Findings and Practical Applications from the Illinois Mine Subsidence Research Program, 1985–1993

Compiled by
Billy A. Trent, Robert A. Bauer, Philip J. DeMaris, and Nelson Kawamura

IMSRP XII 1996
Illinois Mine Subsidence Research Program

Department of Natural Resources
ILLINOIS STATE GEOLOGICAL SURVEY

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Final report to
Illinois Clean Coal Institute
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ILLINOIS MINE SUBSIDENCE RESEARCH PROGRAM

In 1985, the IMSRP was initiated, under the leadership of the Illinois State Geological Survey, to respond to the coal industry's need to lower production costs and the agricultural industry's concerns regarding high-extraction mining. Production costs were to be significantly reduced through longwall coal mining, but major issues related to agriculture and groundwater protection still required attention.

More companies are using longwall mining methods to stay competitive in today's coal market. Higher extraction rates make better use of low-sulfur coal deposits. More of this valuable resource can be extracted, instead of leaving half of it to support the overburden or mining none of it because of poor roof conditions.

Under the Surface Mining Control and Reclamation Act of 1977, mine plans must be designed either for predictable subsidence (longwall or high-extraction retreat) or for maximum stability (room-and-pillar). As a result, in addition to investigating subsidence due to high-extraction mining, IMSRP researchers sought to identify the characteristics and develop formulas for designing stable partial-extraction mines and minimizing surface subsidence.

The policy issues and industrial trends present when the IMSRP began in 1985 are still important. Mine subsidence remains a concern, regardless of mining method used. Research was needed to understand the phenomenon of mine subsidence under Illinois' geologic conditions, and to document the changes that may take place in farmland, groundwater, and the overburden and at the mine level when modern high-extraction mining methods are applied. Concerns about subsidence can only be relieved by providing a solid foundation of facts.

Since its inception in 1985, the IMSRP has sought the reliable, scientific information needed to achieve a reasonable balance among these critical goals:

- maximize coal mine productivity
- preserve farmland productivity
- assure maximum recovery of coal resources
- protect groundwater resources
- provide useful information for designing coal mines and developing guidelines for coal and agricultural operations.

Paul B. DuMontelle served as Program Director from 1985 to 1990; Robert A. Bauer served from 1991 to 1995.

The summary articles in this publication are a valuable resource for Illinois' coal and agricultural industries. Using a scientifically sound, multidisciplinary approach, IMSRP studies have documented the actual impact of mine subsidence on crops, structures, and groundwater resources. Data from subsidence case histories have been analyzed and used to model, predict, and demonstrate general characteristics or trends of subsidence in Illinois.

More than 100 publications and presentations have reported on IMSRP studies. The results of these unique studies have been summarized in this publication for use by the lay person as well as by the specialist in the coal and agricultural industries. The research results and recommendations generated by the IMSRP are important for decision-makers including mining company personnel, farm managers, legislators, homeowners, landowners, and community and county planners.

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Research summaries were prepared by members of the Engineering Geology Section of the Illinois State Geological Survey. The original IMSRP principal investigators provided critical input and reviews: Colin J. Booth and Phillip J. Carpenter of Northern Illinois University, Yoginder P. Chugh of Southern Illinois University, and Robert G. Darmody of the University of Illinois. Deepak Dutta, Southern Illinois University, assisted in the revision of one section.

DISCLAIMER

The articles in this volume are summaries of contract reports and other documents supplied by investigators who were under contract to the Illinois Mine Subsidence Research Program (IMSRP). Drafts of the original reports were reviewed by qualified scientific peers before being accepted. The summary articles in this volume have also been reviewed by qualified scientific peers and, in many instances, by the principal investigators of the projects. Some principal investigators summarized their own projects. Every effort has been made to ensure that the summaries accurately reflect the findings of the original studies. Readers are cautioned, however, to consult original project reports before making important decisions based on the findings reported in this volume. The Illinois State Geological Survey and the IMSRP investigators make no warranties, expressed or implied, about the accuracy and completeness of these summaries.

IDENTIFICATION OF MINE CHARACTERISTICS, CONDITIONS, AND PROCEDURES FOR DESIGN OF STABLE PARTIAL EXTRACTION ROOM-AND-PILLAR MINES IN THE HERRIN AND SPRINGFIELD COAL SEAMS IN ILLINOIS

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Summarized by Philip J. DeMaris

ABSTRACT

An evaluation of geologic factors, geotechnical and mining factors, and design procedures to achieve stable room-and-pillar coal mines was carried out for Herrin and Springfield Coal mines in Illinois. To gain a broad overview of the strengths and limitations of current mining practices, the authors combined information from companies, data from in-mine visits, and published information from the geological and mining engineering literature. Whereas most operators are extracting coal at rates consistent with the material strength of coal seam, roof, and floor, extraction rates could be higher at shallow depths in some mines.

The sequence and thickness of lithologic units in the roof were identified as the most important general factors for predicting roof stability. A set of roof sequences was developed to cover most situations encountered in Herrin and Springfield Coal mines. The authors also found that many mines would benefit from more extensive premining exploration drilling and geotechnical studies of core samples. Accurate measurements of the moisture content of floor materials are essential for identifying potential problem areas and calculating expected floor strengths.

INTRODUCTION

The project objectives were to identify geologic, geotechnical, and mining factors and operating procedures for design of stable partial extraction room-and-pillar coal mines in the Herrin and Springfield Coal seams in Illinois. The results of the project could be used by the industry to develop optimum designs for partial extraction mining systems that minimize surface subsidence.

Multiple methodologies were used for this project. A questionnaire to collect information from the coal companies covered geology, hydrology, premining state of stress, mining conditions, design practices for spans and production pillars, roof falls, observed instabilities in coal pillars, instabilities associated with roof and floor strata, and cases of surface subsidence. These data were collected by examining mine permits and evaluating maps and other materials provided by the mining companies.

Brief visits were also made to 15 mines operating in the Herrin Coal and five mines in the Springfield Coal. A limited number of typical workings (such as mains, submains, panel entries, and rooms) were examined for floor, pillar, and roof stability; geometry of mine layout; type of artificial support; geologic anomalies; and typical mining conditions.

Another approach was to evaluate pertinent literature on geology, mining, and ground control in Illinois Basin coal mines. This information was compared with that obtained from permit applications and field visits. Separate databases were maintained for mine design parameters, geotechnical data on rock samples, roof falls, and mine geology. Data were analyzed using the databases and various software programs at Southern Illinois University.

RESEARCH FINDINGS

Geological, Geotechnical, and Mining Factors Affecting Mining Conditions and Stability

Geologic factors include syndepositional factors such as lithology and unit contacts as well as a wide range of postdepositional features, such as compactional faulting, differential compaction around concretions, and erosional channeling. These factors are grouped as follows:

Roof Strata Roof stability is directly related to the presence or absence of specific overlying lithologic units, their thickness, and the occurrence of certain geologic structures (such as faults). Above the Herrin Coal, the key units are the Energy Shale, Anna Shale, and Brereton Limestone. Above the Springfield Coal, the key units are the Dykersburg Shale, the Turner Mine Shale and the St. David Limestone.

The two major roof types in the Herrin Coal are gray shale and black shale-limestone (Krausse et al. 1979a, 1979b). In-mine mapping and recognition of transitional areas between these two roof types led to the conclusion that there are four basic roof types in Illinois (Damberger et al. 1980): (1) gray shale, (2) transitional, wedge-type, (3) transitional, lens-type, and (4) black shale-limestone. Because of similar depositional settings, similar roof unit sequences occur above the Springfield Coal, but no specific types have been identified.

Coal Seam Structure and distribution of the Herrin Coal in the Illinois Basin have been studied extensively (Treworgy and Bargh 1982). The average thickness of the Herrin Coal, where mined in Illinois, ranges from 6 to 7 feet; but locally it may reach 15 feet. Coal thickness is greater near the Walshville channel where coal is overlain by thick gray shale (Johnson 1972). Splits in the coal are common along the channel and make mining difficult in some cases. The Springfield Coal is commonly 4 to 8 feet, where mined. Near the Galatia channel, the Springfield Coal becomes thicker and lower in sulfur, and it is commonly split by shale partings (Hopkins and Simon 1975).

Floor The 20 feet of floor strata immediately underlying the Herrin Coal is highly variable, but commonly consists of claystone, siltstone, shale, nodular limestone, or sandstone. Generally, the upper strata are weak because of compressive strengths of less than 1000 psi. Weak floor strata may cause pillar settlement, floor heave, surface subsidence, and roof instability.

Faults Tectonic faults affect mining conditions by displacing the coal seam, opening pathways for gas and water into mines, and fracturing and weakening roof strata. Compactional faults or slips, classified as nontectonic (Nelson 1981), weaken roof strata and cause major roof instability in underground mines. These slips are common around some geologic disturbances such as rolls, concretions, and clay dikes. Edges of Energy Shale lenses or contacts between lithologic units often are highly fractured by these compactional faults or slips. On a large scale, major tectonic faults are predictable to a certain degree, whereas nontectonic or compactional slips are generally random in orientation and often localized.

Rolls In the Illinois Basin, "rolls" are downward bulges or protrusions of roof strata into the coal seam; they can severely affect roof stability. Roof instability is associated with most rolls; normal faults are present at many of the contacts with the roof material and the coal seam.

Channels Channels are commonly encountered during mining in the Illinois Basin. The two major systems associated with the Herrin Coal are the Anvil Rock Sandstone and Walshville channels; both are Pennsylvanian in age. The Walshville channel sediments were deposited during peat accumulation (Johnson 1972), but the Anvil Rock sediments were deposited after coal formation, possibly through multiple episodes of channeling (Hopkins 1958). The major channel system associated with the Springfield Coal is the Galatia channel, which also formed during peat accumulation.

Effects of these channels include (1) nondeposition of peat or replacement of peat with channel-fill sediments, (2) splitting of the coal seam by shale and sandstone partings (Walshville and Galatia channels), (3) steep grades due to undulation of the coal seam, (4) unstable roof conditions due to slips and slickensides, and (5) structural and lithological weakness (Nelson 1983). Channel-fill sandstones are often a source of water in mines (Cartwright et al. 1982), which causes deterioration of mining conditions.

Bedrock Valleys Pleistocene valleys (bedrock or buried valleys) that are generally filled with thick deposits of glacial and stream sediments often pose problems when encountered during mining. A rapid influx of meltwater and loose sediments may occur if these materials cannot be supported. When mining advances under the thin bedrock below these buried valleys, roof failure, rib spalling, and squeezes occur more often (Nelson 1983). Mechanical testing of shales underlying valleys has shown these shales to be up to 25% weaker than shales in adjacent areas (Bauer 1987).

Clay Dikes Common features associated with coal strata in Illinois, clay dikes and clay dike faults can weaken roof strata and coal pillars. These features are generally less a problem in strata associated with the Herrin Coal than with strata associated with the Springfield Coal (Nelson 1983). Clay dikes and clay dike faults (1) occur under all roof types, (2) are rare in southern and southwestern Illinois underneath the thick gray shale roof, (3) do not extend far into roof strata and have little influence on roof stability when occurring under limestone roof, and (4) strike parallel to the trend of lithologic boundaries and dip toward the interior of the lenticular roof rock bodies (Krausse et al. 1979a, 1979b).

Miscellaneous Geological Features Other geological disturbances that affect the Herrin Coal include limestone "bosses" (downward or upward protrusions of limestone into coal), igneous dikes (wall-like masses of igneous rock that have intruded into the coal), coal balls (masses of peat permineralized in place), kettle bottoms (fossil tree stumps occasionally found in roof shales), and roof shale concretions (hard, mineralized, oval- to disk-shaped masses). Compactional faults around these features generally cause only local instability.

Tables 1 and 2 list the geologic setting and associated geologic anomalies for the 15 Herrin Coal and five Springfield Coal mines visited.

Development and Occurrence of Roof Sequences

Roof lithology identification and roof type classification are important first steps in understanding roof behavior and occurrence. The major roof types discussed earlier, while useful in delineating regional variation in roof character, have proven inadequate for assessing differences in mine-scale roof lithologies and stabilities. During this project, the need was recognized for a set of commonly encountered roof sequences that could be identified both in mines and drill log descriptions.

The following sequences of roof lithology were developed so that a general assessment of stability could be linked to each sequence. Each sequence has a code that gives rock types in order going upward, when read from left to right: a plus sign (+) denotes "thick" and a minus sign (-) denotes "thin." Comments on the occurrence of sequences in mines are noted.

A. Limestone Roof (+L) In this sequence, limestone with a thickness greater than 2 feet forms the immediate roof. Minor lithologies such as Anna Shale and basal claystone ("clod") with thicknesses less than 0.5 foot are included. Brereton or Conant Limestone are commonly occurring lithologies. This sequence was not encountered in the Springfield Coal mines studied, but it may occur locally.

B. Thin Black Shale/Limestone Roof (-B/+L) This sequence includes thin (<2 ft) black shale under thick limestone (>2 ft). Common sequences seen are Anna Shale

Table 1 Geologic settings for the Herrin Coal mines studied (from Chugh et al. 1990).

Mine	Mining depth (ft)	Roof lithology	Distance to Walshville channel (miles)	Geologic anomalies in roof and coal
1	115	Anna/Brereton with Energy Shale lenses, Jamestown interval locally as immediate roof	20	Clay dikes, compactional slips
2	600	Energy Shale wedges and Anna/Brereton roof	16	Coal balls, "rolls," compactional slips
3	400	Anna/Brereton with Energy Shale lenses, missing Brereton, Anvil Rock Sandstone above	30	Coal balls, limestone "bosses," compactional slips
4	300	Anna/Brereton with Energy Shale lenses	15	Bedrock valley, compactional slips
5	250	Anna/Brereton with few Energy Shale lenses	20	Slips, compactional faults
6	340	Anna/Brereton with Energy Shale lenses, Anvil Rock Sandstone above	20	Faults, limestone "bosses," compactional slips, Anvil Rock Sandstone channels
7	335	Anna/Brereton with Energy Shale lenses, Anvil Rock Sandstone above, areas of thin and/or missing Brereton Limestone	7	Anvil Rock sandstone channels, compactional slips
8	700	Thick Energy Shale, minor Anna/Brereton areas	3	"Rolls," compactional slips, slickensided bedding planes
9	300	Anna/Brereton with Energy Shale lenses, some areas of thin and/or missing Brereton Limestone	3	Limestone "bosses," bedding separations in Brereton, in situ stress, compactional slips
10	125	Thick Energy Shale	20	Kettle bottoms, clay dikes, compactional slips
11	700	Thick Energy Shale	2	Faults, compactional slips, large siltstone "rolls"
12	160	Anna/Brereton with Energy Shale lenses, areas of thin or missing Brereton Limestone	16	Faults, compactional slips
13	275	Energy Shale in thin wedges, Anna/Brereton above	30	Faults, compactional slips
14	950	Anna/Brereton with Anvil Rock Sandstone above, locally thick Anna Shale	55	Faults, compactional slips
15	125	Anna/Brereton with rare Energy Shale lenses	20	Compactional slips

Table 2 Geologic settings for the Springfield Coal mines studied (from Chugh et al. 1992).

Mine	Mining depth (ft)	Roof lithology	Geological anomalies in roof and coal
1	>350	Thick Dykersburg Shale	Faults, compactional slips
2	<350	Turner Mine Shale, thin or missing St. David Limestone, rare thin Dykersburg Shale lenses	Faults, roof concretions, horizontal slickensides, roof concretions, in situ stress
3	<350	Thick Dykersburg Shale	Faults, compactional slips, kettle bottoms, horizontal slickensides
4	>350	Thick Dykersburg Shale	Faults, kettle bottoms, roof concretions
5	<350	Turner Mine Shale, thin or missing St. David Limestone	Compactional slips, roof concretions

beneath Brereton Limestone and Turner Mine Shale beneath St. David Limestone. This sequence is common in both Herrin and Springfield Coal mines.

C. Thick Black Shale/Limestone Roof (+B/+L) This sequence is characterized by thick (>2 ft) black shale (commonly Anna or Turner Mine Shales) overlain by limestone greater than 2 feet (commonly Brereton or St. David Limestones). When the Jamestown interval is thick and overlain by Conant Limestone greater than 2 feet, it is included in this sequence. This sequence, typically bolted with 4- to 9-foot bolts, is common in Herrin Coal mines and present in some Springfield Coal mines.

D. Thick Gray Shale Roof (+G) This sequence of various lithologies, shale to fine-grained sandstone greater than 10 feet thick, is commonly Energy Shale and Dykersburg Shale. Because limestone units (when present) are out of bolting range, this sequence is typically bolted with 6- to 8-foot bolts anchored in the gray shale. This roof sequence is predominant in mines near contemporaneous channels.

E. Thin Gray Shale/Black Shale/Limestone Roof (−G/B/+L) The sequence of thin gray shale (<10 ft) with black shale and limestone (>2 ft) is commonly represented by Energy Shale/Anna Shale/Brereton Limestone or Dykersburg Shale/Turner Mine Shale /St. David Limestone. This lithologic sequence occurs primarily along the edge of shale wedges and lenses and above some lenses. It is common in Herrin Coal mines, and less common in Springfield Coal mines.

F. Gray Shale and/or Black Shale with Thin or Missing Limestone Roof (−G/B/−L) This less than 10-foot-thick sequence of shale unit(s) with thin limestone (when present) is commonly represented by Energy Shale with thin Brereton Limestone (when present) or by Dykersburg Shale with thin St. David Limestone (when present). This sequence is commonly associated with discrete Energy Shale lenses typically present in many areas of the Illinois Basin; it can also represent any multiple set of shale units totaling less than 10 feet without good anchoring limestone (<2 ft) within bolting range.

G. Sandstone Roof (SS) This sequence, which generally includes sandstone within bolting range (8 ft), is commonly represented by a sandstone/siltstone facies (Energy or Dykersburg Shales) of contemporaneous channels such as the Walshville or Galatia. In other cases, sandstone may fill younger downcutting channels.

Interrupted Sequences Any interruption of the roof unit succession also adds to the possibilities for roof instability. These interruptions are sometimes more important than the sequence itself. They can be recognized in cores or core descriptions and include angular or sharp lithologic contacts, broken rock, "white-top" or other disturbed or contorted strata, and evidence of erosion, such as coarse sandstone, remnants of expected roof units, and rounded pebbles. Interruptions constitute weak zones in the roof. Once recognized, they should be evaluated for distribution so that mining and bolting plans can be adjusted as needed.

Development of Floor Sequences

Lithology, sequence, and physical properties of floor units all affect floor stability. A preliminary set of commonly encountered floor sequences has been developed to assist in the identification of floor types. Because field observations in mines and drill log data for most mines are limited, these sequences cannot be as specific as the roof sequences. Mine data gathered for this study suggest that the thickness of floor units varies significantly.

A. Thick Claystone This sequence consists of thick (>4 ft), relatively weak claystone. Typical underclays/claystone are highly slickensided and somewhat carbonaceous in the upper section (1–2 ft) and often referred to as an "underclay." Most of this claystone is either a weak, greenish gray claystone or a slightly firmer, gray silty or sometimes limy claystone.

B. Thick Claystone with Interbedded Thin or Nodular Limestone Thin or nodular beds of limestone slightly increase the overall strength of this claystone sequence.

C. Claystone/Nodular Limestone/Limestone Claystone (2–4 ft) grades downward into nodular limestone and then into massive limestone (>2 ft). This sequence is usually stable, depending on the thickness and physical properties of the claystone unit. It is one of the most common floor sequences seen in the Illinois Basin.

D. Claystone/Sandstone or Siltstone or Shale This sequence contains 2 to 4 feet of claystone underlain by competent and massive units of either sandstone, siltstone, or shale. The sequence is commonly stable, depending on the physical properties and thickness of the claystone unit.

E. Shale, Sandstone, Siltstone, or Limestone A massive unit of shale, sandstone, siltstone, or limestone directly underlies the coal. This sequence, the most stable in the mines studied, is also uncommon.

The roof sequences at the 20 mines visited were identified from data gathered from mine visits and personnel and from ISGS mine notes. It was not possible to identify the full range of floor sequences at the mines visited because of the limited number of exposures. Some companies have sufficient drill core data to approximate this. If roof and floor sequences were evaluated by examining drill core data at the exploration stage, the information would prove valuable at the mine planning stage.

Analysis of Mine Permit Data and Stability Calculations

Information from the questionnaire on mine designs was used to describe and evaluate the ground stability for mined areas with various pillar sizes. Pillar safety factors were calculated using various equations from the literature; supplemental input data from both the literature and other coal mines in the Illinois Basin were also used. Correct moisture content values were found to be critical for valid prediction of floor material strengths and pillar safety factors. Two variations of the floor safety factors for the same set of mines were calculated using the Vesic-Speck and Vesic-Chugh/Haq/Chandrashekhar (Vesic-CHC) methods; each method produces values that must be compared with a different minimum safety value.

Tables 3 and 4 show pillar and floor safety factors for 20 mines in the Herrin Coal and Springfield Coal in the Illinois Basin from 1989 to 1991. For each mine, typical pillar size and entry width for both mains and panels were determined from permit information, maps, and

Table 3 Pillar and floor safety factors for mines in the Herrin Coal.

