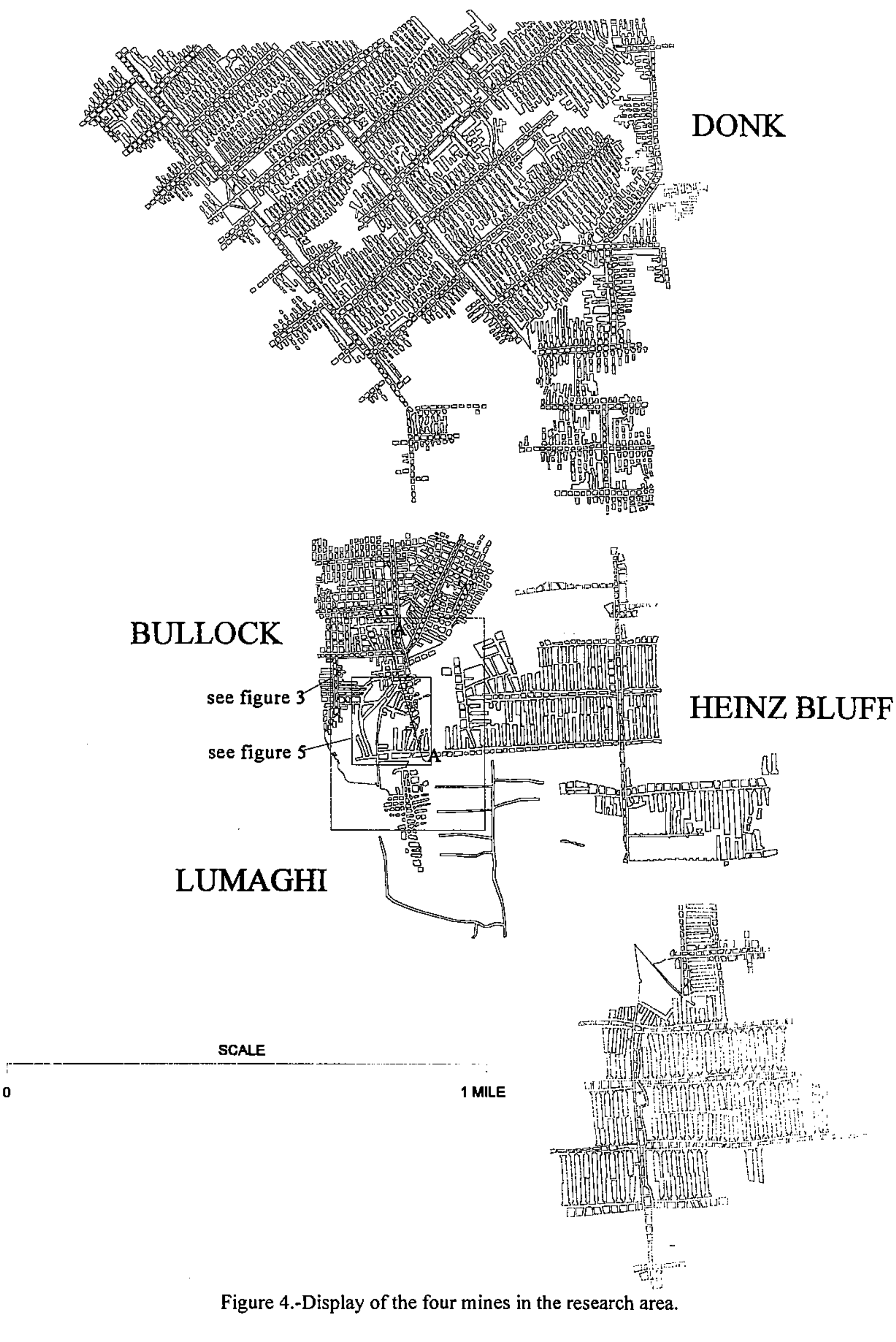

Figure 4.-Display of the four mines in the research area.