	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5
Parameters					
Depth (ft)	80-270	530-560	375-440	255-310	230-274
Compressive strength of coal (psi)*	2892	2780	2673	3597	4245
Size of cube tested (in.)*	3.0	3.0	3.0	3.0	2.2
Weak floor thickness (in.)	38-73	30	36-50	20-55	34-102
Weak floor moisture content (%)	10.1	4.0	2.4	7.5	5.1
Mains					
Pillar length (ft)	55	84	55	51	55
Pillar width (ft)	55	44	55	51	55
Mining height (ft)	6.6	7.0	5.5-6.0	6.0-6.5	6.2-6.4
Entry width (ft)	20	16	20	24	20
Extraction (%)	46	38	46	54	46
Pillar Safety Factor					
Bieniawski	5.5-18.6	2.3-2.5	3.4-4.3	4.9-6.3	7.0-8.6
Holland	4.4-14.7	2.0-2.1	2.6-3.2	3.9-5.0	5.5-6.6
Holland and Gaddy	2.9-9.9	1.3-1.4	1.8-2.4	2.7-3.5	3.8-4.6
Floor Safety Factor					
Vesic-Speck	0.8-3.1	1.8-1.9	2.1-2.6	1.2-2.2	2.1-3.3
Vesic-CHC	0.3-1.4	1.0-1.1	1.3-1.7	0.6-1.1	1.1-1.8
Panels					
Pillar length (ft)	40	84	38	51	45
Pillar width (ft)	40	64	38	41	45
Mining height (ft)	6.7-8.0	7.0	5.5-5.8	7.0-8.0	6.2-7.7
Entry width (ft)	20	16	22	24	20
Extraction (%)	56	33	60	57	52
Pillar Safety Factor					
Bieniawski	3.1-11.8	3.4-3.6	1.9-2.4	3.3-4.4	4.6-6.5
Holland	2.8-10.3	2.7-2.8	1.6-2.0	3.0-3.8	4.0-5.4
Holland and Gaddy	1.7-6.9	1.7-1.8	1.2-1.5	1.8-2.5	2.5-3.7
Floor Safety Factor					
Vesic-Speck	0.6-2.3	2.2-2.3	1.4-1.8	1.1-1.9	1.9-2.8
Vesic-CHC	0.3-1.1	1.3	0.9-1.1	0.5-0.9	1.0-1.5

	Mine 6	Mine 7	Mine 8	Mine 9	Mine 10
Parameter					
Depth (ft)	320-340	290-385	679-732	282-332	162
Compressive strength of coal (psi)*	2650	2892	4065	1855	2309
Size of cube tested (in.)*	3.0	3.0	1.6	3.0	3.0
Weak floor thickness (in.)	6-34	12-98	22-37	30-49	36
Weak floor moisture content (%)	6.0	6.7	4.3	6.7	7.2
Mains					
Pillar length (ft)	56	55	52	55	47
Pillar width (ft)	56	50	52	55	42
Mining height (ft)	7.7-7.8	7.0-7.6	5.7-6.0	7.3-8.0	4.0
Entry width (ft)	18	20	18	20	18
Extraction (%)	43	48	45	46	49

* strength data from a separate study

Table 3 *continued*

Pillar Safety Factor					
Bieniawski	3.8-4.1	3.1-4.4	2.2-2.5	2.5-3.1	8.4
Holland	3.1-3.4	2.7-3.7	1.7-1.9	2.1-2.6	6.1
Holland and Gaddy	2.0-2.1	1.7-2.4	1.2-1.4	1.3-1.6	5.3
Floor Safety Factor					
Vesic-Speck	2.2-5.6	1.1-3.2	1.1-1.5	1.6-2.3	3.0
Vesic-CHC	1.1-3.2	0.6-1.7	0.6-0.8	0.8-1.2	1.4
Panels					
Pillar length (ft)	40	45	52	51	—
Pillar width (ft)	40	40	42	51	—
Mining height (ft)	6.9-7.8	7.0-9.1	6.0-7.0	7.9	—
Entry width (ft)	20	20	18	24	—
Extraction (%)	56	54	48	54	—
Pillar Safety Factor					
Bieniawski	2.3-2.6	2.0-3.3	1.6-1.9	2.0-2.4	—
Holland	2.1-2.3	1.9-2.9	1.4-1.6	1.7-2.0	—
Holland and Gaddy	1.3-1.5	1.1-1.9	0.9-1.1	1.1-1.3	—
Floor Safety Factor					
Vesic-Speck	1.5-3.5	1.0-2.5	1.0-1.3	1.4-1.9	—
Vesic-CHC	0.8-2.0	0.5-1.3	0.6-0.7	0.7-1.0	—

	Mine 11	**Mine 12**	**Mine 13**	**Mine 14**	**Mine 15**
Parameter					
Depth (ft)	685-789	151-185	251-306	916-968	102-124
Compressive strength of coal (psi)*	3175	2892	2080	2892	1855
Size of cube tested (in.)*	2.5	2.4	3.6	2.1	3.0
Weak floor thickness (in.)	6-21	3-30	24-34	6	12-66
Weak floor moisture content (%)	3.7	8.7	7.5	1.9	8.4
Mains					
Pillar length (ft)	83	50	52	62	55
Pillar width (ft)	48	50	52	62	40
Mining height (ft)	7.5-10.0	6.6-6.8	5.4-5.5	4.2-7.3	6.0
Entry width (ft)	17	20	18	18	20
Extraction (%)	39	49	45	40	51
Pillar Safety Factor					
Bieniawski	1.4-2.0	6.2-7.7	4.4-5.4	1.5-2.5	5.8-7.1
Holland	1.3-1.7	5.1-6.3	3.3-4.1	1.2-1.6	5.0-6.0
Holland and Gaddy	0.7-1.1	3.4-4.3	2.5-3.0	0.7-1.4	3.5-4.3
Floor Safety Factor					
Vesic-Speck	1.5-3.3	2.1-11.1	1.7-2.5	2.5-2.7	2.4-5.6
Vesic-CHC	0.9-2.2	1.0-5.6	0.9-1.2	1.9-2.0	1.2-1.9
Panels					
Pillar length (ft)	83	39	40	50	40
Pillar width (ft)	83	39	40	40	40
Mining height (ft)	7.5-10.0	6.8	5.1-6.7	4.8	6.1-6.6
Entry width (ft)	17	21	20	20	20
Extraction (%)	31	58	56	52	56

* strength data from a separate study

Table 3 *continued*

Pillar Safety Factor					
Bieniawski	2.4-3.5	4.2-5.1	2.4-3.7	1.1-1.2	4.9-6.4
Holland	1.9-2.5	3.7-4.6	2.1-3.0	0.9-1.0	4.3-5.4
Holland and Gaddy	1.1-1.6	2.5-3.0	1.4-2.3	0.7-0.8	2.9-3.8
Floor Safety Factor					
Vesic-Speck	2.1-4.5	1.6-7.8	1.3-1.8	1.7-1.8	2.2-5.0
Vesic-CHC	1.3-3.1	0.8-3.8	0.6-0.9	1.2-1.3	1.1-2.5

Table 4 Pillar and floor safety factors for mines in the Springfield Coal.

	Mine 1	Mine 2	Mine 3	Mine 4	Mine 7
Parameters					
Depth (ft)	210-500	200-400	635-930	150-300	400
Compressive strength of coal (psi)*	2700	2575	2250	2050	3200
Size of cube tested (in.)*	3	3	3	3	3
Weak floor thickness (in.)	38	42	17	37	32
Weak floor moisture content (%)	8.3	8.9	4.3	7.7	7.3
Mains					
Pillar length (ft)	40	45	82	54	50
Pillar width (ft)	40	40	82	54	40
Mining height (ft)	5.0-6.3	4.2	6.9	4.5	5.5
Entry width (ft)	20	20	18	16	20
Extraction (%)	56	54	33	40	52
Pillar Safety Factor					
Bieniawski	1.8-5.3	3.2-6.3	2.1-3.1	5.3-10.6	3.3
Holland	1.6-4.2	2.4-4.8	1.5-2.2	3.7-7.4	2.7
Holland and Gaddy	1.1-3.3	2.0-4.1	1.0-1.4	3.0-6.0	2.0
Floor Safety Factor					
Vesic-Speck	0.6-1.5	0.7-1.4	1.8-2.6	1.8-3.6	1.1
Vesic-CHC	0.3-0.7	0.3-0.7	1.1-1.6	0.9-1.8	0.6
Panels					
Pillar length (ft)	40	39	61	32	28
Pillar width (ft)	40	39	61	32	28
Mining height (ft)	5.4-6.3	4.2	6.8	4.5	5.5
Entry width (ft)	20	21	19	18	22
Extraction (%)	56	58	42	59	69
Pillar Safety Factor					
Bieniawski	1.8-5.0	2.9-5.7	1.4-2.1	2.4-4.7	1.6
Holland	1.6-4.1	2.2-4.4	1.1-1.6	2.0-3.9	1.5
Holland and Gaddy	1.1-3.0	1.9-3.7	0.7-1.1	1.6-3.2	1.1
Floor Safety Factor					
Vesic-Speck	0.6-1.5	0.6-1.3	1.3-2.0	1.1-2.1	0.7
Vesic-CHC	0.3-0.7	0.3-0.6	0.8-1.2	0.5-1.0	0.3

* strength data from a separate study

personal communication with mine engineers and surveyors; these values were input for the five stability formulas. Comparisons were made using Holland's formula, which gives lower safety factors than Bieniawski's formula and higher safety factors than the Holland and Gaddy formula. The variations in safety factors for each mine (tables 3 and 4) are thus due to the tabulated ranges of depths, mining heights, and thicknesses of weak floor strata. For lower values of depth and mining height, the pillar safety factor is higher; and for lower values of depth and thickness of weak floor strata, the floor safety factor is higher.

The calculated safety factor for pillars in the mains (or submains, in a few cases) ranged from 1.2 to 14.7, based on the Holland formula. Most coal pillars in all study areas were found to be stable. The calculated safety factor for pillars in panels ranged from 0.9 to 10.3, based on the Holland formula. Most pillars were stable, except for those in the vicinity of major geological structures or weak floor strata. The ages of these workings varied between 2 and 12 years. Because no failed pillars were observed in the study areas, the lowest safety factor that would result in stable pillars for a long time could not be established.

From tables 3 and 4, it may appear that many mines are very conservative in their design approach and that a higher percentage of coal could be extracted; however, the limiting factor in most Illinois mines is floor safety. Settlement of pillars into weak floor strata may cause rib spalling and reduce the effective pillar size, which may further contribute to floor or pillar instability.

CONCLUSIONS

- The evaluation of permit data and mine visit information suggests that many mines could benefit from more extensive premining drilling, selected geotechnical studies of exploration cores, and descriptions of core logs and samples recovered. Within a framework of roof and floor sequences, potential ground stability problems could be more productively analyzed.
- The lithologic sequences and thickness of roof strata are the most important general factors for predicting the stability of the roof. Geological anomalies such as "rolls," clay dikes, faults, and weak floor conditions are locally important for roof stability.
- In most mines, operators are extracting at rates consistent with the coal and immediate floor strata strengths. If engineering analysis and design of opening and intersection spans were performed to a greater extent, then more coal could be extracted at shallow depths in some mines.
- Accurately measuring the moisture content of floor materials is essential for identifying problem areas and calculating valid floor safety factors.

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LABORATORY AND FIELD CHARACTERIZATION OF FLOOR STRATA ASSOCIATED WITH THE HERRIN AND SPRINGFIELD COALS IN ILLINOIS

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ABSTRACT

The characteristics of weak floor strata (claystones and siltstones) associated with actively mined coal seams in Illinois are very important for ground stability in the mine and on the ground surface. In many cases, these factors govern the size of pillars and mine openings. Laboratory and field geotechnical characterization studies of weak floor strata were conducted at six mines from 1985 to 1988. Correlation analyses were conducted among engineering index properties and laboratory- and field-determined strength-deformation properties to identify simple tests that can be used to estimate the ultimate bearing capacity of immediate floor strata. The ultimate bearing capacity (UBC) and strength-deformation properties of the weak floor strata can be estimated from simple tests such as natural moisture content, Atterberg limits, and axial swelling strain. Indirect tensile strength was found to be better than unconfined compressive strength for estimating UBC.

INTRODUCTION AND BACKGROUND

In Illinois, the commonly mined coal seams, Springfield and Herrin, are generally associated with relatively weak (<2,000 psi unconfined compressive strength) and relatively thick (2–7 ft), weak floor strata. The presence of weak floor strata in a partial extraction room-and-pillar mining system may lead to ground control problems of excessive pillar settlement and instability, floor heave and squeeze, roof falls due to differential settlement of pillars, and surface subsidence. Because the floor material is the weakest component of the roof-floor-pillar support system, the strength and deformation characteristics of weak floor strata govern the size of pillars and mine openings. Before these studies were conducted, only limited data were available on the physical and strength properties of immediate floor strata associated with coal seams in Illinois. In the past, some data on engineering index and strength properties of underclays in Illinois were presented by Ganow (1975), Rockaway and Stephenson (1979), and White (1954 and 1956).

PROCEDURES

For this study, five to six areas of the claystone/siltstone floor were sampled in each of six mines. Two mines operated in the Springfield Coal and four mines in the Herrin Coal. Two cores were drilled into the floor at each area. Borehole shear tests were conducted at different depths to obtain unconfined shear strength and angle of internal friction. Plate loading tests were conducted in each area under as-mined and soaked-wet conditions to obtain ultimate bearing capacity (UBC) and deformation modulus at 50% and 90% of UBC of the immediate floor strata. These tests, conducted in relatively freshly mined areas, used 6-, 8- and 12-inch-square plates, depending upon the strength of the floor strata. Soaked-wet conditions were obtained by wetting the test area for 24 hours.

Engineering index properties determined included natural moisture content, Atterberg limits, total clay particle size content, unconfined axial swelling strain, density, specific gravity, and slake durability. Strength properties tested were indirect tensile strength, unconfined compressive strength and modulus at 50% of ultimate strength, and axial point-load index.

RESULTS

The results of investigating correlations among laboratory derived strength-deformation parameters and engineering index properties are summarized in table 1, and complete information can be found in Chugh (1988a, 1988b). The indirect tensile strength and unconfined compressive strength may be estimated from total clay particle size content, liquid limits, axial swelling strain, or moisture content.

Table 1 Correlations between laboratory determined strength deformation parameters and engineering index properties.

(Y)	(X)	No.	r^2	Regression equation
T_o	LL	118	-0.407	Ln Y = 8.985 - 1.0047 Ln X
T_o	Clay	130	-0.290	Y = 884 - 169 Ln X
T_o	SW.AX	82	-0.306	Y = 645 -145 Ln X
T_o	MC	219	-0.151	Ln Y = 5.871 - 0.0819 X
T_o	MC	219	-0.368	Ln Y = 6.3653 - 0.178 Ln X
LL	Clay	183	0.191	Y = 23.446 + 0.294 X
C_o	Clay	61	-0.223	Ln Y = 8.599 - 0.168 X
C_o	LL	66	-0.363	Y = 18252 - 4155 Ln X
C_o	SW.AX	20	-0.541	Y = 6407 - 1353 Ln X
C_o	MC	102	-0.230	Ln Y = 8.6722 - 0.1252 X
C_o	MC	102	-0.273	Y = 6976 - 2220 Ln X
E_{50}	SW.AX	34	-0.495	Y = 880205 - 221059 Ln X
E_{50}	Clay	36	-0.236	$Y = 2.416x10^6$ - 579128 X
E_{50}	MC	128	-0.319	$Y = 1.018x10^6$ - 403434 Ln X

r^2 = correlation coefficient
T_o = indirect tensile strength (psi)
LL = liquid limit (pct)
Clay = total clay size particle content (pct)
SW.AX = unconfined swelling strain - axial (pct)
MC = moisture content (pct)
C_o = unconfined compressive strength (psi)
E_{50} = modulus of elasticity at 50% of C_o value (psi)

The correlations appear similar, whether estimating indirect tensile strength or unconfined compressive strength. The angle of internal friction values, as determined from borehole shear tests, had a mean value of 33° with a standard deviation of 13°. Table 2 shows the correlations between the ultimate bearing capacity and other parameters. Results indicate that UBC can be estimated from the indirect tensile strength. UBC may also be estimated from natural moisture content of the claystone down to a depth of 30 inches, but the correlation coefficient is not very high ($r^2 = 0.119$).

Field-determined UBC was checked against UBC calculated using Vesic's equation. This correlation was considered important for mine operators because pillar design for weak claystone floors is commonly based on Vesic's equation. Cohesive strength of the weak claystone required for calculations was estimated from the indirect tensile strength or unconfined compressive strength values, and angle of internal friction was determined from the borehole shear tests. Cohesive strength (S_o) of the weak floor stratum required for calculations was estimated from T_o or C_o values and angle of internal friction determined from borehole shear tests. The results indicate that (1) UBC for plate-loading tests may be estimated with confidence ($r^2 = 0.535$) from T_o values, (2) the calculated values using Vesic's equation are slightly lower than the measured values, and (3) similar analyses using C_o values predict significantly higher values of UBC with a lower correlation coefficient.

Table 2 Correlations between ultimate bearing capacity (UBC) and other parameters.

(Y)	(X)	No.	r^2	Regression equation
UBC	T_o	49	0.535	Y = 395 + 1.795 X
UBC	DM_{50}	75	0.497	Y = 359.6 + 0.01262 X
UBC	DM_{50}	75	0.505	Ln Y = 0.8147 + 0.559 Ln X
UBC	MC	82	0.119	Y = 1392 - 86 X

UBC = value in psi
DM_{50} = modulus at 50% of UBC

Chugh, Pytel, and Pula (1990) also presented UBC in relation to MC and LL for estimation of UBC underneath a small plate.

$$UBC = 1405 - 86\,(MC) - 1.92\,(LL) \tag{1}$$

where

UBC = value in psi
MC = % moisture content
LL = % of the average liquid limit

In the same report, the effect of plate size on the UBC was determined to be

$$UBC = 1941.08\ B^{-0.466} \tag{2}$$

where B = width of the plate in inches

These equations were derived from tests with bearing plates up to 24 inches square, but no relation was derived for variations in UBC strength with variations in thickness of the weak floor strata. There are no UBC data available for large plates (>24 in.) on weak floor material; however, equation 2 indicates that the UBC below a full-size pillar must be lower than for a small plate test. Therefore equation 3 may be written as follows:

$$UBC\,(pillar) = f_u \times UBC\,(plate) \tag{3}$$

where f_u = reduction factor due to the size effect for UBC

Pula et al. (1990) indicate that f_u is a function of MC of the weak floor strata:

$$f_u = (1207.68 - 103.12\,MC)\,/\,(1207.68 - 103.12\,MC + 1678.72\,/\,B) \tag{4}$$

CONCLUSIONS

The following conclusions can be drawn from results of the correlation studies.

- Indirect tensile strength, unconfined compressive strength, and modulus of elasticity at 50% of immediate floor strata can be estimated from engineering index properties such as clay size particle content, liquid limit, natural moisture content, and axial swelling strain. Correlation coefficients for estimation of indirect tensile strength by the engineering index properties are better than they are for unconfined compressive strength.
- Ultimate bearing capacity (UBC) of plate load tests may be estimated from indirect tensile strength tests and angle of internal friction. This estimation slightly underestimates the measured UBC.
- The probability of an angle of internal friction being less than 20° is about 16%, based on 135 data points.

RECOMMENDATIONS

Statistical analysis of data obtained in this study resulted in the following recommendations for mine operators:

- Test natural moisture content and indirect tensile strength of the immediate floor strata at 6-inch intervals.
- Develop strength versus moisture content for the floor materials of individual mines.
- An angle of internal friction of 20°, instead of 0°, may be used with confidence for calculation of UBC.
- Cohesive strength of the immediate floor strata should be estimated from indirect tensile strength and angle of internal friction rather than from unconfined compressive strength and angles of internal friction, if Vesic's equation is used for estimating UBC.

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LONG-TERM SUBSIDENCE CHARACTERISTICS DUE TO MINE DEVELOPMENT AND PILLAR EXTRACTION AT A SHALLOW PARTIAL EXTRACTION ROOM-AND-PILLAR MINE IN CENTRAL ILLINOIS

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ABSTRACT

Surface subsidence at two sites over a room-and-pillar mine in central Illinois was monitored by the Department of Mining Engineering at Southern Illinois University. Site 1 represented unplanned subsidence with partial extraction room-and-pillar mine development. Site 2 represented planned subsidence with partial extraction room-and-pillar mine development and notching of pillars on retreat. Site 1 was monitored from 1986 to 1991; site 2 was monitored from 1988 to 1992.

Failure of the weak floor was the cause of subsidence in this mine. The process consisted of two stages, before and after failure of the floor strata. Subsidence in the prefailure stage was less than 0.4 foot, but in the more rapid postsubsidence stage, more than 1 foot. Only the prefailure stage was observed over the partial extraction panels (site 1). Both stages were observed over the partial pillar extraction panel (site 2). Subsidence prediction analyses were conducted for both sites; the predicted subsidence was in agreement with the corresponding monitoring data. This long-term monitoring, which showed continued slight movements, was the first study of its kind.

INTRODUCTION

Room-and-pillar mine workings with pillars left as permanent support are designed to be stable for a long time. Time-dependent failure and/or deformation of the roof strata and coal pillars may, however, cause unplanned and discontinuous subsidence to occur from a few years to more than 100 years after mining. These events may cause damage to surface and subsurface structures.

Time-dependent continuous subsidence over room-and-pillar mine workings has drawn attention since the late 1980s. This subsidence mechanism is caused by the settlement of coal mine pillars on weak floor strata (Marino et al. 1986, Chugh et al. 1986, 1987, DuMontelle and Bauer 1986). The problem is particularly significant in Illinois, where actively mined coal seams are generally associated with 3 to 10 feet of thick, weak floor strata. Room-and-pillar mining in Illinois regularly extracts about 50% of the coal. The coal pillars are generally considered stable, given typical coal strength properties. Failure and/or deformation of weak floor strata, however, frequently results in pillar and roof settlement and floor heave. Trough or sag-type surface subsidence is generally observed over such mines. Studies of the characteristics of such subsidence are limited in the literature. Depending on its magnitude, such subsidence may change land slope and agricultural productivity, and/or damage surface structures.

Overview of the Study

A room-and-pillar mining operation in central Illinois was extracting the Springfield Coal. The Department of Mining Engineering at Southern Illinois University at Carbondale monitored surface subsidence at two sites in this mine (Chugh et al. 1987, Chugh and Atri 1988, 1989, Chugh and Hao 1990a, 1990b, 1991, Chugh et al. 1991). Subsidence monitoring over site

1, the unplanned subsidence area, began in January 1986. This area, which consisted of partial extraction room-and-pillar mine development, was monitored until November 1991. At the second site, a planned subsidence area in the same mine, parts of the pillars were removed by notching them on retreat. The pillar-notching section (site 2) was monitored from September 1988 to July 1992.

These projects were supported by the Illinois Mine Subsidence Research Program and Twin Cities Research Center of the U.S. Bureau of Mines, cooperating with the coal company.

Objectives

Site 1 The objectives of the study conducted over the partial-extraction area were to undertake the following:

- monitor long-term vertical and horizontal subsidence movements overlying a room-and-pillar mine panel during and subsequent to mine development. (Horizontal measurements were discontinued in 1989.)
- analyze subsidence data for vertical and horizontal displacement and strain profile characteristics.
- correlate subsidence movements with observed underground movements. (Underground monitoring had to be dropped from the study in November 1987.)
- validate the SIU Panel.2D and Panel.3D (two- and three-dimensional) models of subsidence prediction, and use subsidence-time data from this study to develop viscoelastic or time-dependent model parameters for weak floor strata.

Site 2 The objectives of the pillar-extraction part of the study were as follows:

- develop subsidence characteristics, including time effects, due to pillar extraction in areas where the coal seam is associated with weak floor strata.
- correlate observed surface subsidence movements with in-mine geotechnical measurements of pillar settlement and convergence; continue to test the hypotheses developed by Chugh et al. (1987) to correlate surface and underground movements.
- predict in-mine pillar movements and subsidence movements from the Panel.2D model (Pytel et al. 1988) and the Void Diffusion Model (Hao and Ma 1990); compare predicted values with observed data.

MINE DESCRIPTION AND AREA GEOLOGY

Mine Description

The operation extracted the Springfield Coal, the only seam mined at the time, at a depth ranging from 250 to 350 feet; the seam thickness ranged from 4.5 to 6.0 feet. Mine panels were irregular in shape because of planned avoidance of unstable conditions in areas of thick shale roof. The opening and pillar sizes in different parts of the mine are given in table 1.

Table 1 Opening and pillar sizes in different parts of the mine.

Location	Opening width	Solid pillar (ft × ft)
Shaft bottom	16	84 × 84
Main entries	16	74 × 74
Submain entries	16	74 × 74
Site 1	20	55 × 55
Site 2		
Section A_1 (Network A)	20	70 × 70
Section A_2 (Network A)	20	70 × 55
Section B (Network B)	20	55 × 55
Section C (Network C)	20	70 × 55

At site 1, the panel adjacent to the study panel was mined before subsidence observations began. East-side rooms in the study panel under the monitoring lines were developed from February to May, 1986. West-side rooms were developed on retreat from July to September 1986. The next adjacent panel was mined in 1987. The extraction ratio generally ranged from 40% to 45%, wherever mine development was not affected by adverse roof conditions. Floor heave was commonly observed in the mine at a long-term rate of approximately 0.2 inch per month; peak heave rates of 3 to 4 inches per month were observed immediately after mine openings were developed. Figure 1 shows the layout of the partial-extraction area (site 1).

The panel at site 2 (fig. 2) was developed from October 1988 to May 1989 for Section A. Pillars were notched from May 22, 1989, to June 7, 1989. During pillar notching (fig. 3), two additional cuts, 20 × 20 feet, were developed with a continuous miner. The extraction ratio was 49% in Section A_1 and 55% in Section A_2.

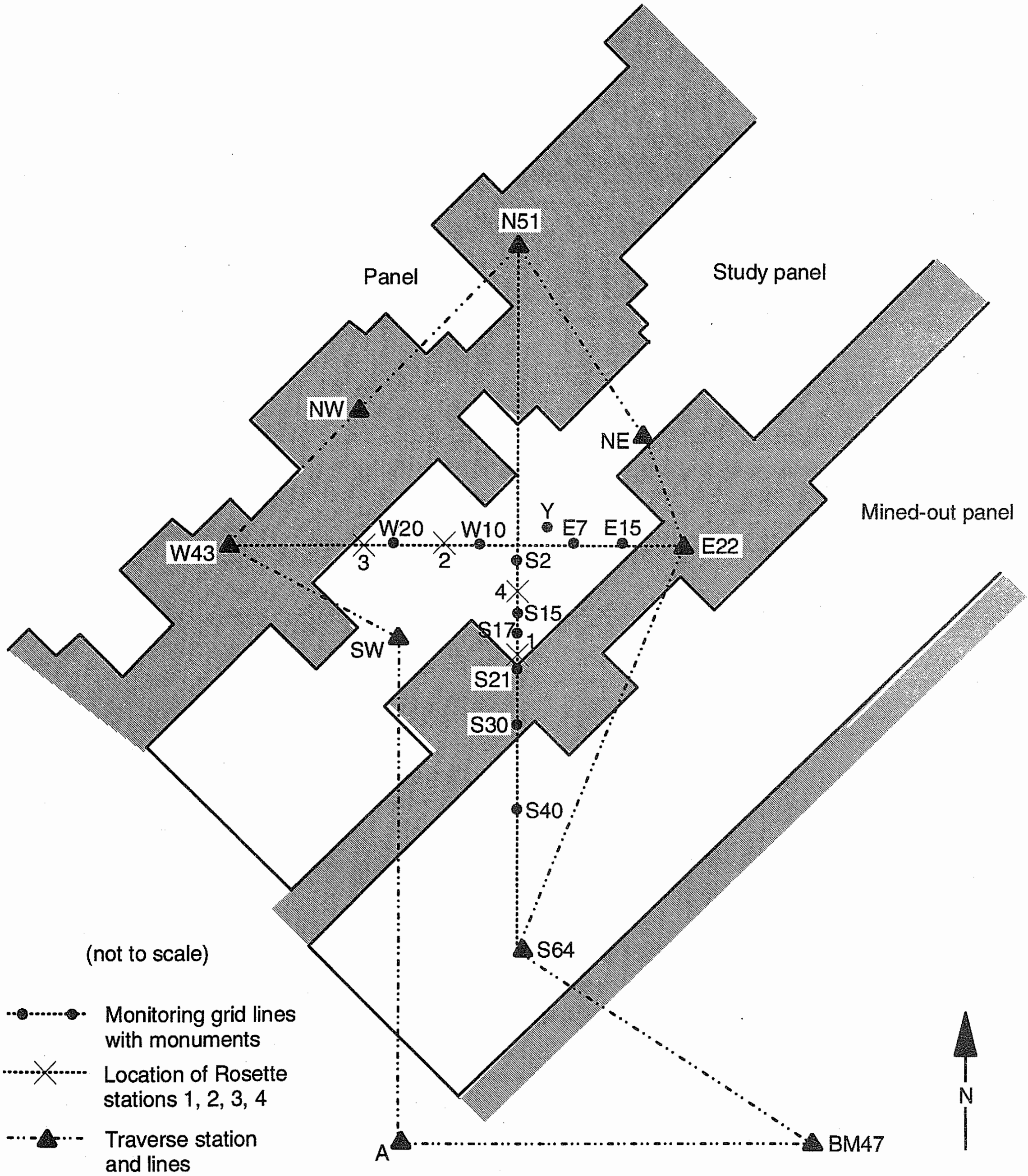

Figure 1 Layout of partial-extraction area (site 1).

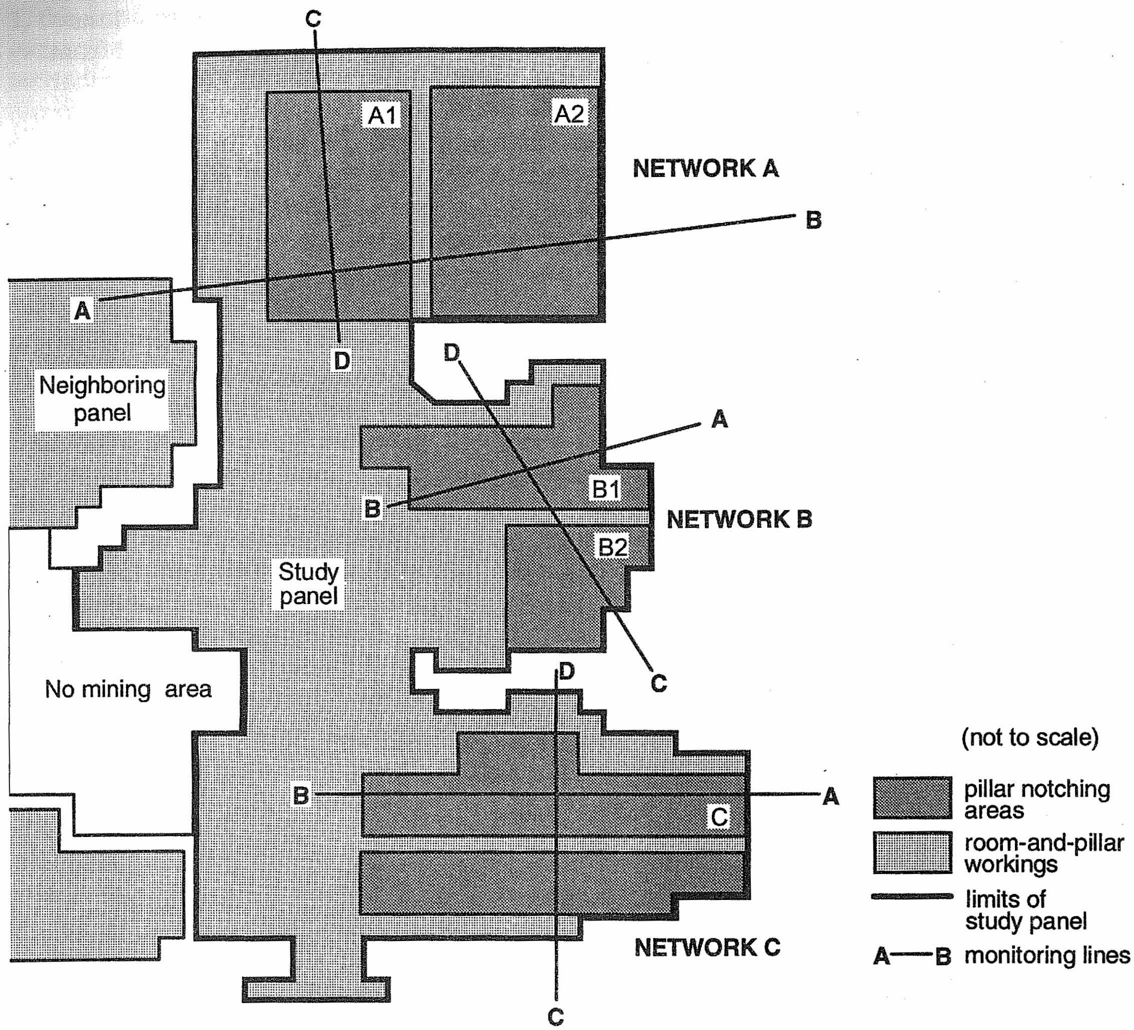

Figure 2 Panel layout and monitoring lines (site 2).

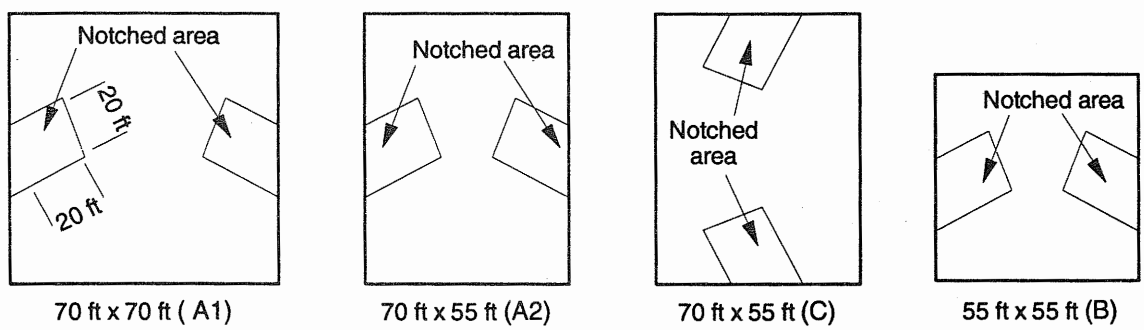

Figure 3 Pillar notching in the study panel (site 2).

Area Geology

The surface topography at site 1 is flat to gently rolling, with a relief of about 20 feet. The land is used for agriculture. At site 2, most of the area is wooded and grades range from 0 to 30%. The thickness of glacial deposits is about 140 to 150 feet at site 1 and 135 to 225 feet at site 2.

The total thickness of the rock overburden, primarily shale and limestone, is approximately 115 to 125 feet over the seam. The total overburden is about 260 to 350 feet thick and has an average value of 300 feet.

The coal seam dips at a gradient of about 25 feet per mile toward the southeast, and its thickness ranges from 5 to 6 feet. The immediate roof stratum is a thin layer of black shale, 1 to 8 feet thick, overlain by a competent limestone bed 4 to 5 feet thick. The unconfined compressive strength of the black shale is less than 1200 psi, whereas the limestone strength is about 30,000 psi.

The immediate floor stratum is 4 to 8 feet of thick underclay, which is sensitive to water, as determined from swelling strain and clay mineral composition data (Chugh 1986). The Rock Quality Designation of this highly slickensided unit is poor to very poor (0–50), and slickensides were randomly oriented. Limestone nodules 0.25 to 2.0 inches in diameter are found 2 feet or more below the coal seam, and their frequency generally increases with increasing depth below the coal seam. The moisture content of the underclay (Chugh 1986) down to 50 to 55 inches below the coal seam is comparatively higher (7.5–9.4%) than that below 55 inches (4.0–4.5%). In situ borehole shear tests and bearing capacity tests (Chugh 1986) of the immediate floor strata indicated an unconfined shear strength of 100 to 200 psi and an angle of internal friction of 20° to 30°.

The underclay is generally underlain by relatively thin (0-12 in.) layers of shale, limestone, mudstone, or claystone to a depth ranging from 10 to 14 feet. Below these strata, a weak moist underclay with characteristics similar to the immediate floor underclay, is present. The thickness of this bed ranges from 12 to 24 inches, and is generally associated with mudstone, claystone, and silty or sandy shales. Water at a pressure of about 10 psi was generally encountered at a depth of 14 to 16 feet below the coal seam (Chugh 1986).

SUBSIDENCE MONITORING

Site 1

Surface Monitoring Two main monitoring lines were installed at site 1. The lines were located at about a ±45° angle with respect to the longitudinal axis of the panel because agricultural plots on the surface were previously oriented in this direction; they were left at this angle to maintain normal cultivation of the land. Along these two lines, 177 monuments were set up at about 25-foot intervals (112 along the north–south line and 65 along the east–west line). An adjacent panel on the east side had already been mined, leaving a panel barrier about 180 feet wide. Therefore, the east–west grid line was extended up to this panel barrier so that the barrier pillar subsidence due to mining the study panel could be observed. (In other words, the barrier pillar was monitored to determine how it was affected by mining of the study panel.) On the south side, the monitoring line could not be extended to an area where no effect of mined-out workings would be expected; however, the west end of the east–west monitoring line was extended beyond the effect of mine workings so that the angle of draw and angle of break could be determined in this area. The west end monument (W43) was also utilized to check the stability of the original benchmark (BM47).

Rectangular rosettes established around four of the monuments were used to determine movements and the directions of movement. The monuments were designed to minimize spurious effects due to variations in weather, especially due to the ground freezing in winter. Base-line survey data for this study were obtained in February 1986. Twenty-one subsidence surveys were completed by November 1991.

Measurement of Pillar Settlements Underground A 20-foot multiple point borehole extensometer (MPBX) was also installed in the roof directly above the SONDEX system, which was grouted in place at a depth of about 20 feet. The distance between the MPBX in the roof and the top of the SONDEX pipe in the floor was measured with a tape extensometer. If no differential movement in roof strata had occurred, the change in the distance between the bottommost MPBX anchor in the roof and the top of the SONDEX pipe in the floor was interpreted to be pillar settlement. If differential roof strata movements had occurred, the change in distance between the uppermost MPBX anchor in the roof and the uppermost SONDEX ring in the floor represented the pillar settlement. Underground monitoring was discontinued in November 1987 when the panel was sealed off because of excessive movements in the floor strata.

Site 2

Three monitoring networks, A, B, and C, to monitor the effect of pillar size on subsidence characteristics (fig. 2) were set up over a panel.

Network A In a wooded area, the two principal monitoring lines for Network A, AB and CD, were installed along the dip-rise and strike directions of the panel in October 1988. Line AB, about 2,100 feet long, had 89 monuments and line CD, 1,600 feet long, had 58 monuments. A base-line survey was performed in October 1988, prior to the development. A control point, about 400 feet beyond the C end of line CD, was also set up as the reference bench mark for subsidence surveying. Five surveys were completed before pillar notching. Eight surveys were completed during and after pillar notching. The last set of data was taken in July 1992.

Network B The two monitoring lines for Network B were installed in a flat area in July 1989, just before pillar notching started. Line AB, about 1,000 feet long, had 20 monuments and line CD, about 1300 feet long, had 37 monuments. These lines were extended about 350 feet over the unmined areas on two ends of the monitoring lines, to be out of the range of influence of pillar notching. Two control points were utilized as references.

Network C Network C was installed in a gently rolling to flat area on September 20, 1989. It consisted of two monitoring lines along the dip-rise and strike directions. Line AB of this network was about 1,760 feet long and had 45 monuments, and line CD was about 1,500 feet long and had 38 monuments. No significant subsidence data were acquired from Network C (Hao and Chugh 1990).

Monitoring on Networks B and C was terminated at the landowner's request, and all monuments were removed in February 1990.

Subsidence Monument Design Subsidence monument design and installation were different for all three networks at site 2. In Network A, subsidence monuments were originally designed to minimize spurious effects due to variations in weather, especially due to freezing of the ground in winter. Drilling through tree roots made installation of these monuments difficult; therefore, only rebars were used for most of the monuments. Compensation for freeze/thaw errors required setting up some additional frost-free monuments close to the rebar monuments. The average interval between monuments was about 25 feet.

In Networks B and C, 2-foot or 1-foot-long bolts (driven into the ground) were used as monuments because most of them were set up in the soybean field or pasture land and were to be removed once subsidence measurement was complete. In Network C, mostly pasture, the bolt monuments were installed below ground surface, a measure taken to protect cattle from accidental injury. This was the only type of monument permitted by the landowner.

Monitoring of Horizontal Strain In Network A, a steel tape with a spring was utilized to measure the distance between monuments. The smallest graduation of the steel tape was 0.01 foot. The distance was visually approximated to 0.001 foot when 12 pounds of tension was applied by a spring-tension device. Each distance was measured at least twice until two consecutive readings were within ±0.005 foot. All distances were normalized to the base-line data. The horizontal distance between two monuments was then calculated from the slope distance and height difference of the two monuments. In Network B, strain could not be measured because all the monuments were in a private soybean field and high grass land. In Network C, horizontal displacement was monitored using the TOPCON GTS-2R total station system. Because all of the monuments were installed below ground level, this was the only way to develop the horizontal displacement and strain data.

Measurement of Roof–Floor Convergence About 42 roof–floor convergence points were installed in Section A underneath Network A. Each convergence point was located almost at the center of an entry. The convergence was measured using a tape extensometer that had a resolution of 0.001 inch.

Data Analysis For Network A, analysis included calculation of the coordinates of 58 monuments; subsidence, slope, and curvature; horizontal strain; and angle of draw. Of the ten sets of data analyzed, five sets had been observed before pillar notching and five sets after pillar notching. Because the main concern of the project was the effect of pillar extraction on surface subsidence and deformations, the last observation before pillar notching (May 1989) provided the base-line data for calculating subsidence due to pillar extraction. To eliminate the effect of tree roots on the monuments, the investigators used the program STATGRAPHICS to smooth the subsidence profiles.

The slope and curvature were calculated from the smoothed profiles using the difference formula. Only three sets of horizontal strain data along line AB, observed after pillar notching, were used in the analysis because the remaining observed data were erratic. Some values of the strain data could not be computed because trees interfered with measuring the distance between adjacent points. The strain data at these points were estimated, based on the strain values from adjoining points. Theoretically, angle of draw is the angle between the vertical line at the panel edge and the line connecting the panel edge to the zero subsidence point on the surface. Here the zero subsidence was replaced by an amount of subsidence or ground heave equal to two times the mean square error in measured subsidence value. The edge of the development panel was used for the calculation of the angle of draw.

In Network B, surface subsidence, slope, curvature, and subsidence rate for the seven sets of observed data were calculated without any adjustments. In Network C, about 0.7 inch of maximum surface subsidence was measured before the monuments were removed. Horizontal strain and displacement data obtained were generally erratic.

Surveying Accuracy

Elevations at both sites were surveyed using a precise level and two Invar rods. The second order, class II accuracy standard (U.S. Department of Commerce 1976) was followed. A closure error of 0.2 to 1.5 millimeters in 1 kilometer was obtained, less than the 8 millimeters in 1 kilometer prescribed limit.

RESULTS AND DISCUSSION

Partial Extraction Area: Site 1

Table 2 summarizes the observations from site 1. In general, trough-type, continuous, and time-dependent subsidence continued to occur more than 5 years after development of the mine workings, although some locations in the monitoring line showed more movement than others in the final year of measurements. The effect of an individual pillar on the shape of the surface subsidence profile was not discernible.

Subsidence A maximum subsidence rate of 0.020 to 0.025 foot per month was noted for the first 2 months after development of the mine workings. This rate decreased to 0.006 to 0.008 foot per month during the next 2 months. The rate continued to decrease to 0.0025 to 0.0030 foot per month 18 months after mine development. After the adjoining panel was mined, the subsidence rate increased to an average of 0.0061 foot per month over the center of the panel for the next 22 months. This increase was thought to be related to the settlement of barrier and panel pillars on weak floor strata. In May 1990, the subsidence rate had decreased to 0.0023 foot per month. In May 1991, measurements indicated that only 0.0041 foot (0.00034 ft/month) of additional subsidence had occurred throughout the year.

Table 2 Subsidence parameters, site 1.

Parameters	North–south line	East–west line
Maximum subsidence	0.2812 ft	0.2716 ft
Maximum slope	0.0007	0.0006
Maximum horizontal displacement	0.05 ft	0.069 ft
Maximum tensile strain	<0.0002	<0.0002
Maximum compressive strain	<0.0002	<0.0002
Subsidence factor	0.051	0.049
Angle of draw	28°	30°
Angle of break	5°	-13°

Mining thickness = 5.5 ft and mining depth = 265–270 ft; extraction ratio = 40–45%
Note: Only the maximum subsidence, slope, and strain are from the last set of survey data (Chugh and Hao 1992). Other parameters were determined by a previous survey (Chugh and Atri 1988).

Angle of Draw Angle of draw, based on zero vertical displacement (two times the mean square error of surveys), was calculated at three points on the surface around the unmined side of the panel before the adjacent panel on the west side was mined out. The average value of the angle of draw was 29° through 1991. The angle of draw could not be calculated in 1992 because by then all the monuments were within the radius of influence of mined-out areas. The inflection points could not be defined in 1992 for the same reason and also because of highly irregular mining geometries. Bad roof conditions in the panel resulted in selective mining and irregular subsidence profiles.

Horizontal Displacement Horizontal displacement values along the north–south and east–west monitoring lines were on the same order as the measurement accuracy; therefore, strains were too small to measure. No measurable change was observed in horizontal displacement and strain from the 1987–1988 monitoring year to the 1988–1989 monitoring year. As a result, measurements of horizontal displacement at site 1 were discontinued after July 1989.

Correlation Between Underground and Surface Subsidence Movements Pillar settlements and immediate floor settlements were monitored from January 1986 until November 1987. The principal investigators hypothesized that surface subsidence at the mine was primarily due to pillar settlement on weak floor strata. Subsidence at a certain point on the surface was expected to begin when mining was within the critical radius of influence (about 175 ft). A significant increase in stresses that could cause pillar settlements vertically below that point was expected, however, only after workings were developed within 50 to 65 feet of this point. A time lag was therefore expected between the observed subsidence at a surface point and the expected pillar settlement vertically below it.

As soon as mining advanced beyond the pillar below the surface point, the rate of pillar settlement was expected to increase because vertical stresses on the pillar would be considerably higher. Downward pillar movement may or may not be immediately transmitted to the surface. The pillar settlement rate decreases as a function of time or distance from active mining; however, the decreasing rate of surface subsidence may not be the same as the decreasing rate of pillar settlement because the extended overburden is recompacting or separated beds are slowly coming back into contact with each other. After a long time, the total downward pillar movement and surface subsidence should approach the same value.

As hypothesized, the pillar settlement rate at this site was observed to be greater than the subsidence rate after the workings were developed. The pillar settlement rate was decreasing exponentially when underground observations had to be discontinued because of adverse ground conditions in the panel. The pillar settlement rate had been greater than the subsidence rate, except after August 1987. During this period, the subsidence rate increased significantly, and it was greater than the corresponding pillar settlement rate. The investigators thought that this could be due to a significant load transfer onto the barrier pillars, an occurrence that caused the barrier pillars and the entire panel to subside much faster. The load transfer may be associated with excessive settlements of pillars in the center of the panel.

Pillar Extraction Area: Site 2

Table 3 summarizes the observations from site 2. Pillar size had a very important effect on surface subsidence and related deformations. Two patterns of subsidence were observed after pillar extraction: immediate subsidence and delayed subsidence. In this study, immediate subsidence occurred over the 70 × 55-foot and 55 × 55-foot pillars, whereas delayed subsidence occurred over the 70 × 70-foot pillars (Hao and Chugh 1990).

The observed maximum values of rate of change in subsidence, slope, and curvature due to secondary mining were much larger than those observed over site 1, but still less than those resulting from longwall mining. Subsidence factors due to secondary mining (0.18 to 0.393) were much larger than the values due to the first mining (0.049), but these are still smaller than subsidence factors in longwall mining (about 0.7).

Table 3 Subsidence parameters, site 2.

Parameters	Section A_2	Section A_1
Maximum subsidence	2.18 ft	1.16 ft
Maximum slope	0.0100	0.0043
Maximum convex curvature	0.109 (1/1000 ft)	0.037 (1/1000 ft)
Maximum concave curvature	0.063 (1/1000 ft)	0.033 (1/1000 ft)
Maximum rate of subsidence	0.28 ft/day	0.004 ft/day
Maximum tensile strain	0.007	—
Maximum compressive strain	0.0055	—
Subsidence factor	0.36	0.19
Offset of inflection point/mining depth	0.32	0.23
Angle of draw	>57 °	37 °
Pillar size	70 × 55 ft	70 × 70 ft

Mining thickness = 6.0 ft; mining depth = 300 ft

Immediate Versus Delayed Subsidence In the cases of immediate subsidence, about half of the total subsidence occurred immediately after the pillars were notched. This rapid subsidence was caused by the bearing capacity failure of weak floor strata and the sinking of pillars into weak floor strata. The subsidence rate decreased significantly thereafter, but continued for almost 1 year after pillar notching. In the cases of delayed subsidence, subsidence immediately after pillar notching was very slow. Several months (even years) later, subsidence began to occur very rapidly, similarly to subsidence over an abandoned mine. Its occurrence was probably due to the creep characteristics of the weak floor strata, changes in physical characteristics of weak floor strata, and/or additional loading on pillars.