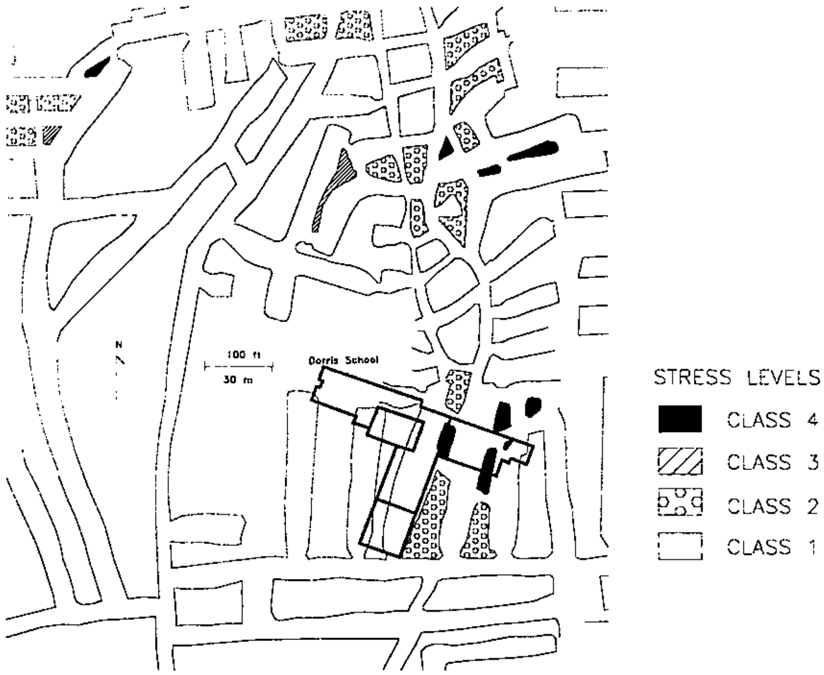

Figure 5.-Dorris Elementary School with pillars from Bullock Mine shaded according to stress level, class 4 is the highest stress; see figure 4 for location.

horizontal discontinuities in the distinct element model (horizontal lines on the right side of figure 6) .

The mines are approximately 60 m (200 ft) below the surface, overlaid by 30 to 34 m (100 to 110 ft) of glacial material and 27 to 30 m (90 to 100 ft) of Pennsylvanian age rock The glacial material consists of 9 to 12 m (30 to 40 ft) of loess overlying silty clay till and sandy stream deposits. The topmost rock stratum is a claystone that has altered to a silty clay of high plasticity. This altered zone is approximately 8 m (25 ft) thick and washed out easily during drilling. The significant features are the two stiffer limestone strata of the mine roof. The upper one is about 1.2 m (4 ft) thick, and the lower one is 6 to 8 m (20 to 25 ft) thick. This lower unit forms the immediate mine roof.

Based on observations made with a downhole camera as well as water level measurements, the mines are flooded and the water is pressurized. An attempt was made to obtain a sample of the mine floor underclay and assess its thickness. The stratum is a highly plastic gray clay at least 1.2 m (4 ft) thick. This thickness was estimated by allowing the drill string to penetrate under its own weight.

Boundary Conditions and Material Properties Used in Numerical Model

A two-dimensional, plane-strain, distinct element model was used to simulate the overburden and abandoned mine along line AA shown in figure 3. The horizontally bedded rock mass and overlying glacial materials were modeled as eleven deformable blocks stacked as a layer cake (figure 6). The blocks are composed of finite-difference triangles and represent layers defined by horizontal discontinuities between strata with significant changes in stiffness.

The deformable block properties are listed in Table 2 and properties of the horizontal discontinuities are listed in Table 3. These values were considered to be reasonable approximations. In order to simulate tributary loading over entries adjacent to the pillars but outside the cross sectional plane, overburden density was doubled. Once again, the objective was to determine if the pillar stresses estimated using the assumption of tributary area loading was reasonable so that any correlation with historical surface subsidence could be considered valid.

Results of Computer Simulations

To simulate abandoned coal mines, blocks representing entries were deleted and gravity loading was applied for 15000 calculation cycles. Support provided by water pressure was not considered and the resulting distribution of vertical stress at two depths is shown in figure 7. The lower line graph is the computed vertical stress acting on the pillars and the upper line graph is the computed vertical stress within the rock mass above the mine roof. Note that the larger stresses occur over pillars adjacent to wider mine openings which is consistent with the tributary area assumption. The maximum value of stress computed for the mine pillars (the lower line graph) is 8.0 MPa which is consistent with maximum stresses on class 4 pillars in figure 5. These results lend validity to the assumption of tributary loading on pillars.

Comparison Between Pillar Stress Conditions and Subsidence Occurrence

While numerical modeling provided an independent check of the tributary loading assumption made in the GIS analysis, the objective was to correlate pillar stress conditions with occurrences of subsidence. Compare the Class 2, Class 3, and Class 4 pillars in figure 5 with the shaded pillars in the center of figure 3. There is good correlation between the subsidence bowl which impacted Dorris Elementary School and the level of pillar stress. This would appear to imply that the GIS analysis assuming tributary loading can provide a basis for assessing the likelihood of subsidence occurrence.

This hypothesis does not appear to be valid for pillars in the top of figure 5. Although there are pillars rated at stress levels of Class 2 and greater, subsidence has not been measured in this area. This does not invalidate the hypothesis but it does demonstrate difficulties with proving that the hypothesis is valid. It is likely that subsidence will occur over highly stressed pillars, but pillar stress analysis cannot predict when subsidence will occur. Furthermore, subsidence may have occurred but it was not measured since there are no structures in this area which could have suffered damage.