In this study, immediate subsidence occurred over Sections A_2 and B_1. Delayed subsidence occurred over Sections A_1, B_2, and probably C. Delayed subsidence had not been observed in Section C by the time the subsidence monuments were removed. Because the pillars were smaller in Section C than in A_1, it was estimated that delayed subsidence occurred no later than 1990.

Influence of Pillar Factors on Subsidence Patterns Pillar size and position of notching in the pillar seemed to significantly influence which type of subsidence occurred over the mine. Small pillar sizes resulted in immediate subsidence, whereas large pillar sizes resulted in delayed subsidence. When a pillar was notched on both of the long sides of a rectangular pillar, as in Section A_1, thin pillars with narrow bearing areas resulted. This was likely to cause immediate subsidence. When a pillar was notched on both of the short sides of a rectangular pillar, as in Section C, the remnant pillar was wider than a remnant pillar in Section A_1, and thus the bearing area was greater. This condition was likely to delay subsidence.

Strain The strain profiles had a well defined distribution, but were not proportional to the curvature profiles. This effect was probably due to steep slopes, profile smoothing, and estimating strains. Topography has a significant influence on horizontal displacement and strain, but not on subsidence, slope, and curvature (He 1985).

Correlation Between Surface Subsidence and Underground Movements For site 1, Chugh et al. (1987) presented a hypothesis to correlate surface subsidence and underground movements. The principal investigators similarly hypothesized, for site 2, that surface subsidence over the extraction area with notched pillars was primarily due to pillar settlement on weak floor strata. Surface subsidence at any point was expected to begin when mining was within the critical radius of influence (about 200 feet at this site). A significant increase in stresses, which could cause pillars to settle vertically below this point, was expected only after pillars were notched within 50 to 60 feet of this point. A time lag was thus expected between surface subsidence and underground movement. According to the hypothesis, after pillar notching, the final surface subsidence and pillar settlement should have been related as follows:

- If the surface point is over the central part of the notched area, the surface subsidence should be equal to or slightly less than the pillar settlement.
- If the surface point is over the unnotched area, the surface subsidence should be greater than the pillar settlement.
- When the surface point overlies the notched area with large pillars (delayed subsidence) but is adjacent to the notched area with small pillars (immediate subsidence), the surface subsidence at this point may be greater than the pillar settlement.

Pillar settlement data in this study were very limited but calculated from observed convergence data. Correlations of surface subsidence and underground pillar settlement matched the above hypothesis. For example, for a surface monument and a convergence point in Section A_1 (notched area with large pillars) close to and within the range of possible influence of Section A_2 (notched area with small pillars), the final observed surface subsidence was greater than the pillar settlement.

MODEL VALIDATION FOR PREDICTION OF SURFACE SUBSIDENCE

Site 1

Subsidence prediction analysis was conducted using the SIU Panel.3D model (Pytel and Chugh 1991). The three-dimensional mining area analyzed was three adjacent panels with the monitored panel in the center. Subsidence was monitored for 6 years. Mining geometry and geotechnical parameters were obtained from the closest borehole for which strata properties were available. Subsidence prediction analyses were conducted for two periods of time, 101 and 696 days after subsidence monitoring began. The predicted subsidence was in good agreement with the corresponding observed subsidence data for the area, particularly over the study panel. Maximum subsidence differences were 6% for 696 days and 14% for 101 days. Weak floor strata parameters calculated from surface subsidence data were reasonable and used with confidence in the SIU Panel.3D model for predicting subsidence in room-and-pillar mine workings, particularly for long periods of time. Subsidence prediction accuracy is significantly affected by the mining extraction schedule in different areas, and therefore this schedule should be accurately determined.

Site 2

Subsidence prediction analysis for site 2 was first conducted with the SIU Panel.2D model and then with the Void Diffusion Model (VDM). In the VDM, the overburden strata may be treated as a linear homogeneous medium or as a nonlinear homogeneous medium (Hao and Ma 1990). Because the overburden strata may not fracture in room-and-pillar mining, as is typical in longwall mining, the linear homogeneous medium assumption was used in this study. A close comparison was found between the predicted and observed subsidence profiles along Line AB of site 2 in this study.

CONCLUSIONS

According to the survey results of the last monitoring period (1992), surface subsidence in both monitoring areas was still active locally. Data for the north part over the partial extraction panels (site 1) showed an increase in the subsidence rate, as compared with the previous monitoring year. In the partial pillar extraction panel (site 2), additional subsidence may not have been significant, although it was still active in Section A_1.

Subsidence in this mine was caused by weak floor deformation or failure. The whole subsidence process may consist of two stages, before and after failure of the floor strata. The prefailure stage tends to be very long in the case of partial extraction development and the postfailure stage is unpredictable. Both stages may coexist after pillar notching, depending on the pillar size; but the prefailure stage is relatively short. In the prefailure stage, a minor amount of subsidence (<4–5 in.) occurs slowly as pillars settle into weak floor strata during and following coal extraction. During the postfailure stage, relatively large subsidence (>1 ft) occurs as the weak floor strata fail.

Only the prefailure subsidence was observed over the partial extraction panels (site 1). The subsidence rate may decrease or increase over time. Because prefailure subsidence is minor, the impact on surface structures may be insignificant. Whether and when the postfailure subsidence stage will occur is very difficult to predict (Hao and Chugh 1992).

Both stages of subsidence were observed over the pillar extraction panel (site 2). Differences were apparent between Section A_1 (70 × 70-ft pillars) and Section A_2 (70 × 55-ft pillars). In Section A_1, the prefailure stage was observed before and after pillar notching; whereas in Section A_2, the postfailure stage immediately followed pillar notching. The two types of postfailure subsidence following pillar notching were termed delayed subsidence and immediate subsidence (Chugh and Hao 1990b, Hao and Chugh 1990).

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LABORATORY-DERIVED COAL STRENGTH PROPERTIES

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Summarized by Robert A. Bauer

ABSTRACT

Large block samples of coal were collected in three underground mines in the west-central and southeastern parts of the Illinois Coal Basin. Samples were taken from mines in the Herrin Coal at depths between 300 and 900 feet. Most of the blocks ranged from 6 inches to 3 feet on a side. The bituminous coal samples were trimmed in the laboratory to produce cubes and prisms of coal of various sizes and shapes; 135 samples were tested for their ultimate compressive strength. Variations in size and shape in relation to strength of the coal samples were mathematically determined and compared with mathematical relationships obtained for coal samples from other parts of the world.

INTRODUCTION

Coal strength values are very dependent on the size and shape of the sample. A decrease in unit strength accompanies an increase in size of the tested sample of the same shape. For coal, this holds true only until a specific size is reached. Tests indicate that when the sample exceeds a particular size, the unit strength of the sample no longer decreases. At one location in South Africa, for example, this critical size was found to be about 5 feet on a side (Bieniawski 1968). Changing the shape (i.e., variations in the ratio of width to height of pillars) also changes the unit strength. This change in unit strength occurs for pillars with variations in width-to-height ratios of pillars with the same square cross-sectional areas, or pillars with the same cross-sectional areas but square versus rectangular.

BACKGROUND

The strength of a coal pillar, calculated as ultimate load divided by its cross-sectional area, is dependent on three elements: (1) the size effect, (2) the shape effect, and 3) the coal's mechanical properties.

Size Effect

The size effect is defined by testing laboratory-size cubes and in situ cubical pillars of coal. For cubical samples, the strength decreases with increasing specimen size until the strength becomes constant. The size of sample is called the "critical size" when the strength becomes constant. Size effects are shown in figure 1 for cubical bituminous ranked coal samples from five other areas of the world. The relationship exhibited by these data is as follows:

$$S = K(w)^{-0.488} \tag{1}$$

where
S = sample or pillar strength in pounds per square inch (psi)
K = constant
w = cube edge length in inches

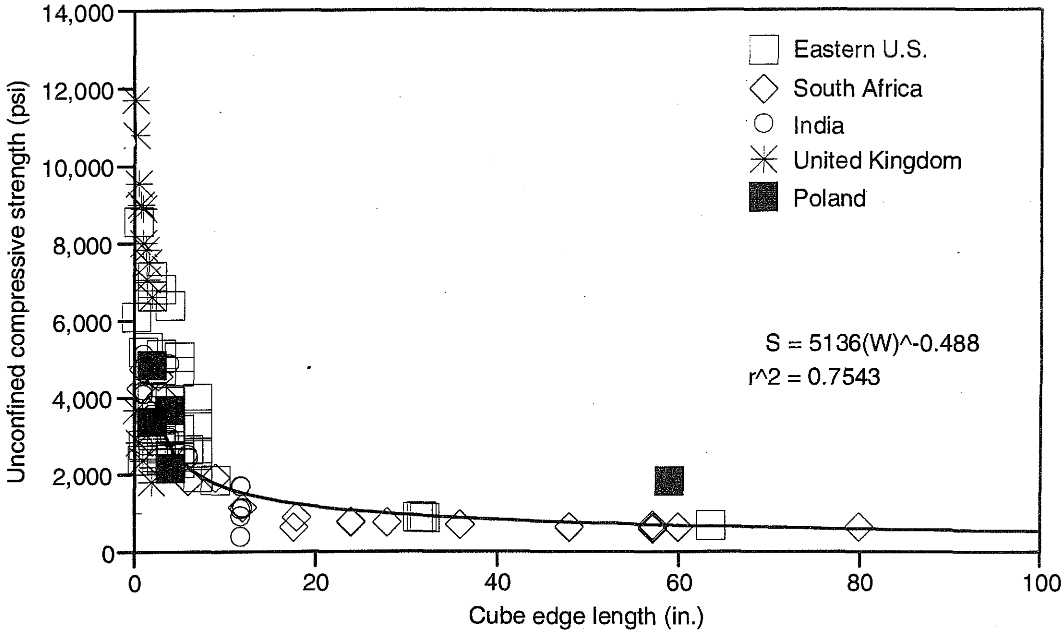

Figure 1 Strength of coal cubes from other areas of the world.

Holland (1973) proposed that K be derived by testing 3-inch cubes and multiplying the testing strength by the square root of the cube edge length. Therefore, K is the unit strength of a 1-inch cube and it is the same as K in formula 1. Holland suggested testing 3-inch cubes because the strength of smaller cubes is extremely variable and dependent on the presence or absence of discontinuities (cleat and bedding planes). Testing larger samples produces slight variations in strength and a more realistic value. Working in South Africa, Bieniawski (1968) used large-scale in situ tests of pillars to determine that the critical size is a 5-foot cube. This means that the unit strength of coal does not change for samples larger than these cubes. This unit strength value, therefore, is equal to the unit strength in full-size pillars. Hustrulid (1976) showed that in the eastern United States the critical size is 36 inches. He calculated the unit strength of a cubical pillar by using

$$\sigma_1 = K / (36)^{-0.5} \tag{2}$$

for cubical pillars with heights greater than 36 inches and

$$\sigma_1 = K / (h)^{-0.5} \tag{3}$$

for cubical pillars with heights less than 36 inches.

In the above equations, the constant K *must be determined for each coal seam*. It is obtained as shown by Gaddy (1956):

$$K = \sigma_c (D)^{-0.5} \tag{4}$$

where σ_c = the uniaxial compressive strength of a laboratory-tested coal sample with a cube side length of D (in inches)

Again, K is a constant strength of a unit size and, in this case, an approximation of the strength of a 1-inch cube, as determined from tests of 2- to 4-inch cubes. Holland (1973) suggests that at least 30 cube samples be tested to derive this value for a 6-foot-thick coal seam; 3-inch cubes were satisfactory, but nothing less than a 2-inch cube should be used.

Shape Effect

The shape effect is usually defined by one of two types of equations:

$$\sigma_p = \sigma_1 (A + B(w/h)) \tag{5}$$

and

$$\sigma_p = K(w^{\alpha} / h^{\beta}) \tag{6}$$

where σ_p = pillar strength or normalized laboratory-derived value
σ_1 = the strength of a cubical pillar at the *critical* sample size or laboratory-derived value that will be normalized by the w/h
w = pillar or sample width
h = pillar or sample height
A and B = constants
α and β = constants expressing shape effects

Published values of A and B and α and β are presented in tables 1 and 2.

Table 1 Published constants of A and B for equation 5.

Source	Formula A + B(w/h)	w/h range
Bieniawski (1968)	0.556 + 0.444 (w/h)	1.0 – 3.1
Bunting (1911)	0.700 + 0.300 (w/h)	0.5 – 1.0
Obert et al. (1960)	0.788 + 0.222 (w/h)	0.5 – 2.0
Sorenson and Pariseau (1978)	0.693 + 0.307 (w/h)	0.5 – 2.0
Van Heerden (1974)	0.704 + 0.296 (w/h)	1.14 – 3.4

Table 2 Published constants of α, β, and n for equations 6 and 7.

Source	α	β	n
Bieniawski (1968)	0.16	0.55	0.805
Greenwald et al. (1939)	0.5	0.833	0.833
Hazen and Artler (1976)	0.5	0.5	1.00
Hedley and Grant (1972)	0.5	0.75	0.875
Holland (1956)	0.5	0.5	1.00
Holland (1962)	0.5	1.00	0.875
Morrison et al. (1961)	0.5	0.5	1.00
Salamon and Munro (1967)	0.46	0.66	0.90
Steart (1954)	0.5	1.00	0.75
Zern (1928)	0.5	0.5	1.00

A formula presented by Tsur-Lavie and Denekamp (1982) combines the effects of both size and shape:

$$\sigma = K(w/h)^{\beta} \times A^{n}, \quad n = (2 + \alpha - \beta)/2 \tag{7}$$

where A = cross-sectional area
n = represents size effect (see table 2 for calculated values)

Equation 5 is also used to develop laboratory-derived relationships between shape and strength. In equation 6, used mostly to estimate pillar strengths, various authors used different unit strengths for K. Salamon and Munro (1967) have K equal the unit strength of 1 cubic foot of coal. Holland's (1956) K represents the unit strength of a 3-foot cube. Later, Holland (1964) has K represent the strength of a 1-inch cube.

Mechanical Properties

The strength of coal is dependent on the type (rank) of coal, whether it is anthracite, bituminous, or subbituminous. Strength is dependent on the minerals that make up a coal. Scher's (1979) tests on 1-inch cubes of Herrin Coal from Illinois showed that the frequency of bands of coal minerals (vitrain, clarain, durain, and fusain) and the fusain content influence coal strength. Therefore, large block samples and samples from the entire seam height should be tested to determine a representative strength.

The block samples collected for this study from underground coal mines in Illinois are only adequate for investigating the effects of size and shape on the strength of laboratory samples and not of in situ coal pillars. Therefore, the laboratory-derived relationships presented by equations 1 and 5 were investigated.

SAMPLE SITE CHARACTERISTICS

Mine Characteristics

The general characteristics of the three mines and sample strengths are summarized in table 3. It is important to note that the sampling areas were selected where there were no observable deep-seated pillar failures at or near the sample locations. In almost all cases the specimens were taken from the middle section (horizontally) of the pillars that were least disturbed by slabbing or block movement.

Table 3 Summary of mine and Herrin Coal sample strength characteristics.

Mine no.	Depth (ft)	Extraction (%)	Cleat spacing (in.)	Pillar w/h ratio	1-in. cube	2-in. cube	3-in. cube	4-in. cube
1	900	45–55	0.12–0.5	10	4301	2945	2556	
2	440	40–46	0.5–1.0	10.2–10.75		1770	2106	
3	315	50	1.0–4.0	5.7–7.14	3491	2844		2748

Mine 1 In southeastern Illinois near the Indiana border, Mine 1 uses room-and-pillar methods to extract the Herrin Coal at an average depth of 900 feet. The thickness of the coal ranges from 58 to 72 inches, and the seam lies above a layer of claystone (underclay) 2 to 5 feet thick. The claystone is typically dark gray, brittle, hard, and has fissures with numerous slickensided surfaces. When remolded, the claystone has a high percentage of silt-size particles and behaves as a low plasticity soil. The claystone softens in water, and a floor squeeze has been reported in one local area of the mine. The roof above the coal is a dark gray shale 3 to 5 feet thick below a hard limestone. The roof rock appears to be stable, except for minor failed slabs

and block movements. A report by Ingram and Molinda (1988) on in situ stress measurements in several coal mines in the Illinois Coal Basin indicates that there are no high lateral stresses present in Mine 1. Rock bolts and some timber cribs have been used for roof support in the intersection areas.

The coal seam near the block sample locations is 61 to 64 inches thick. Cleats are typically spaced 1/8 to 1/2 inches apart and individual beds are 1/2 to 1 inch thick. Cleat directions are parallel with the sides of the pillars (northeast–southwest) and cut across the joint system observed in the roof rock (north–south). The coal and the claystone exhibit brittle behavior near the surface of the openings. Distressed zones are typically 30 to 80 inches deep at the corners of pillars in the oldest sections of the mine and in undercut areas. In the most recently mined areas, visible cracks are generally less than 20 inches from the corner of the pillar. The outside surface of a pillar almost always slopes inward toward the center of the pillar in response to yielding (plastic deformation and creep) of the underlying claystone.

All coal samples were taken from sound portions of the pillars that did not contain visible cracks. Most samples were obtained from the top portion of the coal bed in one area of the mine. A total of 15 block samples were extracted from the ribs (walls). The coal tended to be more fractured and broken in the middle and lower sections of the seam closest to a claystone layer within the lower third of the coal seam.

The mine is a room-and-pillar operation. In the sample locations, the pillars are square and typically 50 feet on a side (w/h = 10). Rooms are generally 18 to 20 feet wide in the entries and 21 to 24 feet wide in the panels. The extraction ranges from 45% to 55%.

Mine 2 Also located in the southeastern part of the Illinois basin, Mine 2 extracts the Herrin Coal at a depth of about 440 feet. The block samples were taken from room-and-pillar portions of the mine.

The Herrin Coal is underlain by a 0.5- to 2-foot thick layer of claystone (underclay) that is a fractured, slickensided, and low-strength rock. In the undercut area, the claystone exhibits brittle behavior (stress slabbing, deterioration, and rashing) at the exposed surface of the pillar. The moist claystone shows no visual evidence of floor heave in the study areas.

The roof above the Herrin Coal is a 0.5- to 3-foot thick layer of black shale (Anna Shale). The Brereton Limestone overlying the shale is typically 3 to 5 feet thick. In some areas, the limestone is absent and, in others, the Energy Shale is present in the roof. Roof falls have developed in the Anna Shale up to the base of the limestone. High roof failures (up to 10 ft) have occurred where the limestone is absent and the roof wet. The shale is brittle, and slabs and blocks formed by joints and stress-induced fractures are present in the sample areas. In at least one location of the upper level workings, steel trusses and rock bolts have been used to stabilize the roof. In situ stress measurements that Ingram and Molinda (1988) performed in the rocks at mine level show high horizontal stresses with typical K_o values (ratio of maximum horizontal to vertical stress) of 3 and orientation generally east to west.

At the sample locations, the coal is 65 inches thick and contains a 3-inch-thick fusain layer in the upper third of the seam. Cleats are typically spaced 1/2 to 1 inches apart. The distressed zone in 3-year-old pillars is 0.5 to 2 feet deep. Near-surface pillar slabbing typically has occurred to a depth of 1 to 2 feet. There is no evidence of pillar failure in the sample areas of the mine.

Samples of the Herrin Coal were obtained from the upper portion of the seam. Care was taken to select representative locations that did not show evidence of fracturing within the block. Mine personnel report measured unconfined compressive strengths of 2500 to 4500 psi for the Herrin Coal.

The pillars at the sample locations are square and vary in dimension between 55 and 58 feet on a side (w/h = 10.2 to 10.75). Room widths are typically 17 to 20 feet and the extraction is 40% to 46%.

Mine 3 The third set of samples was taken from a mine in west-central Illinois. The mine operates in the Herrin Coal at a depth of approximately 315 feet. The coal has an average thickness of 7 feet and is extracted using room-and-pillar techniques. Block samples of coal were taken from three locations in one area of the mine.

The coal is underlain by 10 to 12 inches of claystone that, in some layers, is essentially clay. At the sample locations, the claystone is gray, soft to stiff, plastic, wet, and contains numerous slickensided surfaces that dip roughly 30° from horizontal. The lower portion of the claystone appears to be stronger than the 0.3-foot thick layer immediately below the coal. Slickensided surfaces are spaced 0.1 to 0.2 feet apart. A 1-inch-thick discontinuous coal seam is present at various elevations in the claystone. Floor squeeze has occurred in some portions of the mine and squeeze behavior controls the performance of the workings.

In Mine 3, the Herrin Coal is typically overlain by a dark gray to black Anna Shale below the hard gray Brereton Limestone. At the sample sites, the shale ranges from 24 to 36 inches thick and is slickensided across the horizontal bedding. Mine personnel report roof falls and loose blocks in areas where the limestone is absent. The shale is brittle and exhibits loosening behavior and some localized stress slabbing.

The Herrin Coal is strong relative to coal at the other mine locations; as such, samples were very difficult to extract from the pillars. At the sample locations, the coal is 7 feet thick and bedded; bedding plane partings are spaced 0.3 to 1.2 feet apart. Pyrite is present primarily in the middle third of the coal seam. Cleat spacing ranges from 1 to 4 inches, and many of the cleat surfaces were observed to be wet. The coal samples were taken from the same general areas of the mine where floor behavior studies have been carried out by other investigators in the Illinois Mine Subsidence Research Program.

The pillars are typically square (50 ft on a side), although some are slightly rectangular (40 × 50 and 50 × 60 feet; w/h = 5.71 to 7.14). Rooms are 20 feet wide and the extraction is roughly 50%.

TEST RESULTS AND CORRELATIONS

The sealed block samples were transported from the mines to the rock mechanics laboratory at the University of Illinois and stored in a wet room to prevent deterioration and breakdown of the coal. (The wet room is maintained at a constant temperature of 73°F and 100% relative humidity.) The blocks were then cut with a diamond-tipped rock saw; water was used as a lubricant. Specimens were cut to widths ranging from 1 to 6 inches, and samples were made into cubes or prisms. Each specimen was subjected to a unconfined compressive strength test; 135 specimens were tested.

Testing Procedures

Unconfined compressive strength was tested using a Tinius-Olsen machine at the Illinois State Geological Survey. The machine has a load range of 300,000 pounds. Load is measured using one load cell beneath the lower platen, and vertical displacement is determined using a linear variable displacement transformer (LVDT) unit between the two platens. Horizontal displacements on each side of the cubes were measured with LVDTs. Load displacement output data were collected on a portable computer. Sample preparation followed ASTM 4543, except for the guidelines on sample dimension ratios. Strength testing followed ASTM 2938.

Correlations Between Compressive Strength and Sample Geometry

In this study, the geometry of the specimens is defined using the width-to-height ratios of the tested samples. The width is the minimum dimension normal to the applied load and the height is the dimension of the specimen in the direction of load. Seventeen samples were tested for Mine 1, 25 for Mine 2, and 94 for Mine 3.

Size Effect

Unconfined compressive strength test results on 1-, 2-, 3-, and 4-inch cubes representing the three study sites are summarized in table 3 and on figure 2. The average cube strength values for the mines are roughly comparable, but Mine 1 has a larger range of strength values than

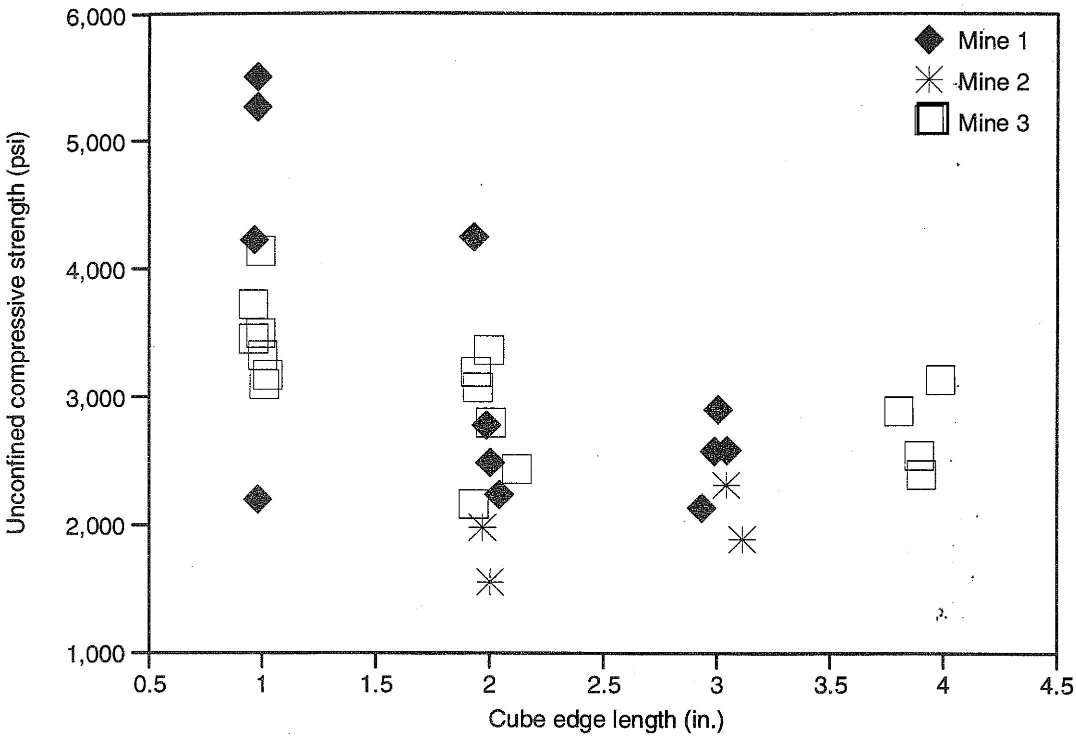

Figure 2 Strength of Herrin Coal cube samples in this study.

Mine 3 has for cubes comparable in size. The range of strength values from Mine 1 is three times greater for the 1-inch cubes and about two times greater for the 2-inch cubes. The difference in range of strength values illustrates the variation in intact coal strength influenced by the cleat spacing (discontinuity density) of 0.12 to 0.25 inch for Mine 1 versus 1 to 4 inches for Mine 3. The cleat spacing in Mine 1 is less than the cross-sectional dimension of the 1-inch-squared samples. Observations and test results indicate higher strengths where the specimen contained no or poorly developed cleats. Conversely, lower strengths were measured where cleats were present in the sample. Such conditions are most likely to develop where the cleat spacing is less than or approaches the sample size. Some specimens contain cleats, whereas others do not contain discontinuities or potential vertical failure surfaces. Variations in size and volume of samples has no observable effect on the tangent modulus values for the study.

These strength values for cubes are consistent with previously published results for Herrin Coal. Chugh and Singh (1985) reported a range in strength of 3226 to 4907 psi for 2.5- to 3-inch cubes. Scher (1979) reported a range of 2432 to 8044 psi and an average of 5347 psi for 69 1-inch cubes. Talbot (1907) reported a range of 1000 to 1346 psi and an average of 1,173 for 1-foot cubes. Figure 3 shows how all of these samples compare with those from this study.

Shape Effects

The effect of shape on unconfined compressive strength was investigated by comparing the variation in strength with various width-to-height (w/h) ratios for samples with (1) 4 × 4-inch cross-sectional areas, (2) constant heights of 2 inches and various square cross-sectional areas, and (3) various widths and lengths that have 4 in.^{2} of cross-sectional area. Figure 4 shows the data for the ratio of prism strength to cube strength for various width-to-height ratios for samples with a 4 × 4-inch base. The limited data indicate that for lower w/h ratios, the prism/cube strength = 0.7 + 0.3 (w/h) formula matches; and for higher ratios, the p/c = 0.56 +0.44 (w/h) formula matches. For constant height samples of 2 inches (fig. 5), the relationship p/c = 0.8 + 0.2 (w/h) is the best match. For samples with a variation in width and length equaling a constant cross-sectional area of 4 inch^2 and various heights, the best match is provided by the p/c = 0.64 + 0.36 (w/h) formula (fig. 6).

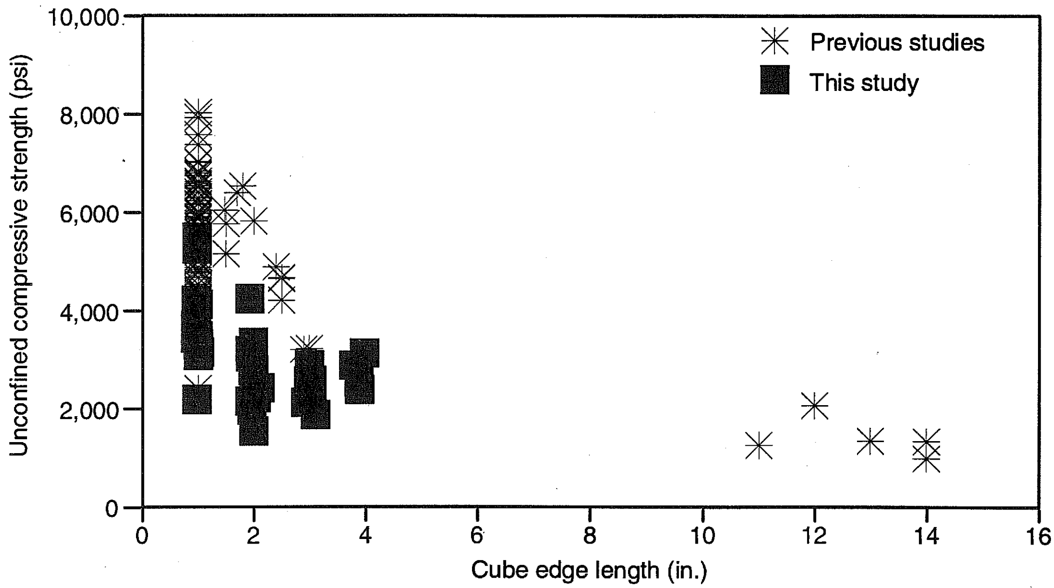

Figure 3 Strength of Illinois coals, as determined from this and previous studies.

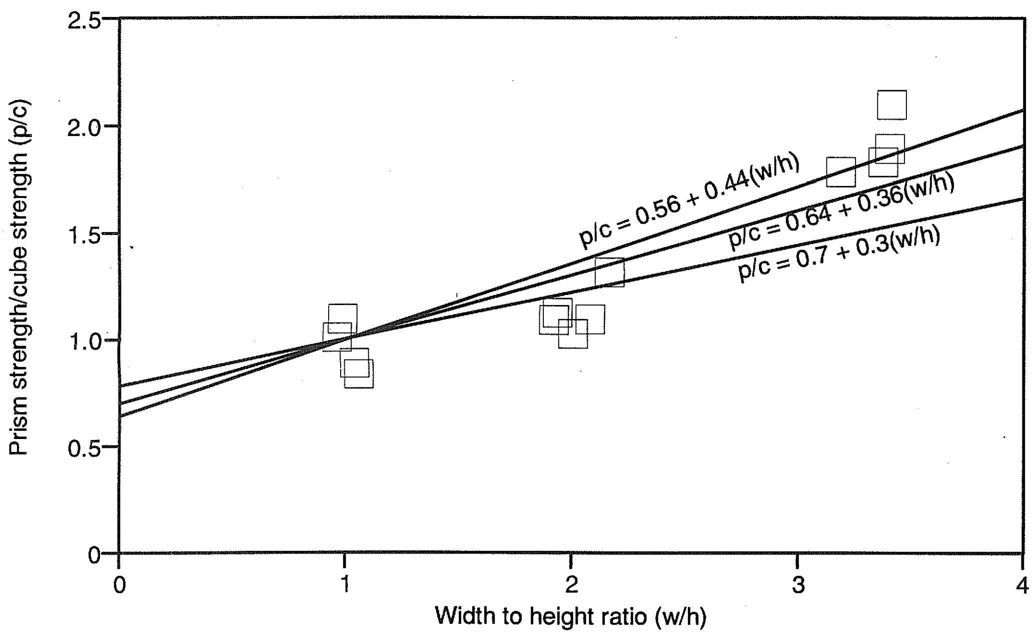

Figure 4 Relationship of strength to variations in shape for Herrin Coal samples with a constant square base of 4 × 4 inches.

Mechanical Properties

The test results typically yield a large variation in compressive strength of the coal, particularly for w/h values less than 1 and a minimum width of 1 inch. For example the unconfined compressive strengths at w/h = 0.5 for 1-inch-wide samples cover almost the full range of strength values given for the Herrin Coal in the Illinois Basin.

The effect of cleats and layers of minerals on coal strength is also greatest on samples with w/h ratios less than 1 because of the failure mechanisms in unconfined compression. When the height exceeds the width of a coal sample, failure typically occurs as a result of

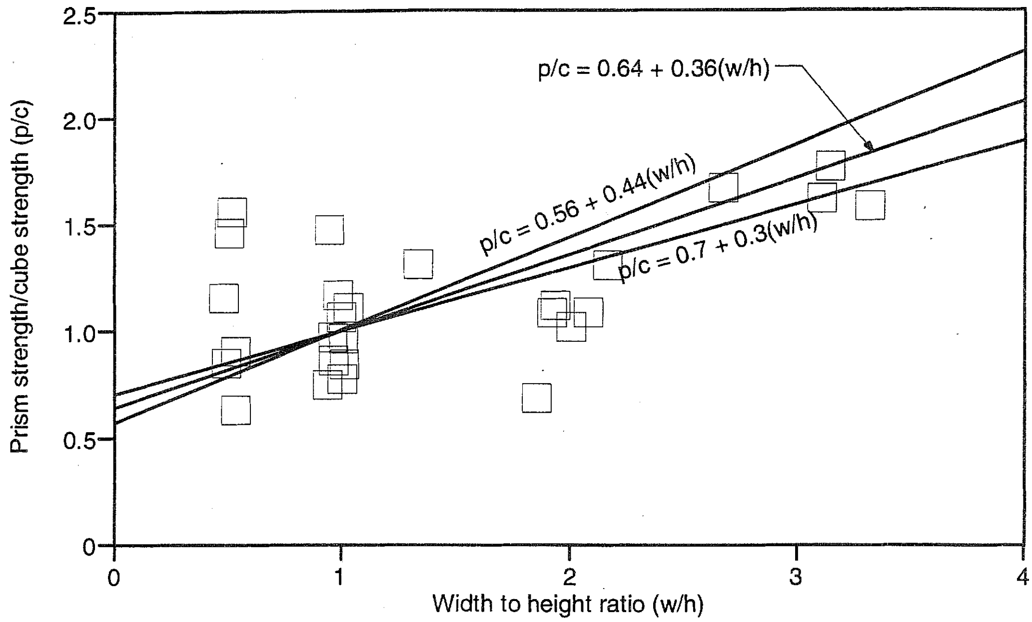

Figure 5 Relationship of strength to shape for Herrin Coal samples with a constant height of 2 inches.

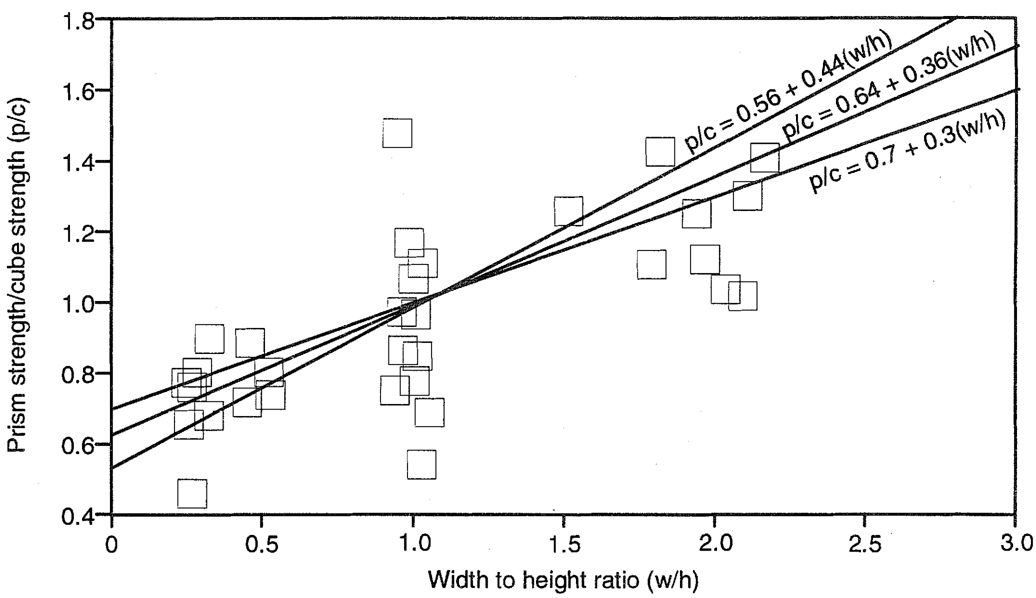

Figure 6 Relationship of strength to shape for Herrin Coal samples with 4-inch^2 cross-sectional areas.

tensile splitting and compressive/diagonal shear. Cleats and layers of mineral tend to facilitate splitting failures by reducing the axial tensile strength and permitting lateral displacement/failure of the specimen. The net effect is a reduction in the compressive strength, as compared with a noncleated specimen from the same block sample. Again, when the cleat spacing approaches the cross-sectional dimensions of the sample, large variations in coal strength are likely to occur where cleats can affect or control the minimum strength of the sample. At w/h greater than 1, the impact of cleats and partings on strength is reduced because the sample tends to be in confined compression in the elastic range, at least near the core giving more representative strength values for pillar geometries.

CONCLUSIONS

Results from this study reconfirm Holland's (1973) findings on minimum sample size. This study found that coal samples should have a minimum dimension of at least 2 inches to provide a realistic strength estimate from a limited number of samples. For samples 2 inches or larger, the difference in the maximum and minimum intact strength at a given location is generally less than 1000 psi. One-inch samples may be adequate, but in all cases the w/h ratio should exceed 1.

Cleat spacing has a large impact on variations in strength of testing samples. Sample sizes that are not greatly influenced by the cleat spacing should be selected. Sample size should be determined on a site-by-site or mine-by-mine basis, depending on the consistency of the cleat spacing.

Strength of coal samples should be determined on a mine-by-mine basis. Areas within individual mines may also warrant strength determinations, if cleat spacing, mineral assemblages, or other coal seam conditions change.

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A FIELD GEOTECHNICAL STUDY OF THE PERFORMANCE OF COAL PILLARS IN A ROOM-AND-PILLAR MINE IN THE ILLINOIS COAL BASIN

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Summarized by Nelson Kawamura

ABSTRACT

Field geotechnical studies at two sites 560 feet apart in a room-and-pillar mine in the Illinois Basin examined the performance of coal pillars where weak floor strata underlie the coal seam. At each site, the pillar was instrumented with multiple position borehole rod extensometers (MPBX), vibrating wire stressmeters (VWS), and a rectangular set of points to monitor stresses and displacements. An MPBX was also installed in the floor to measure lateral displacements; sets of convergence points were placed in entries and intersections around the instrumented pillar and across the panel to measure roof-to-floor convergence; and surface monuments were installed at one site. Monitoring data indicate that the yielded zone extends 6 to 8 feet into the pillar and presents an in situ deformability modulus of about 67,000 psi. For the preliminary estimate of the extent of the yielded zone, Wilson's approach is suggested.

INTRODUCTION

The performance of coal pillars is adversely impacted by weak floor strata that typically underlie coal seams in the Illinois Basin. The weak floor strata govern the design of mine layouts to a depth of about 600 feet (Chugh et al. 1990).

Most studies related to in-mine performance of coal pillars in the United States have been conducted in the Appalachian and western coalfields (Holland 1964, Newman 1988, Bieniawski 1983, Lu 1986, Peng 1986). In the recent past, Hanna et al. (1985), Chugh (1986), and Chugh et al. (1986) have attempted similar studies, with limited scope, in Illinois Basin coal mines. Additional studies are required to better understand the performance of coal pillars where weak floor strata underlie the coal seam. This research, under the sponsorship of the Illinois Mine Subsidence Research Program, was undertaken with the specific objectives to (1) monitor vertical and horizontal stresses and displacements in two pillars during and after mine development; (2) determine the confined core and yielded zones within pillars; (3) determine in situ deformability modulus of coal pillars; (4) correlate underground movements with observations of surface subsidence, and (5) make visual observations of ground conditions and pillar performance in mining areas.

MINE CHARACTERISTICS

The mine selected for the study is located in the Illinois Basin and extracts a 5.8-foot-thick coal seam at a depth of about 150 feet. The overburden strata are mainly sandy shales and sandstone, and the immediate roof stratum is gray sandy shale that is relatively competent. The 5- to 9-foot-thick weak floor strata are basically interbedded shales and claystone underlain by relatively strong interbedded dolomite.

The mining panels are approximately 400 feet wide and 1,000 to 1,500 feet long; pillars are 50 × 60 feet center to center; and entry and crosscut widths are 18 feet (extraction factor, e = 43%). The land overlying the mine is mainly used for agriculture, but gas and other pipelines run through the mining property.

FIELD GEOTECHNICAL STUDIES

Geotechnical studies were carried out at two underground mine sites located in the same panel. These sites, identified as Sites 1 and 2, were 560 feet apart. At each site, the following instruments were installed:

- multiple position borehole rod extensometers (MPBX) in the coal pillar and the weak floor stratum immediately beneath the pillar to monitor lateral displacements of the pillar and the floor;
- vibrating wire stressmeters (VWS) in the pillar at different distances from the pillar rib to monitor changes in vertical and horizontal stress;
- a rectangular set of points on the pillar side to measure vertical and horizontal deformations of the coal pillar;
- sets of points in entries and intersections around the instrumented pillar and across the panel to measure roof-to-floor convergence;
- a surface subsidence monitoring network over Site 2.

All instruments, except a few sets of convergence points, were installed when only one side of the selected pillar had been mined and before the other three entries surrounding the pillar were developed. Brief descriptions of the instruments, test procedures, data collection, and data analyses are presented below.

Borehole Shear Tests

Location	Weak floor strata
Materials	Interbedded shales and claystone
Parameters	Cohesion and internal friction angle (peak and residual) for calculating the ultimate bearing capacity (UBC)
Apparatus	Rock borehole shear tester inserted in a 3-inch-diameter borehole
Tests	For each depth, 3 to 5 shear tests with normal stresses, which ranged from 150 psi to 400 psi

Pillar Stress Changes

Location	Pillar, at midheight
Materials	Coal
Parameters	Horizontal or vertical stress changes
Instrument	Vibrating wire stressmeter (VWS), two at Site 1 (9 and 18 feet inside the pillar) and seven at Site 2 (1 to 14 feet inside the pillar)

Roof–Floor Convergence

Location	(1) corners of the coal pillars, (2) middle section of the pillars but along the entry edges, (3) center of the opening, and (4) intersection of the crosscut and entry
Parameters	Convergence rate
Instruments	⅝-inch-diameter, 6- to 12-inch-long bolt
Apparatus	Tape extensometer
Convergence points	28 sets at Site 1, 27 sets at Site 2

Horizontal Differential Movements Across the Pillars

Location/material	One at midheight of the coal seam, approximately 20 feet from the pillar rib, and the other at the same distance from the pillar rib but in the floor stratum immediately below the coal seam
Parameters	Horizontal differential movements
Instrument	Multiple position borehole rod extensometer (MPBX) sonic probe (Irad Gage, Inc.)
MPBXs	Two at Site 1, two at Site 2

Pillar Deformations

Location/material	Coal pillar near the rib, at Site 2
Parameters	Vertical and horizontal deformations
Instruments	Three pieces of rebar set in a rectangle into the pillar rib (at each point, a 1.5-foot-deep hole was drilled into the pillar and a ¾-inch rebar grouted with cement into the hole)

Surface Subsidence

Location	Surface above Site 2
Parameters	Surface subsidence
Instruments	Nine tiltplates, 38 monuments, and two benchmarks installed 300 to 350 feet outside the panel
Apparatus	Autoset level tiltmeter

RESULTS AND DISCUSSION

Laboratory Study

Lithologic Description of Floor Strata The immediate floor strata generally consist of underclay and interbedded shale and dolomite. The shale is carbonaceous, dark brown to black, moderately to well indurated, laminated, slightly fissile, micaceous, and slickensided throughout. The first 2 inches (0.17 ft) of this unit is a poorly developed carbonaceous clay. It becomes pyritic from 8 to 20 inches (0.7 to 1.7 ft), arenaceous from 4.8 to 5.1 feet, and dolomitic from 6.3 to 9.3 feet. The shale is underlain by interbedded shale and dolomite, which have no apparent structure. Magnesium oxides coat fractures in this unit.

Geotechnical Data The moisture content of the shale in the floor at Site 2 generally ranges from 5% to 10%, whereas the dolomite has only about 2% moisture. The values of unconfined compressive strength (C_0) for the shale range from 200 to 400 psi. The underlying dolomite has C_0 values about 10 times higher than those of the shale. The indirect tensile strength data vary between 0.25 and 0.5 times the C_0 values for shale. The weak floor strata may be classified as CL to ML, based on the Unified Soil Classification System. The equations for using moisture content (MC) to estimate the ultimate bearing capacity (UBC) and deformation modulus at 50% of the UBC (DM_{50}) for a 12-inch-square plate load test are given below:

$$UBC = e^{(7.38 - 0.145\,MC)} \tag{1}$$

where UBC = value in psi
MC = value in %

$$DM_{50} = e^{[10.88 - 0.47\ln(MC)]} \tag{2}$$

where DM_{50} = value in psi

The estimated UBC is 578 psi and DM_{50} is 21200 psi, based on the average moisture content of 7% for the immediate floor stratum. These values compare favorably with the average measured value of 584 psi for UBC and 19400 psi for DM_{50} resulting from a previous study conducted in the same mine (Chugh and Pytel 1990).

Field Geotechnical Studies

Borehole Shear Test (BST) Data At Site 2, BSTs were conducted to approximately 9 feet below the coal seam. The cohesion typically ranges from 50 to 110 psi, with an average value of 90 psi and a standard deviation of 32 psi. The angle of internal friction ranges from 18° to 39°, with an average value of 29° and a standard deviation of 9°.