Another compounding factor is the influence of mine flooding. Based on downhole camera inspection of mine conditions and water level

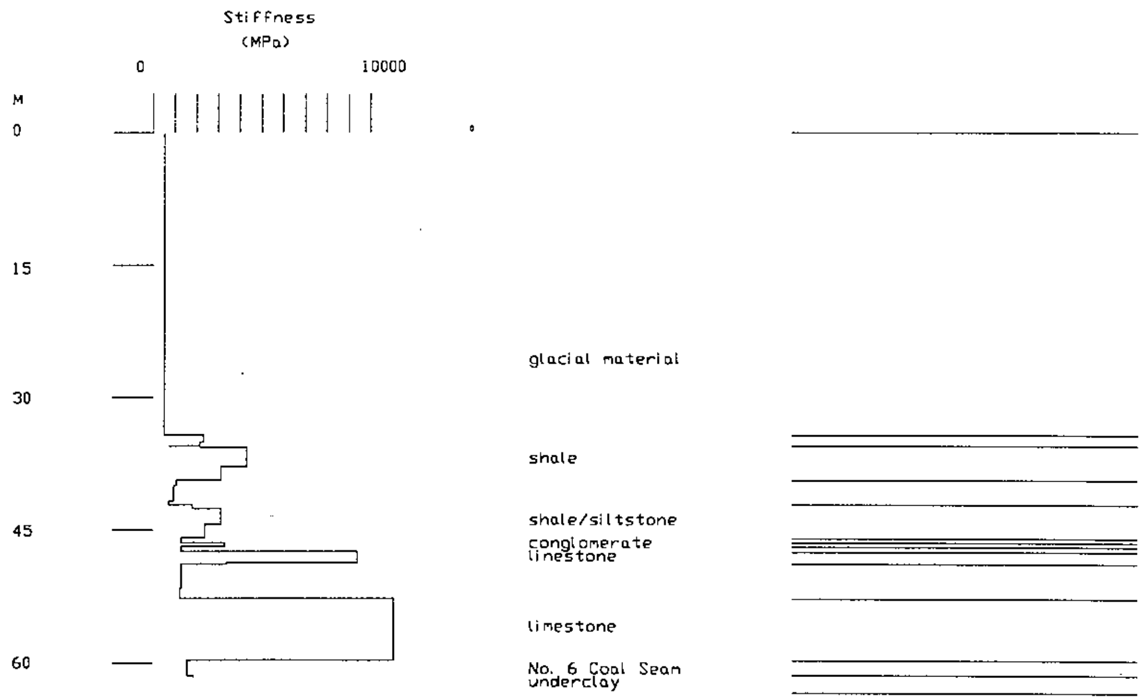

Figure 6.-Stiffness histogram and geologic model used for numerical simulation.

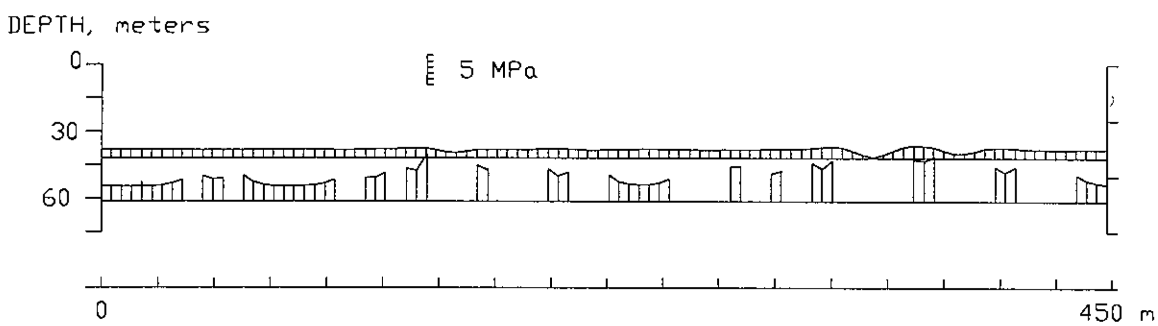

Figure 7.-Distribution of computed vertical stress acting on pillars and along top of main roof stratum; cross section is along line AA in figure 3.

measurements, it is known that the mine is flooded and the water is pressurized. Support for the mine roof is provided simultaneously by pillars and water pressure. Consequently, the actual pillar stress is less than that computed by tributary area loading. If the water pressure dissipates then pillar stresses will increase and the likelihood of subsidence occurrence will increase (USEPA, 1981).

Summary

This paper presents a study which was conducted to assess the correlation between pillar stress and subsidence occurrence over abandoned coal mines. Historical data were assembled and subsidence contours were generated for each date that measurements were made. These contours were overlaid on a CAD base map which included the digitized mine pillars and entries. The CAD layers were selectively activated and a time lapse animation was created to observe the areal progression of subsidence occurrences. Assuming tributary loading on pillars, stresses were computed for several thousand pillars using GIS software. An independent check of the tributary loading assumption was made by numerical modeling of the overburden and abandoned mine. Pillars were then classified by stress level and this classification map was overlaid with the subsidence contours.

Pillar stresses estimated using the hypothesis of tributary loading are consistent with those estimated using the numerical model. Subsidence occurrences are not random events and have developed in a manner which is physically consistent with the layout and stress level of mine pillars. The combination of CAD techniques and GIS analysis offers a valuable tool for subsidence risk assessment.

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