Roof–Floor Convergence There were four categories of convergence points: (1) corner points at corners of coal pillars; (2) middle points at the middle section of the pillars but along the entry edges; (3) side points at the center of the opening; and (4) center points at the intersection of the crosscut and entry. Data for each category were anaylzed separately.

The average convergence rate at Site 1 during the first 30 days was within a small range of 0.024 to 0.034 inch per day, regardless of the location of the points. These data indicate that settlement of the pillar into weak floor strata was approximately uniform. During the next 30 days, the average convergence rate decreased to 0.003 to 0.009 inch per day. At Site 2 during the first 30 days, the average convergence rate was 0.107 inch per day in side points, about 0.060 inch per day in corner and middle points, and 0.089 inch per day in center points. The average convergence rate, independent of the location of the points, decreased to approximately 0.025 inch per day during the next 30 days.

The convergence at Site 2 was significantly higher than that at Site 1. The causes were probably wet conditions and the geologic structure at this site. Dripping water was observed at several locations at Site 2. A small anticlinal structure with a difference in elevation of 3 to 4 feet was also found near Site 2, approximately two crosscuts away.

Because there was no significant difference in the convergence rate at different locations around a pillar, the average convergence data for Sites 1 and 2 as a function of time are defined. These data were analyzed in terms of the standard Burger's model to determine time-independent and time-dependent deformability parameters of weak floor strata (Chen and Chugh 1990). For coal pillars on weak floor strata, this equation was developed:

$$C = 1.9\,\gamma\,h\,T\,(1 - \mu^2)\,[1/k_2 + 1/k_1\,(1 - e^{(-k_1\,t/\eta_1)}) + t/\eta_2] \qquad (3)$$

where

C = roof–floor convergence since development of the pillar (in.)
γ = average overburden density (pounds/in.^{3})
h = overburden depth (in.)
T = thickness (in.) of weak floor strata (less than half the pillar width)
μ = Poisson's ratio (assumed 0.35)
t = time since development of pillar (hours)
k_1, k_2 = viscoelastic parameters (in psi)
η_1, η_2 = viscoelastic parameters (in psi-hour)

A nonlinear regression procedure used for the model fitting shows an excellent agreement between the predictive model and the observed data. The viscoelastic parameters k_1, η_1, η_2 estimated from in-mine roof-floor convergence data at Site 1 are 26000 psi, 2.83×10^6 psi-hour, and 4.01×10^7 psi-hour, respectively. At Site 2, the corresponding values are 14700 psi, 1.71×10^6 psi-hour, and 1.69×10^7 psi-hour. If it is assumed that almost all convergence is due to deformation of weak floor strata, these parameters represent time-independent and time-dependent deformability parameters of weak floor strata.

Horizontal Differential Movements Across Coal Pillars Some MPBX anchors near the pillar rib showed large differential movements that were probably due to the development of cracks near the pillar ribs. The differential movements were generally larger at Site 2 than at Site 1, probably because of the geologic and hydrologic conditions indicated earlier. Analysis of the data indicated the presence of two zones, both in the coal pillar and the floor strata: a zone of large displacements and a zone of small displacements. The two zones represent the intact zone in the center of the pillar surrounded by a yielded zone near the pillar rib. The boundary between these two zones is located about 6 to 8 feet from the pillar corner.

Pillar Stress Changes The cells at Site 1 indicated a significant increase in stress in both horizontal and vertical directions during the development of the pillar. The vertical cell, 18 feet from the pillar rib, recorded an increase of 100 psi. The horizontal cell, 9 feet from the pillar rib, recorded a stress increase of 400 psi. Both VWSs indicated a slight drop in stress afterwards and then remained approximately constant during the next 60 days.

At Site 2, during pillar development, all the cells except the vertical cell at the center of the pillar showed a decrease rather than an increase in stress. The vertical stress at the center of the pillar increased approximately by 100 psi and then dropped by 80 to 90 psi in a short time. All the other cells, including three vertical cells 1 to 10 feet from the pillar rib and three horizontal cells 5 to 14 feet from the pillar rib, registered a decrease in stress ranging from 100 psi to 400 psi. These stresses continued to drop slowly during the next 60 days. This pillar was probably incapable of taking an additional load because the immediate floor strata had been weakened by water.

Pillar Deformations Computed from Displacements Measured with a Rectangular Set of Points After 50 days, the horizontal displacement was approximately 60% of the vertical displacement. Because the lengths of the vertical and horizontal components of the set of points were approximately the same, the ratio of the horizontal strain to the vertical strain was about 0.6. This is not unreasonable, considering discontinuities in the coal seam.

The overburden depth was approximately 120 feet and the extraction factor 0.43; therefore, the average stress increase due to the pillar development was approximately 235 psi. A vertical strain of 0.0035 for the pillar was calculated, based on the assumption that the total time-independent vertical displacement from the set of points was 0.09 inch. (The length of the vertical component of the rectangular set of points was 26 inches.) The in situ Young's modulus for the coal pillar may, therefore, be equal to 67,000 psi. This value, based on data from the rectangular set of points, may be reasonable in the yielding zone. For the intact coal pillar, a value of 85,000 psi to 100,000 psi may be more appropriate.

Surface Subsidence and Its Correlation with Underground Movements At the end of 70 days after mining at Site 2, a maximum subsidence of 1.1 inches was observed on the surface.

The subsidence characteristics at this site are given below:

Maximum subsidence	1.1 inch (after 70 days)
Angle of draw	49°
Subsidence factor	0.016
Offset of inflection point	17 feet

Because the surface was still subsiding, the final subsidence factor was expected to increase.

A convergence monitoring line with eight points was installed at Site 2, approximately parallel to the surface subsidence monitoring line. Because the local geological and hydrological conditions significantly affected the roof–floor convergence, the convergence along the line was irregular. A direct comparison between the convergence and the surface subsidence was, therefore, difficult.

ANALYSES OF PILLAR AND FLOOR STABILITY

The analysis is based on the progressive failure theory of coal pillars, as proposed by Wilson (1977, 1981, Wilson and Ashwin 1972). The width of the pillar yield zone and the strength of the pillars are calculated using Wilson's formula and compared with the field data observed in this study. The bearing capacity of the floor strata underneath full-size pillars was estimated using the Vesic-Speck (Speck 1981) approach.

The following parameter values are used in this analysis. Some are based on a previous study (Chugh and Pytel 1990). Where the parameter values are not available, typical values for the mining area are used:

Mining height (H)	5.8 feet
Overburden density (γ)	160 pcf
Overburden thickness (h)	120 feet
Triaxial factor (q)	3.0
Unconfined pillar strength (S_1)	420 psi
Pillar width (W)	32 feet
Pillar length (L)	42 feet
Entry width (W_0)	18 feet
Cohesive strength of floor (S_0)	90 psi
Weak floor strata thickness (T)	7 feet

The field observed data mentioned before indicated the yield zone to extend approximately 6 to 8 feet into the pillar rib, as compared with the 5.5 feet indicated by Wilson's analysis.

The coal pillar bearing capacity was also estimated utilizing the progressive failure theory, and the safety factors were calculated (Wilson 1981, Mark 1990). The results of the pillar stability analysis using the above approach are presented below:

Bearing capacity	420 psi
Average stress on pillar	300 psi
Safety factor	1.4

The results using the Vesic-Speck (Speck 1981) approach are presented below:

Bearing capacity	380 psi
Average stress on pillar	300 psi
Safety factor	1.3

Pillar and floor safety factors are approximately the same at this mine because the coal is relatively weak and its strength values are approximately equal to those of the weak floor stratum underlying the coal seam.

CONCLUSIONS

- At Site 1, a vertical stress increase of 100 psi was measured 18 feet from the pillar rib during the development of the pillar; the increase in horizontal stress 9 feet from the rib was 400 psi. At Site 2, wetting of weak floor strata significantly reduced its deformability; therefore, the roof-to-floor convergence increased and the pillar's ability to carry load decreased. Vertical cells 1 to 10 feet from the pillar rib and horizontal cells 5 to 14 feet from the pillar rib recorded stress decreases of 100 psi to 400 psi during the pillar development.
- Differential horizontal displacement data in the coal pillars indicate the presence of an outer yielded zone and an inner intact zone. The extent of the yielded zone predicted by Wilson's approach agrees well with the measured values, which were within the range of 6 to 8 feet into the pillar.
- Rectangular sets of points provide reasonable estimates of in situ deformation modulus of coal in the yielded zone, which in the study mine was about 67,000 psi.
- The differences between pillar settlements and surface subsidence would indicate bedding separations in the bedrock, perhaps below the sandstone bed. This should be checked with an instrumented borehole from the surface.
- Pillars at this mine are stable, as observed in the mine; however, the pillars are slowly settling into weak floor strata, thus producing increments of areal subsidence on the surface.

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ULTIMATE BEARING CAPACITY OF WEAK FLOOR STRATA UNDERLYING FULL-SIZE LONGWALL CHAIN PILLARS

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ABSTRACT

Surface and underground instrumentation was used at three sites 1,000 to 1,500 feet apart at two longwall coal panels in Franklin County, southern Illinois. The purpose was to examine design techniques for coal pillars associated with weak floor strata. Surface monuments were used to determine surface vertical and horizontal displacements. Underground instrumentation was used to monitor roof-to-floor convergence, pillar deformation, pillar loads, roof sag, and floor deformation. Plate loading tests were also carried out to determine the ultimate bearing capacity (UBC) of weak floor strata. This study illustrates the possibility of using the Pytel–Chugh (1990) approach to estimate the UBC underneath a longwall chain pillar. For the prediction of surface subsidence and stress distribution in longwall mines, the Longwall Ground Mechanics (LGM) model may be useful.

INTRODUCTION

The design of coal pillars associated with weak floor strata is extremely important in Illinois Basin coal mines. Actively mined coal seams are locally associated with 2- to 5-foot-thick, weak claystone beds underlying the seam (Chugh, Phillips et al. 1990). The design is currently based upon the ultimate bearing capacity (UBC) of the weak floor strata and does not account for settlement. Pillar settlements on weak floor strata with associated floor heave in mine openings may result, however, in changes to the geometry of mine roadways; differential settlement of pillars; failure of roof, pillar, and floor; and surface and subsurface ground movements. It is important, therefore, that pillar designs for conditions of weak floor strata be based on bearing capacity as well as on pillar settlement.

The goal of this study was to develop validated techniques for designing coal pillars where coal seams are associated with weak floor strata. Specific objectives of this research were as follows:

- to verify and/or to develop size reduction factors for the strength and deformability of weak floor strata;
- to identify appropriate techniques for calculating the UBC of full-size pillars in room-and-pillar and longwall mines;
- to develop time-independent and time-dependent deformability parameters for weak floor strata at the study mine (parameters to be based on observed roof–floor convergence and floor deformations as a function of time);
- to use a three-dimensional model based on roof–pillar–floor interaction for predicting surface settlements, pillar loads, and pillar settlements in room-and-pillar and longwall mining; and to compare the results with corresponding field-observed values.

In 1991, under the sponsorship of the Illinois Mine Subsidence Research Program and U.S. Bureau of Mines, the authors initiated a study to establish the UBC and deformability of large pillars by instrumenting longwall chain pillars. In January 1992, an Illinois coal company agreed to cooperate in the study; the research was conducted at their mine in Franklin County in southern Illinois. The study involved both surface and underground instrumentation and monitoring, data analysis, and predictive analytical modeling.

REVIEW OF LITERATURE

Effect of Test Specimen Size on the Bearing Capacity of Weak Floor Strata

Typically, the weak floor strata immediately under a coal seam in the Illinois Basin contain planes of weakness and other discontinuities. There are more discontinuities in larger than in smaller areas, therefore the bearing capacity of larger areas is less than that of smaller areas.

Chugh, Pytel, and Pula (1990) obtained the following statistical relationship between UBC and plate size for seven mines in Illinois:

$$UBC = 1941.08\ B^{-0.466} \tag{1}$$

where

B = width of the plate (in.)
UBC = value in psi

Estimation of the Bearing Capacity of Weak Floor Strata Underlying Full-Size Pillars

Most available techniques permit calculating UBC for homogeneous floor strata conditions, assuming infinite thickness of weak floor strata (Pytel 1988). A broad analysis of these techniques (Pytel et al. 1988; Chugh, Phillips et al. 1990; Haq 1990) has indicated that the UBC of full-size pillars on layered strata that have a weak layer overlying a stiff layer may be calculated using the approaches of Vesic (1970), Vesic-Speck (Speck 1981), Pytel-Chugh (1990), and (4) Vesic-Chugh/Haq/Chandrashekhar (CHC).

Data acquired during 5 years of field work in a large number of Illinois mines form the basis for proposing this relationship between UBC and natural moisture content (MC) of the weak floor strata down to a depth of 12 inches below the coal seam (Chugh et al. 1993):

$$UBC = e^{(7.38\ -\ 0.145\ MC)} \tag{2}$$

where

UBC = value in psi
MC = value in %

Estimation of the Deformability of Weak Floor Strata Underlying Full-Size Pillars

Reasonable time-independent deformability parameters for weak floor strata can be determined only through plate loading tests. A large number of such tests have been conducted by the Department of Mining Engineering at Southern Illinois University in the last few years. A correlation between the tangent modulus of deformability at 50% of the failure load (DM_{50}) and moisture content based on statistical analyses was developed, assuming homogeneous

$$DM_{50} = (e^{15.857})\,/\,(MC)^{0.47} \tag{3}$$

weak floor strata of infinite thickness:

where

DM_{50} = value in psi
MC = value in %

Chen and Chugh (1990) attempted to estimate the field time-dependent parameters of weak floor strata from short-term incremental plate loading tests and to compare these estimates with those determined from in-mine convergence data and laboratory incremental creep studies. A simplified mathematical equation, based on the Burger's model, was developed as follows (Chen and Chugh 1990):

$$w = 0.95\sigma\, B\,(1 - \mu^2)\,\{1/E_2 + 1/E_1\,[1 - e^{(E_1\, t/\eta_1)}] + t/\eta_2\} \quad (4)$$

where

w = displacement under the plate (in.)
σ = constant average stress on the plate (psi)
μ = Poisson's ratio
B = width of the plate (in.)
t = time (days)
E_1, E_2 = elastic parameters
η_1, η_2 = viscoelastic parameters

The parameters (E_1, η_1, and η_2) indicate a stress-dependent pattern. In general, the parameter values decrease as stress levels increase.

E_1, E_2 = value in psi
η_1, η_2 = value in psi-days

Time Effects on Surface Subsidence

The effect of time on surface subsidence varies depending on factors such as overburden conditions, extraction depth, caving height, gob compaction characteristics, and backfill forms.

Yu et al. (1993) developed the following relationship between subsidence and time for a longwall mine in the Illinois Basin:

$$S = 1/2\, S_{max}\,\{1 - \tanh[(t - T/2)/C]\} \quad (5)$$

where

S = subsidence of a surface point at time t (in.)
S_{max} = maximum subsidence of the point at time T (in.)
T = total time for a subsidence cycle, defined from the time when the face enters the influence area to the time when the face leaves it (days)
C = a constant (days)

Both T and C are empirical parameters that depend upon overburden thickness, material properties, and geological conditions. For the study area, the values of T and C were 100 days and 6 days, respectively.

Prediction of Surface Subsidence and Pillar Loads Based on Roof–Pillar–Floor Interaction

A reliable estimate of the floor safety factor (ratio of floor UBC and actual load acting on the pillar) requires a fundamental understanding of the roof–pillar–floor interaction in the time domain. This is the basic condition for predicting time-dependent surface and subsurface movements as well as load transfer in different parts of the mine. The distribution of loads and displacements around the mine workings can be calculated through an approximate three-dimensional analytical technique (SIU PANEL.3D) based either on the theory of plates on an elastic or nonelastic foundation (Pytel and Chugh 1990) or on the Longwall Ground Mechanics (LGM) model (Yang et al. 1993).

EXPERIMENTAL TECHNIQUES

Mine Description and Geology

The mine extracts the Herrin Coal in Franklin County at an average depth of 650 feet. The thickness of the coal in this area varies from 8.3 to 10 feet, which includes a 5- to 13-inch

(0.4- to 1.1-ft) shale parting ("blue band") 18 to 20 inches (1.5 to 1.7 ft) above the base of the coal. Cores from boreholes near this site indicate an immediate roof of black shale, approximately 4.5 to 5.5 feet thick, and a competent thick Brereton Limestone layer immediately above. The underlying floor strata consist of light gray underclay, from 2 to 5 feet, underlain by 10 to 15 feet of hard calcareous shale with limestone nodules throughout. The cores show 30 to 50 feet of glacial materials above the bedrock.

The chain pillars are designed on 120 × 60-foot centers for the headgate of the first panel, and 100 × 60-foot centers for the second panel; the three-entry system had 15.5-foot-wide entries. The pillars are offset at the crosscuts by approximately 15 feet. The longwall face is 960 feet wide and 7,000 feet long east to west.

Field Geotechnical Studies

Subsidence Instrumentation The surface subsidence monitoring networks extended over two longwall panels and were located at three sites 1,000 to 1,500 feet apart. Site 1 consisted of four lines: one main line across the first panel and three longitudinal lines at the center of the panel. Site 2 had only one line across the second panel. Site 3 consisted of a main line across the panel and two longitudinal lines at the edge of the second panel. The monuments were located at 60-foot intervals around the center of the panel and at 30-foot intervals around the edges of the panel and chain pillars.

Each subsidence monitoring point consisted of a 7-foot-long, frost-free-designed roof bolt with a diameter of 7/8 inch. Vertical and horizontal displacements were monitored; the vertical displacement was measured by level surveying with second order, Class II accuracy.

Underground Instrumentation The objectives of the underground mine instrumentation were to monitor incremental stress changes in pillars, differential displacements of pillars in the horizontal plane, roof sag, and floor deformations around the pillars as the longwall face approached and passed the instrumentation site. In addition, plate loading tests were conducted on weak floor strata.

Pillar stress changes were measured with vibrating wire stressmeters (VWS) installed in boreholes drilled for this study at Sites 1, 2, and 3. The VWS were preloaded up to between 100 and 200 units above the no-load gauge reading. Stress change was calculated from the following equation:

$$\sigma_r = (422400/T_0)^2\ [1 - (T_0/T)^2 / (11.4 - 0.66 \times 10^{-6}\ E_r)] \qquad (6)$$

where

σ_r = stress change in rock (psi)
T_0 = initial meter reading
T = current meter reading
E_r = modulus of elasticity of the rock (psi)

The accuracy of the stressmeter for the measurement range in this study was 2 to 3 psi.

The convergence stations at Sites 1, 2, and 3 were installed around the two instrumented chain pillars. Bolt heads and eye bolts were used as convergence stations. A digital convergence rod and a tape extensometer were utilized to measure convergence. The convergence rod can measure roof-to-floor convergence with an accuracy of ±0.001 inch, and the tape extensometer can resolve to 0.005 inch.

Horizontal pillar deformations were monitored using the multiple position borehole rod extensometer (MPBX) sonic probe manufactured by Irad Gage, Inc. The probe had three components: borehole C-anchors, a probe guide and an expansion shell anchor. A magnet was set in the anchor body and a maximum of ten anchors installed in one hole. PVC pipe running through the anchors functioned as the probe guide tube. The measurement accuracy was approximately 0.5% of the length being measured. The MPBX sets installed in chain pillars at Sites 1, 2, and 3 were 5 to 20 feet long.

Vertical floor deformation was measured with an MPBX and horizontal floor deformation with an inclinometer setup. The Digitilt Inclinometer consisted of a movable sensor in a guide casing, a portable digital indicator, and an interconnecting electrical cable. Boreholes 3 inches in diameter were drilled to 5 feet below the coal seam, and plastic casings 2.75 inches in diameter were installed in the holes at Sites 2 and 3. The annular spacing between the borehole walls and the casing was filled with plaster. The inclinometer had a sensitivity of 10 sec at 0° inclination and a measuring range of ±30° from the vertical. Casing inclination measurements were taken at 1-foot intervals in the borehole. The bottom of the guide casing was considered the stable point, and the displacements were calculated based on that point.

Roof sag was measured similarly to the way convergence was measured, but 5-foot bolts were used. Holes with a diameter of 1.5 inches were drilled into the floor, and bolts with a diameter of 0.875 inch were cemented to the hard floor at the bottom of the holes at Sites 1, 2, and 3.

Laboratory Geotechnical Studies Core samples of weak floor strata were taken at Sites 2 and 3, and the following geotechnical tests were conducted in the laboratory: Atterberg limits, natural moisture content, specific gravity, indirect tensile strength, and unconfined compressive strength with determination of Young's modulus and Poisson's ratio.

RESULTS AND DISCUSSION

Plate Loading Tests

Ten plate loading tests were conducted at Sites 2 and 3: six under as-mined conditions and four under soaked-wet conditions. The UBC was determined using Vesic's failure criterion (1970). The deformation modulus of the immediate floor strata was calculated at 50% of the UBC (DM_{50}) by using the following equation:

$$DM = \Delta P \; D \; (1 - \mu^2)/\Delta W \qquad (7)$$

where

DM = deformation modulus (psi)
ΔP = incremental pressure (psi)
D = equivalent plate diameter (in.)
μ = Poisson's ratio (an average value of 0.35 was taken)
ΔW = incremental plate settlement (in.)

Plate loading tests indicated that UBC decreased as plate size increased. At Site 3, the UBC decreased from 1500 to 700 psi as the plate size increased from 6 to 12 inches. The weak floor UBC under soaked-wet conditions was only about 20% of that under as-mined conditions.

Stress Changes in Chain Pillars

The maximum measured stress change at Site 1 was 620 psi, which was much less than those measured at Sites 2 and 3. This may be attributed to the VWS damage due to mining activity or improper VWS installation. The pattern of stress changes with face retreat at this site was similar to those at Sites 2 and 3. In general, compared with the maximum stresses measured at the three sites, the stress induced by the second panel was probably between 1.5 and 2 times that induced by the first panel.

The stress changes at Site 2 increased rapidly when the face was roughly 200 feet away from the monitoring stations, peaked when the face had passed them for about 100 feet, dropped slightly immediately after that event, and then increased again slowly. The maximum stress change, 1241 psi, was registered closest to the longwall panel. The stresses in the chain pillars typically decreased from the longwall side toward the virgin coal rib. After the longwall face passed, the average stress change in the pillar close to the longwall was 1.8 times that in the pillar close to the virgin coal rib.

The change in stress in the pillars as a function of face position and the decrease of stress from the longwall side toward the virgin side at Site 3 were similar to those at Site 2. The yielded zone in the pillar was between 5 and 15 feet.

Using theoretical and finite element analysis, Yu et al. (1993) developed the following formula to calculate the vertical stress in the abutment zone:

$$\sigma_y = \gamma H/2 \{(1 + m)[1 + (w/x)^2] + (1 - m)[1 + 2.46 (w/h)^{0.4} (w/x)^4]\} \qquad (8)$$

where

- γ = density of the overburden (pcf)
- H = mining depth (ft)
- w = half width of the rectangular opening (ft)
- x = distance from the opening center (ft)
- h = mining height (ft)
- m = $\mu/(1-\mu)$
- μ = Poisson's ratio
- σ_y = value in psf

The parameters for the study mine are as follows:

- H = 650 ft
- h = 7.8 ft
- γ = 160 pcf
- μ = 0.3

The distance H tan β was used as equivalent opening width to calculate the stress, where β is the angle of draw (King and Whittaker 1971). The average angle of draw for the study mine was 20°. Calculated from the parameters above, the maximum stress in the pillar was 2717 psi. The measured maximum stress, plus the original stress and the stress induced by entry development of the entry at Site 3, was 1519 + 1.6 γ H = 2663 psi, indicating the general validity of the formula.

Surface Subsidence

Subsidence Across the Panel The maximum subsidence at the three sites ranged from 5.1 to 5.7 feet, representing subsidence factors of 0.65 to 0.75. The location of the maximum subsidence was skewed toward the tailgate side because of the influence of the adjacent mined-out panel. As the overburden settled, the skewness gradually shifted toward the headgate side. The angle of draw at Site 2 was the largest, thus the corresponding slope and curvature were smaller. This may be because the overburden was stronger at this site than at the other two sites. The maximum tensile strains on the headgate and tailgate sides were located at about 168 and 159 feet from the panel edge for Site 2, and 115 and 120 feet for Site 3, respectively.

Subsidence Along the Panel The location of the maximum tensile strains for the middle, southern, and northern fork lines at Site 1 were 75 feet, 105 feet, and 105 feet behind the face (in the gob area), respectively. The location of the maximum tensile strain for both lines at Site 3 was about 75 feet behind the face, consistent with observations at Site 1. In general, the maximum traveling horizontal strain, slope, and curvature values along the longitudinal direction were less than the static values across the panel. For example, the maximum values for the traveling horizontal strain, slope, and curvature along the middle line at Site 1 were 0.00965, 0.026, and 1.46 mile^{-1}, 51%, 55.3%, and 38% of the static values, respectively. The subsidence data clearly showed the bridging effect at the corner of the mined-out area and suggested that the surface slope along the panel was smaller than that across the panel.

Subsidence as a Function of Time or Face Position In general, the surface subsidence of a point can be divided into three phases:

Phase I Before the longwall face reached the subsurface position directly below the surface point, the subsidence occurred slowly. About 5% to 10% of the total subsidence was induced in this phase.

Phase II This phase began when the face was directly under or slightly past the point and lasted until the face had passed about 250 to 350 feet beyond the point. During this phase, subsidence occurred at an accelerated rate, and about 80% to 90% of the total subsidence was complete at the end of this phase.

Phase III The face advanced beyond the 250- to 350-foot mark in this phase. The subsidence rate reduced exponentially as the distance from the face to monitoring point increased. This condition indicated the development of residual subsidence. About 5% to 10% of the total subsidence occurred during this phase.

Roof–Floor Convergence

Similar to surface subsidence, roof–floor convergence can be described through three phases; however, the convergence had a relatively faster rate than subsidence in the third phase. The relationship between convergence and face location can also be represented by equation 5 with different parameters. Convergence in the area closest to the longwall was the greatest, and it decreased toward the virgin coal rib. Convergence at the center of the entry was greater than that at the sides.

Floor Deformations

Most of the deformation occurred in the first 31 inches below the coal seam. If one assumes that the competent rock was located 41 inches below the floor surface, then the maximum floor heave was about 1.4 inches, which accounted for only 30% of the floor–roof convergence. The remaining 70% of the convergence was due to roof bending and pillar deformations. The floor moved away from the pillar rib; the maximum horizontal displacement of the floor was about 2.8 inches.

Estimation of the Viscoelastic Parameters

Pillar settlement was determined from roof-to-floor convergence data and treated as vertical floor deformation underneath the pillar. The time–pillar settlement data were fitted into the Burger model in equation 4, and viscoelastic parameters for Site 2 were calculated as $E_1 = 3.90 \times 10^4$ psi, $E_2 = 2.66 \times 10^4$ psi, $\eta_1 = 1.97 \times 10^5$ psi-day, and $\eta_2 = 1.97 \times 10^5$ psi-day. The correlation coefficient for these estimates is 0.87. The values above represent parameters for average stress of about 475 psi.

Verification of the Longwall Ground Mechanics Model (LGM)

The LGM model was used in this study to compare calculated values of stress, deformations, and surface subsidence with the measured values. The measured data are from Sites 1 and 2. The predicted results corresponded closely with the field measurements. Thus, the LGM model can be used to predict ground behavior in longwall mining at this time.

Relationship Between Measured Load and Deformations as the Basis for Determination of UBC of Weak Floor Underlying a Full-Size Pillar

For the pillar closest to the longwall at Site 2, a UBC of about $841 + 1.6\,\gamma\,h$ psi is suggested; whereas for the pillar further from the panel at Site 2, the UBC is about $483 + 1.6\,\gamma\,h$ psi. This discrepancy could be caused by floor failure underneath the pillar closest to the longwall, which could affect the floor strength underneath the adjacent pillar. The UBC of the weak floor is about $587 + 1.6\,\gamma\,h$ psi. (In this study, $\gamma = 160$ pcf and $h = 7.8$ feet.)

Comparison of the UBC Measured Under a Full-Size Pillar with UBC Calculated from Various Design Formulas

The UBC measured under a full-size pillar (see previous article in this report) was the basis for an attempt to verify the UBC calculation formulas. The parameters used in the calculations were as follows:

natural moisture content (MC)	= 4%
liquid limit (LL)	= 36.5%
UBC from plate loading test	= 1000 psi
plate size (B × L)	= 12 × 12 in.
length of pillar (L_p)	= 84.5 ft
width of pillar (W_p)	= 44.5 ft
entry width (W_e)	= 15.5 ft
thickness of the weak layer (t)	= 4 ft
angle of internal friction for the upper weak layer (ϕ_1)	= 20°
angle of internal friction for the lower competent layer (ϕ_2)	= 30°
compressive strength for the upper weak layer (C_{01})	= 700 psi
compressive strength for the lower competent layer (C_{02})	= 2000 psi

Among the four UBC calculation methods mentioned here, the UBC value obtained by the Pytel-Chugh approach is the closest to the measured values of 1600 to 2000 psi, and therefore, may be the most appropriate method for estimating the UBC of floor strata underlying a full-size pillar in a longwall mine. This approach can account for a two-layered system that has a weak layer overlying the stiffer layer and includes the effect of adjacent pillars and of non-zero values for the angle of internal friction and cohesion for both layers.

Laboratory Geotechnical Studies

The values of moisture content were 0.3% to 4.4% at Site 2 and 1.4% to 5.4% at Site 3. The values of liquid limit at these sites were 23% to 46% and 24% to 38%, respectively. The statistical relationships developed by Pula et al. (1990) were used to estimate UBC based on moisture content (equation 2); the values are 1039 psi for Site 2 and 1032 psi for Site 3, respectively. The estimated UBC values based on liquid limits are 709 psi for Site 2 and 800 psi for Site 3, respectively. The calculated UBC values are close to the field-tested values from a 12-inch-square plate. According to the Unified Soil Classification System, these samples can be classified as inorganic clays of low plasticity and low compressibility.

CONCLUSIONS

- The ultimate bearing capacity (UBC) of weak floor strata, as determined from plate loading tests, decreased as the plate size increased. The UBC from a 12-inch plate loading test can be confidently estimated from the moisture content of weak floor strata, as determined in the laboratory by using the relationship developed by Pula et al. (1990).
- Estimates of the UBC of weak floor strata underlying a full-size longwall chain pillar at this mine ranged from 1627 psi to 1985 psi.
- The Pytel-Chugh approach (Pytel and Chugh 1990) appears to be the most appropriate method examined for estimating the UBC of floor strata underlying a longwall chain pillar.
- The deformability and viscoelastic constants for the longwall panel's roof–pillar–floor system can be determined in terms of Burger's model parameters.
- The Longwall Ground Mechanics (LGM) model appears to predict accurately the surface subsidence and stress distribution in longwall mine geometry.

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TWO-DIMENSIONAL SUBSIDENCE PREDICTION MODEL FOR PARTIAL EXTRACTION ROOM-AND-PILLAR MINING

Personal Computer Version

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Summarized by Billy A. Trent

ABSTRACT

This approximate two-dimensional analytical model for prediction of subsidence in room-and-pillar coal mining is based on the flexure theory of composite beams resting on elastic or inelastic foundations. Although the model was originally developed in Fortran for mainframe computers, industry representatives recommended that a personal computer version of the model be developed. The goal of this project was to provide Illinois mine operators with a high-speed computational tool to analyze subsidence and roof–pillar–floor interaction in room-and-pillar mining geometries.

INTRODUCTION

Definition and Physical Problem

The flexural theory of composite beams resting on elastic or inelastic foundations is the basis for this approximate two-dimensional analytical model referred to as SIU Panel.2D. The physical problem consists of the overburden, the coal pillars, and the floor strata (fig. 1); the problem is analyzed approximately for loads and deformations at different points.

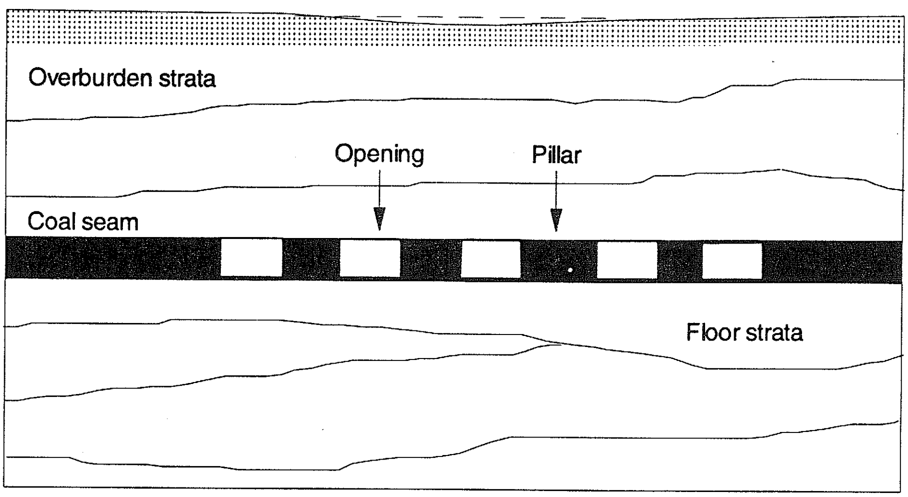

Figure 1 Physical problem.

The overburden strata are idealized as a composite elastic beam with a specified width and stepwise varying flexural and shear stiffness. The loads imposed on the composite beam are transmitted to weak floor strata through coal pillars with elastic or elastic-plastic behavior. Coal pillars are represented by one-dimensional springs with linear or nonlinear characteristics (fig. 2). The floor strata underneath the coal pillars are idealized as a two-layer rock mass with a weak upper layer resting on a nondeformable rock layer. The weak upper layer represents all weak floor strata as a single homogeneous, isotropic layer exhibiting equivalent elastic and time-dependent deformation behavior. Time-independent stress-deformation behavior of weak floor strata may be represented by one of several models such as the elastic half-space, one-parameter Winkler, confined clay layer, or Vlasov elastic layer (Pytel et al. 1988) models; whereas time-dependent deformation behavior is represented by a standard Burgers model.

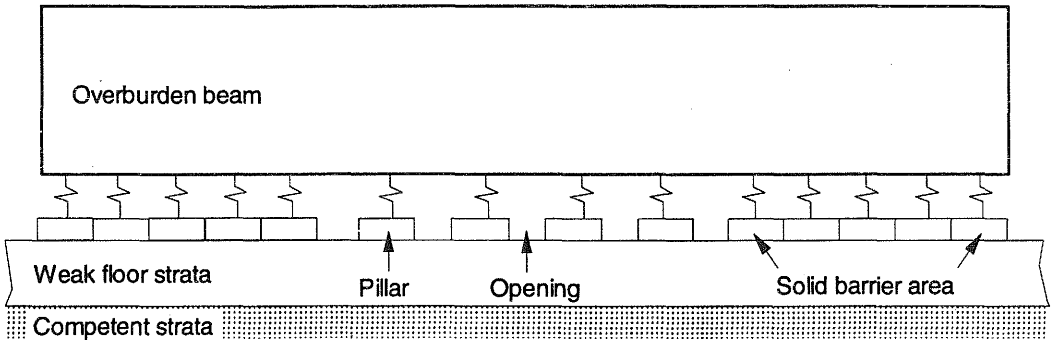

Figure 2 Substitute mechanics system.

Assumptions

The model assumes that vertical bed separations do not occur in overburden strata during flexure because of small mining deformations in room-and-pillar mining. Lateral movements can occur, however, along different overburden layers and roof–coal–floor interfaces that are assumed to be smooth. Imposed external loads on the beam are assumed to be gravitational only because of the weight of the overburden. These loads induce only vertical reactive forces at the pillars (fig. 3). Lateral stresses cannot be considered in the analysis.

Grid Network and Blocks

The overburden beam, coal seam, and floor strata are subdivided into small blocks as a grid network. The size of the grid network may vary in different areas and depends upon the desired calculation accuracy or the size of pillars and openings used in the mining layout. Generally, the size of the blocks in the panels should be equal to the width of suitable pillars. Calculation accuracy may be increased, however, by dividing each pillar into several adjacent blocks of smaller size.

In this model, the solid coal barriers between panels are called interpanels. The term pillar is used whenever a pillar of actual physical dimensions is being considered; whereas the term block denotes the support elements created for purposes of calculation within interpanels, solid coal barriers, and some pillars. (The interpanels and the left and right solid barriers beyond the mine workings must be divided into blocks for calculation.) The number and size of these blocks depend upon the mine geometry. In addition, the following elements apply during problem formulation:

- At least two blocks must be assumed to be within each interpanel. The block size (width) is calculated automatically as the ratio of interpanel length to the assumed number of blocks.
- The number of blocks within the left or right solid coal barriers beyond the mine workings is automatically determined as the greater of the following ratios: (1) the average overburden thickness divided by the width of the first pillar in the adjacent panel, or (2) half the length of the adjacent panel divided by the width of the nearest pillar within this panel.
- Up to three panels may be considered in the analysis.

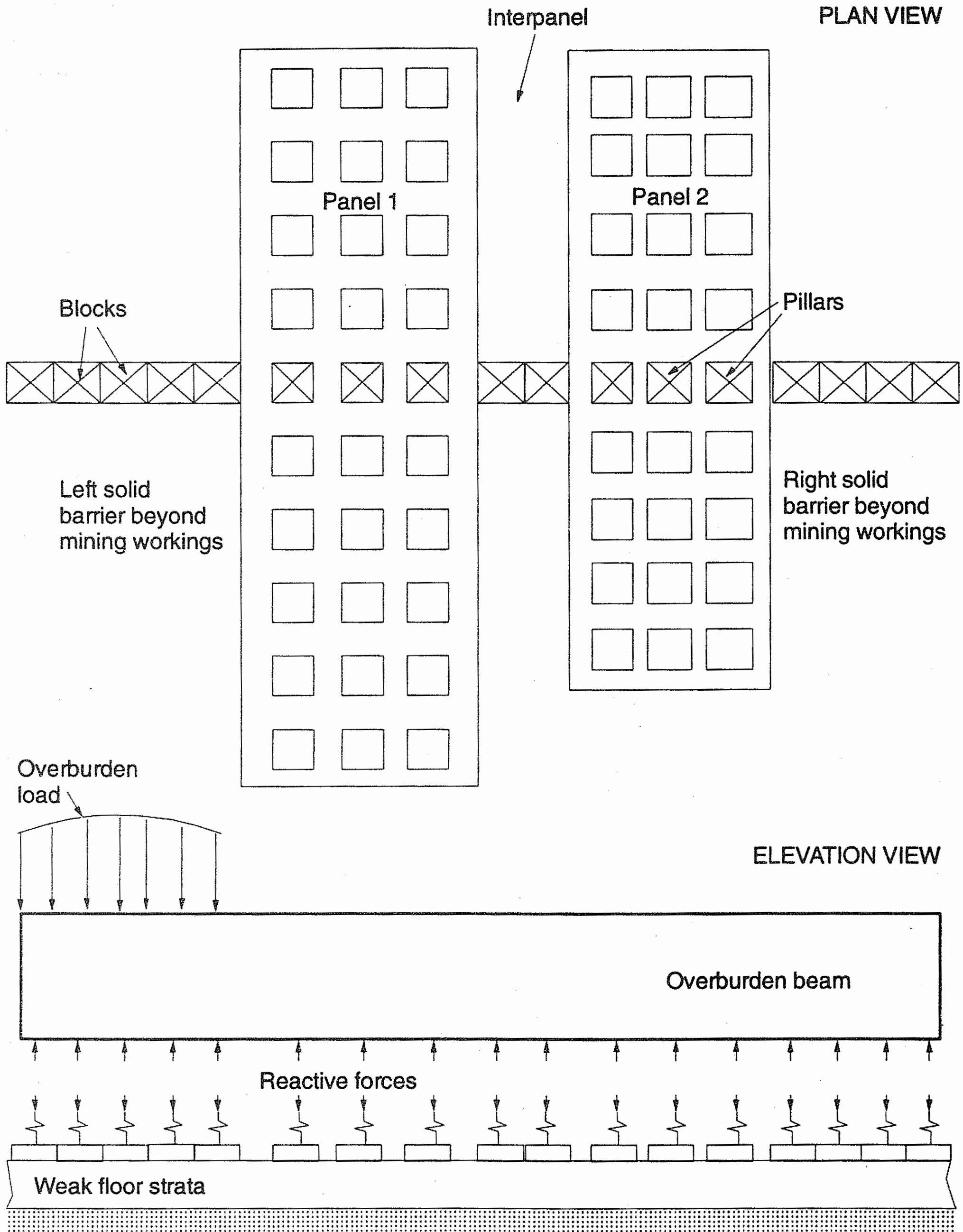

Figure 3 Overall problem with details of geometry and forces, showing plan and elevation cross-sectional views.

Capabilities and Limitations

No more than 75 openings, pillars, and blocks may be created within the coal seam in a mine layout where panels are separated by interpanels. The mining geometry within each panel may be different, but adjoining panels should be parallel so that two-dimensional idealization of the problem is justified. A panel must not have more than 25 pillars. The panel cross section, along which subsidence will be predicted, should preferably be the panel width.

The program permits three options in load-deformation behavior of the coal-measure rocks:

- linear elastic behavior of all strata including overburden, coal seam, and floor;
- as above and time-dependent behavior of weak floor strata only;
- elastic-plastic behavior of coal pillars with no time-dependent effects.

The time sequence of mining can be modeled and the overburden and floor strata lithologies varied to apply to different mining conditions.

Justifying application of the beam theory requires a small panel-depth-to-panel-width ratio. Model formulation assumes small strain theory. In situ horizontal stresses and bed separations cannot be simulated. Nonhomogeneous floor strata can be modeled only as a two-layer system with the weak layer overlying the nondeformable layer. A regular three-dimensional panel geometry and mining sequence is required in the plane perpendicular to the cross section being considered.

MODELING OF THE PHYSICAL PROBLEM

Overburden Strata

The principal investigators assumed that in a partial extraction room-and-pillar mining system, at least the overburden remains in a linear elastic deformation phase. The overburden can then be transformed into a composite beam that has unit width and stepwise varying flexural stiffness and shear stiffness reflecting varying deformability characteristics of the roof strata in a given section. The stiffness of the overburden strata beam depends on the degree of bonding between the layers. This model can be applied to extreme cases of bonding or the lack of bonding, for example, when overburden layers are fully bonded (overburden is treated as a monolithic beam), or when overburden strata interfaces are perfectly smooth (overburden consists of a set of beams stacked on top of each other).

Floor Strata

All weak floor strata below the coal seam are transformed into an equivalent homogeneous rock mass. The floor strata below the weak floor strata are assumed to be rigid. Four different linear models of weak floor strata mechanical behavior are available, depending upon the ratio of pillar width to thickness of the deformable weak floor strata:

- one-parameter Winkler's model, which assumes that the deflection of the rock/soil medium (floor strata) at any point on the surface is directly proportional to the stress applied at that point and is independent of stresses at other points.
- elastic half-space model, for which the deflection of the weak floor strata surface can be obtained by incorporating Boussinesq's solution for the concentrated force acting on the surface of an isotropic elastic half-space. Settlement value depends on the shape of the loaded area and the distance from the center of the loaded area to the given point.
- confined clay layer model, which uses the elastic settlement of a uniformly loaded strip area on a clay foundation (Taylor and Matyas 1983).
- Vlasov's model of an elastic layer, which assumes that a state of strain in the foundation imposes relationships for horizontal and vertical displacements.

The broad comparative analysis of the weak floor models applicable in this case has been presented elsewhere (Chugh et al. 1990). The one-parameter Winkler's model has been found to be suitable for typical conditions in Illinois. The base and thus the thickness of weak floor strata may be estimated from the plot of natural moisture content related to depth within the floor strata immediately below the coal seam. A sharp decrease in moisture content implies the base of the weak floor strata.

The time-independent behavior of these models depends upon two parameters only:

- the Poisson's ratio, which may be determined from laboratory tests on rock cores;
- the secant modulus of elasticity of the rock mass determined from plate load tests using standard procedures (Brown 1978) and a reduction factor due to size effect (depending on the nature of the rock material and its natural moisture content) (Pula et al. 1990).

Plate loading tests at a constant load may be conducted to obtain time-dependent deformation of weak floor strata. The data can then be analyzed to estimate other parameters in a weak floor strata model. Because plate loading tests cannot be conducted for a long period of time, however, the parameter values reflect only short-term behavior of weak floor strata. In-mine convergence measurements are suitable for determination of long-term values of weak floor parameters. It is important to note that time-dependent parameters determined from convergence measurements represent overall rock mass behavior associated with the opening and pillars rather than with weak floor strata only; these parameters are representative of the overall physical problem. Roof–floor convergence monitoring does not, however, directly give the magnitude of the pillar settlement, which is the basis for estimating time-dependent parameters. The ratio of convergence to adjacent pillar settlement depends upon several parameters, among which the Poisson's ratio, relative weak floor strata thickness, and the extraction ratio seem to be the most important.

Immediate Roof Strata

All weak roof strata above the coal seam are transformed into an equivalent homogeneous single rock mass. It is assumed that the overburden strata above the weak, immediate roof strata cannot be compressed vertically; the model of mechanical behavior (time-independent and time-dependent) utilized for the immediate roof strata and for the immediate floor strata must be the same.

Coal Pillars

Coal pillars are represented by a set of nonlinear springs sandwiched between the overburden strata and the deformable weak floor strata. The coal pillar deformation response is based on studies of the peak and residual strength model by Wilson and Ashwin (1972) and Hardy et al. (1977). This model implies that a coal pillar with a width-to-height ratio greater than 6 will have a central core of infinite strength. An expression of the stress–strain relationship for such a rectangular pillar may be found in Pytel (1990). The pillar (extraction) height is assumed in the model to be equal to coal seam thickness; however, if the pillar height is less than the coal seam thickness, the unextracted coal layer has to be included in the immediate roof strata characteristics. More detailed discussions of the theoretical bases for model development and analysis are given in Pytel et al. (1988) and Pytel and Chugh (1989).

Hardware and Software

The program, designed to be used with an IBM-compatible computer, was stored on one high-density, 5.25-inch diskette (1.2M) or one low-density 3.5-inch diskette (720k). All operations started from and returned to the main menu. An interactive data editor was used to prepare the appropriate input data files, particularly a data file used for calculations and a file for storing general information. The main program used for analysis produced several output data files that were described in the PANEL.2D menu. The program also produced a combined result file for graphics and could be used with commercially available plotting packages such as Lotus 1-2-3, Quattro Pro, or Grapher. Additional programs were designed for execution of all interface modules. Figure 4 shows the overall program structures and how the different programs were related.

SUMMARY AND CONCLUSIONS

This two-dimensional time-dependent analysis of the interaction of overburden, coal pillar, and weak floor strata presented a beam model consisting of a composite roof beam resting on multiple elastic foundations (pillars) underlain by a composite rock mass (immediate floor strata). Different material models may be considered for the immediate floor strata. The analysis can include all openings and pillars in a panel. The model enables identification of the relative significance of different geometric and mechanical behavior parameters that govern the system.

The critical point of analysis is the creation of the input data file, which includes data for either time-dependent conditions (such as opening and pillar geometry, lithology, and geologic conditions) or time-independent, external influences (such as mining geometry, mining rate, or deformability of weak strata). The principal investigators have compared field observations made at several Illinois mines with in-mine pillar settlements and surface subsidence

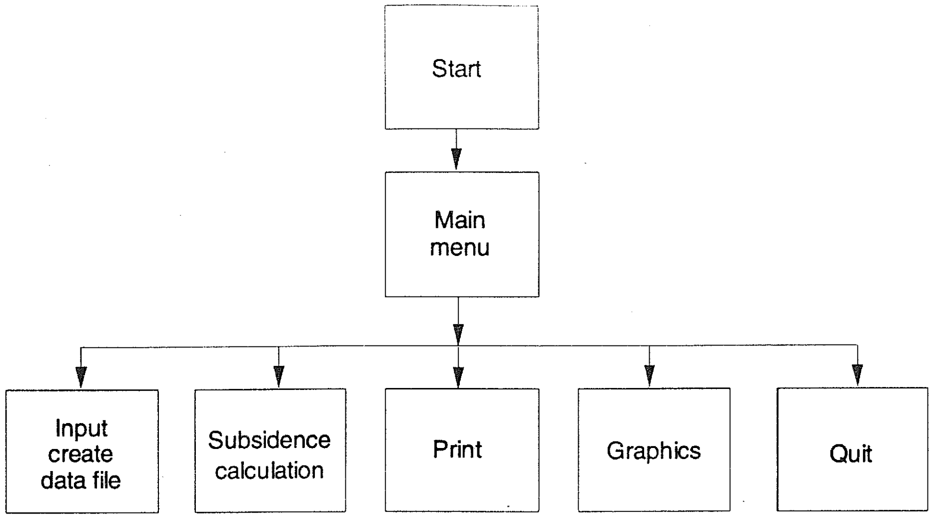

Figure 4 Structure of the program.

movements predicted by the Panel.2D model (Chugh and Pytel 1988, 1989, 1990, Pytel and Chugh 1991). Field observations and computer predictions were in agreement.

FURTHER DEVELOPMENTS

The two-dimensional model was developed under a Mineral Institute contract from the Department of the Interior, Mine Systems Design and Ground Control Generic Center. A workshop on the use of the model was held at Southern Illinois University at Carbondale, in conjunction with the annual meeting of the Illinois Mining Institute in September 1989.

Because the Panel.2D model proved successful, a three-dimensional model (Panel.3D) was developed at Southern Illinois University. Funding was provided by sources other than the Illinois Mine Subsidence Research Program. The principal investigators extended the two-dimensional model to three-dimensional mining geometries for the following reasons:

- In a partial extraction room-and-pillar mining system, rooms on the left and right sides of advancing entries are developed at different rates and different times. Analysis of such mine development geometries and their time-dependent effects requires three-dimensional capabilities.
- A model to analyze three-dimensional geometries will also permit analysis of roof–pillar–floor interaction in other mining systems such as longwall mining. The model may assist in the design of chain and yield pillars and in the analysis of the interaction between adjoining mined-out panels.

The Panel.3D model is based on the theory of thin plates on inelastic foundations. The mine structure was modeled as an equivalent indeterminate plate resting on multiple deformable foundation elements transmitting the load to the weak floor strata. The problem solution was based on the finite difference method, which permits the operator to relate the actual mining progress with equivalent time-dependent overburden and floor deformability. An incremental advance approach is used, including all mined-out areas, with suitable time or time differences of extraction. The model, which can be easily applied for routine mine design, permits determination of surface subsidence and average load acting at different points in the panel. Predictions from the Panel.3D model are being compared by the principal investigators with actual conditions in Illinois mines (Pytel and Chugh 1991).

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MONITORING OVERBURDEN AND SURFACE CHANGES ASSOCIATED WITH HIGH-EXTRACTION COAL MINING IN ILLINOIS

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ABSTRACT

In Illinois, the high-extraction mining methods being used more frequently in underground coal mines cause immediate collapse of the overburden and subsidence of the ground surface. Three study sites were selected for monitoring of the overburden and documenting the changes that take place from the mine level up to the ground surface. Vertical differential movements in the subsiding overburden were slight, indicating that it dropped almost as a mass. Interfaces between materials with contrasting strengths resulted in small differential vertical and horizontal movements. Close monitoring of time domain reflectometry cables showed that movement starts in the upper part of the overburden as the longwall face approaches. Then small vertical and horizontal displacements, starting near the mine level, work their way up through the overburden as the area is undermined. High-angle fractures developed in the overburden, but did not extend down to mine level; they were more numerous near the mined-out coal seam and in the sandstone units.

Within 3 months of the undermining, 90% of the subsidence over the longwall panels had occurred. Residual subsidence, representing 10% of the total subsidence, continued for 3 years at one longwall site. At another panel, about 2% subsidence was recorded within 1.5 years after undermining.

INTRODUCTION

Three study sites were selected for monitoring of the overburden over high-extraction mines in Illinois, and the changes that take place from the mine level to the ground surface were documented:

- Extensometers recorded vertical movements at various levels in the rock over the mine.
- Piezometers monitored groundwater reactions in both the rock and soil.
- Coaxial cables (time domain reflectometry cables) were grouted in vertical boreholes from the mine level to the ground surface to determine both vertical tension and horizontal shearing in the overburden.
- Surveying monuments were placed in the ground above the mine panels to record downward and horizontal movements of the ground surface.
- Drilling before and after subsidence made it possible to document fractures in the rock overburden, determine in situ rock properties from downhole geophysical logging, conduct rock strength testing of cores from the drill hole, and test for in situ hydraulic conductivity.

WILLIAMSON COUNTY SITE

The purpose of this investigation was to study the effects of high-extraction retreat (HER) mining on the overburden. Two instrument clusters were installed over an HER panel: the east cluster was located near the beginning of the panel and the west cluster was located on the center of the panel. Each cluster had a six-rod extensometer, piezometers, surveying monuments, and a coaxial cable. This study was the first time such information was collected over a HER operation in Illinois. The geotechnical monitoring program was conducted for 3 years. Unfortunately, the mining company did not complete the panel and only the instrument cluster located near the start of the panel was undermined.

Geologic Setting

Physiography The study site is located in the Mount Vernon Hill Country, a physiographic division of Illinois (Leighton et al. 1948). The geomorphology of the area is characteristic of a maturely dissected, sandstone–shale plain of low relief mantled by thin (<40 ft) Illinoian drift. Surface topography above the panel is gently rolling with a maximum relief of about 40 feet and slopes ranging from less than 3% to more than 18%.

Surficial Geology At the study site, deeply eroded Illinoian till is overlain by 3.3 to 4.6 feet of loess. Alluvial sand, silt, gravel, and clay are found in the bottomlands. Glacial drift thickness may have local variations but generally ranges from about 14 to 60 feet.

Bedrock Stratigraphy and Structure The bedrock units at the study site are the Carbondale and the Modesto Formations, which belong to the Pennsylvanian System of Illinois. Both formations are composed primarily of shales and siltstones (70–80%) and fewer units of sandstone and limestone. The Cottage Grove Fault System is 1.5 miles north of the site.

The coal seam mined is the Herrin Coal Member, which lies between 250 and 350 feet above mean sea level (m.s.l). The thickness of the Herrin Coal averaged approximately 6.0 feet near the study area. The Energy Shale, the immediate roof of the mine, is typically 10 to 20 feet thick, which places the Anna Shale and Brereton out of bolting range. An unusual aspect of the roof sequence is the thick, sandstone-rich, Anvil Rock Sandstone/Lawson Shale interval, which averages 37 feet in the area.

Mine Description and Instrument Layout

Mine plans called for a panel 2,300 feet long, 210 feet wide, and at a depth of 250 feet. The panel width was increased to 385 feet and the southern edge of the panel was moved northward during mining when roof conditions were discovered to be poor. The operations at the mine were suspended after the panel had progressed only 900 feet. Only the east instrument cluster was undermined by the high-extraction retreat method. The west cluster was undermined by the room-and-pillar method, adjacent to the solid unmined portion of the panel.

Each instrument cluster consisted of a time domain reflectometry (TDR) cable, multiple position borehole rod extensometer (MPBX), and bedrock observation wells. A line of surface monuments extended from each instrument cluster; each line was oriented nearly east to west, perpendicular to the anticipated front of the subsidence wave. Control monuments and drift piezometers were placed well away from any undermined areas.

Results

Surveying and Subsidence Characteristics Both frost-isolated monuments and simple rebar monuments were installed. The surface monument locations were based on the mine layout and spaced 20 to 25 feet apart. About 95% (on average) of the recorded subsidence occurred in the first 10 weeks after subsidence began.

Some subsidence characteristics could not be accurately determined because of the geometry of the instrumentation layout relative to the changed panel orientation and the irregular dimensions of the mined-out area near the east instrument cluster. The instruments were too close to the beginning of the panel to calculate the maximum percent-subsidence (maximum subsidence/mining height); but the relationship between percent-subsidence and the ratio of the distance to the panel edge falls within the known range of values for high-extraction retreat mining in Illinois (Hunt 1980). Maximum lateral movements of about 1 foot were recorded on the inside of the panel. The lateral movements were generally to the west and north, toward the mined-out void.

Multiple Position Borehole Extensometer (MPBX) A six-anchor MPBX was installed with the anchors grouted at depths of 50, 75, 100, 125, 150, and 175 feet below the ground surface. The extensometers mechanically monitor vertical overburden movements at each of these levels by transmitting the anchor movements by fiberglass rods to the surface. Displacements of the anchors relative to each other and to the reference plate indicate the magnitude and general depth interval of the vertical component of ground movements.

The maximum change in elevation was a drop of 3.16 feet at the extensometer. The MPBX indicated differential vertical movements at various depths from the ground surface to the bottom anchor. Anchor 6 (initial depth 175 ft) dropped 4.00 feet, anchor 5 (depth 150 ft) dropped 4.99 feet, anchor 4 (depth 125 ft) dropped about 4.58 feet, anchors 1, 2, and 3 moved 3.26 feet, and the ground surface dropped about 2.7 feet. The anomalously small movement of anchor 6, as compared with the displacement of anchor 5, suggests that a large, abrupt movement between 150 and 175 feet broke the fiberglass rod-anchor assembly. No significant anchor movements were detected 2 months after subsidence.

The lack of vertical movement or change in strain recorded by the MPBX after the initial failure suggests that fracture openings that developed between the depths of 50 and 150 feet did not close significantly. Furthermore, the lack of differential movement indicated that subsequent subsidence was caused principally by closure of voids below the depth range monitored by the MPBX. A later, nearly uniform decrease of about 0.12 feet in all the rod readings was caused by closure of voids above anchor 1, as shown by the same downward movement of the surface monuments and reference head. Some vertical differential movements in the overburden were associated with interfaces between materials of contrasting stiffness such as bedrock versus drift. Large vertical strains of 5.3% were detected between anchors 3 and 4, which spanned the interval of a massive sandstone unit. These large differential movements can be attributed to the sandstone being stiffer than the underlying material and deflecting less than the underlying, less rigid material.

Time Domain Reflectometry (TDR) The TDR technique was used to document fracture development that subsidence caused in the overburden. A TDR tester sends ultrafast, rise-time voltage pulses down the coaxial cable, and deformations in the cable reflect signals back to the tester. Vertical tensile and horizontal shear movements can be detected with the 0.5-inch-diameter unjacketed coaxial cable.

The TDR cable was sheared and broken 8 feet below the ground surface during initial subsidence. After the shear was recorded, a new piece of cable was spliced to the top end of the grouted cable. The shear at 8 feet was located near the base of the fragipan (cemented layer). The lower portion of the cable had been displaced 0.2 feet toward the mined-out area relative to the upper 8 feet of cable. The spliced TDR cable was read and a second shear signal at a depth of approximately 38.5 feet was recorded. The shearing action that occurred near the sides of the panel was interpreted to have resulted from differential lateral displacement at the bedrock and soil interface, which suggests the drift deformed as a separate beam.

JEFFERSON COUNTY SITE

At this site, the characteristics of two longwall panels before and after subsidence were determined by using core drilling, geotechnical instrumentation, and in situ testing. Geotechnical instrumentation included surface monuments, piezometers, a pump well, an inclinometer/extensometer (sondex), and two time domain reflectometry cables to monitor overburden and ground surface response. The instruments were monitored before, during, and after subsidence during a 5-year period.

Geologic Setting

Physiography The study site is located in the Mount Vernon Hill Country, a physiographic division of Illinois. The geomorphology of the area is characteristic of a maturely dissected, sandstone–shale plain of low relief under a mantle of thin Illinoian drift. There are restricted uplands and broad alluviated valleys along the larger streams (Leighton et al. 1948).

Surface topography above the panels is gently rolling with about 40 feet of relief. The topography in the area is primarily bedrock-controlled (Horberg 1950), but bedrock features were modified by glacial action and somewhat subdued by a thin cover of drift (Leighton et al. 1948). Dendritic drainage is predominantly bedrock-controlled in the vicinity of the panel site (MacClintock 1929). The panels are located in the drainage basin of the Big Muddy River, which drains into the manmade Rend Lake Reservoir. Any surface water over the panels generally drains east into the west arm of the reservoir.

Surficial Geology The Bluford silt loam is the predominant modern soil that developed over the study area (Darmody 1990). Slopes range from 1% to 2% over most of the area and reach 4% in the shallow drainageway on the north side. The Peoria loess (2–4 ft thick) overlies the Sangamon paleosol, which developed atop the Illinoian glacial drift deposit (L.R. Follmer, ISGS, personal communication 1993), here only 4 to 8 feet thick.

Bedrock Stratigraphy and Structure The mine operates in the Herrin Coal at a depth of approximately 700 feet. The Herrin Coal ranges from 7 to 11 feet thick in the study area. The bedrock is of Pennsylvanian age and composed of rock units of the Carbondale, Shelburn, Patoka, and Bond Formations. The immediate roof of the Herrin Coal in the study area is the Energy Shale, which is more than 100 feet thick. The Energy Shale, predominantly silty shale and thinly bedded siltstone, also has some thin zones of sandstone.

The Mt. Carmel Sandstone channels provide the best local water sources. Drill holes in the study area show the Mt. Carmel Sandstone at a depth of 70 feet, locally ranging up to 80 feet thick. The bottom 50 feet is predominantly sandstone with minor shale and siltstone interbeds, whereas the upper 30 feet contains some sandstone and silty shale, but siltstone predominates.

The bedrock below the study area is relatively undeformed, producing relatively flat-lying strata. The regional dip of the strata is approximately 10 to 15 feet per mile to the east-northeast. The Rend Lake Fault Zone passes through this and neighboring mines (Keys and Nelson 1980) and consists of north-striking parallel normal faults. Several miles south of the mine, the Rend Lake Fault Zone begins to trend slightly to the north-northwest, and it strikes roughly N20°W adjacent to the study area. The longwall study panels are aligned east to west, laid out to avoid these faults; the position of the fault just to the east of the study panels determined the eastern extent of both panels 3 and 4. Because this fault dips westward, no fault effects were expected in the subsided overburden.

Mine Description and Instrument Layout The study area consisted of longwall panels 3 and 4, adjacent entries, and the ground surface above them. Panels 3 and 4, running east to west, are 600 feet wide and approach 1 mile in length. The total unsupported panel width is 617 feet, giving a panel-width-versus-mine-depth (W/D) ratio of 0.86. The panels were mined from east to west. The carbonaceous base of the roof shale is often mined with the coal, resulting in mining heights of 9 feet to slightly more than 10 feet in the study panels.

Over panel 3, survey monuments transverse and longitudinal to the panel as well as controls outside of the panel were installed as part of the monitoring plan. Bedrock and drift piezometers were placed over the chain pillars and the edge and centerline of the panel. The instrumentation over panel 4 was two TDR cables (over the edge and centerline), an inclinometer/sondex (over the centerline), four bedrock piezometers, and one pump well (centerline). Two drift piezometers, two control survey monuments, and one bedrock piezometer were installed approximately 420 feet north of the north edge of panel 4.

Results

Surveying and Subsidence Characteristics After about 3 months, when the longwall face had advanced more than 3,200 feet (distance/depth = 4.4) and was near completion, the transverse line over the third panel subsided 6.00 feet for a ratio of subsidence to mined-out height of 63%. Panel 3 subsided a total of 6.67 feet or 70% of the mined-out height after 3 years (Mehnert et al. 1992).

When the longwall face of panel 4 had advanced 2,190 feet (distance/depth = 3.0) past the transverse line, subsidence over the centerline was 6.05 feet or 59% of the mined-out height. After almost 3 years, the centerline of panel 4 subsided 6.62 feet or 64% of the mined-out height, which is less than the subsidence recorded over panel 3. This lower subsidence ratio is due to the fact that the extended line over panel 4 was being undermined as it was constructed; therefore, the undisturbed level of the ground surface was not measured and no adjacent panels were subsequently mined. The chain pillar between panels 3 and 4 yielded and subsided 0.50 feet after the panel 4 longwall face had advanced 815 feet (distance/depth = 1.1) past the transverse line. The total subsidence over the chain pillars was more than 1.44 feet after 3 years. A 23° angle of draw (zero subsidence = 0.03 ft) was measured on the north side of panel 3, before mining of panel 4 began.

Strain For the transverse line over panel 4, the maximum tensile strain calculated was 0.030 at 125 feet inside the panel edge (distance/depth ratio of 0.172). Maximum surface compression was 0.026 at 150 feet inside the panel edge (distance/depth ratio of 0.207). The tensile zone was approximately 112.5 feet wide for this "critical width" panel.

For the longitudinal line over panel 4, strain measurements were performed over the centerline of panel 4. The maximum tensile strain calculated was 0.028.

Exploratory Drilling Although drilling through the postsubsidence overburden was more difficult because of the loss of drilling fluid in some highly fractured zones, core recovery was excellent before and after subsidence. Undermining caused the fracture frequency in the lower bedrock to increase dramatically, whereas only smaller increases were noted toward the surface. The larger increases occurred in the stronger materials, which deform more like brittle material (Bauer 1984).

Geophysical Logs A comparison of subsidence-induced changes in shear-wave velocity shows four large velocity decreases of 12% to 18% that correlate with coals and thin calcareous zones where more fracturing and bed separations occurred within the overburden. The general decrease of 1% to 10% in the shear-wave velocity throughout the rest of the overburden is the result of wave attenuation through a fractured medium filled with fluid.

TDR Cable *Inside Panel Edge* As mining progressed, the cable 99 feet inside the panel edge failed in shear at a depth of 262 feet, in tension at 138 feet, in shear at 111 feet, and finally at a depth of 3 feet. The failure at a depth of 111 feet occurred in the upper part of the Mt. Carmel Sandstone. The failure at 138 feet was close to the base of the Mt. Carmel Sandstone, which is in contact with a shale unit. The failure at a depth of 262 feet was at the location of a 0.3-foot-thick coal seam. The failures in this cable occurred near contacts between strong and weak lithologic units and where weak units, such as thin coal, were located.

At Centerline of Panel The cable in the center of the panel failed in tension at a depth of 117 feet below the ground surface. No distortions were detected before this break. The failure at 117 feet corresponds to the top of the Mt. Carmel Sandstone in contact with a shale unit. A tensile strain of about 1% was measured using the sondex in the depth interval from 107.3 to 126.3 feet. After the failure at 117 feet, the cable deformed at depths of 51 and 113 feet.

Inclinometer/Sondex The inclinometer/sondex assembly was installed in an 8-inch-diameter borehole near the centerline TDR cable. The borehole was grouted to within 40 feet of the top of the coal seam. The sensing rings were spaced every 20 feet from ground surface down to 460 feet, and every 10 feet from 460 to 680 feet deep. The 3.34-inch-diameter ABS plastic inclinometer casing was placed inside the 4-inch sondex pipe to a depth of 674 feet.

As the longwall face approached the inclinometer/sondex hole, the upper 50 feet of overburden yielded 0.2 foot of vertical extensional movement. In the lower 500 feet of overburden, very small displacements were recorded. When the mine face advanced within 50 feet of undermining the sondex, the upper bedrock continued to yield, while the lower portion of the bedrock underwent small (0.01 ft) compressional displacements. When the longwall face was 38.5 feet past the borehole, neither the sondex nor the inclinometer sondes could be lowered below 423 feet, which is the depth of a 0.8-foot-thick coal seam over a claystone unit. The next day the sondex could not be lowered below 245 feet. Five days later, the instruments could not be lowered below 145 feet; but a week later the sondex passed this point, only to be stopped at the 245-foot point again.

The amount of strain between each sondex ring ranged from 2.7% (extension) to 1.4% (compression). The changes in vertical strain were mostly related to changes in lithology. The largest vertical strains developed in the upper part of the bedrock, very near ground surface. The smaller strains occurred in the Mt. Carmel Sandstone. As the longwall face approached, vertical extensional separations occurred near the top 50 feet of overburden. After the longwall face had advanced 100 feet, "beams" of rock approximately 100 feet thick began to separate. This response can be interpreted from an S-shaped graph of changes versus depth.

Six sets of inclinometer readings were recorded, starting when the panel face was located 485 feet away from the inclinometer and continuing until the face was 637 feet past the instrument. As the face approached the inclinometer, no significant horizontal displacements were detected until the face was between 125 feet and 60 feet away. At this time, noticeable horizontal displacements were measured. Major differential displacements, each about 1 inch, were measured at four different depths when the face was 60 feet away. The relative displacement at a depth of 175 feet was located within an interlaminated siltstone. The next displacement occurred at 260 feet, just below a thin coal. The other two displacements were deeper, at 530 feet within a shale layer and 590 feet, probably through a slickensided claystone.

When the face was 218 feet past the inclinometer, two substantial relative displacements were measured. The shallower displacement occurred at a depth of 50 feet, through the base of a black, fissile shale; this displacement had a magnitude of 7 inches (0.6 ft). This shear plane was also detected by the centerline TDR cable. At a depth of 150 feet, close to the contact between the Mt. Carmel Sandstone and the interlaminated siltstone, the inclinometer casing was displaced enough to block the downward passage of the probe.

SALINE COUNTY SITE

At this site, the characteristics of two longwall panels before and after subsidence were determined by using core drilling, geotechnical instrumentation, and in situ testing. Geotechnical instrumentation included surface monuments, drift and bedrock piezometers, a pump well, two multiple position borehole rod extensometers (MPBX), and one time domain reflectometry (TDR) cable to monitor overburden and ground surface response. The instruments were monitored before, during, and after subsidence for 1.6 years.

Geologic Setting

Physiography This study site in the Mount Vernon Hill Country physiographic division of Illinois is similar to the Jefferson County site. Surface topography above the panels is gently rolling with 50 feet of relief. The topography in the area is primarily bedrock-controlled (Horberg 1950). Bedrock features, modified by glacial action, have been somewhat subdued by a mantle of deeply eroded drift covering the region (Leighton et al. 1948). Dendritic drainage is predominantly bedrock-controlled in the vicinity of the panel site (MacClintock 1929). The panels, located in the drainage basin of the Saline River, are adjacent to the Harrisburg Reservoir. Any surface water over the panels generally drains south into the Middle Fork of the Saline River.

Surficial Geology The Bluford and Wynoose silt loams, the predominant modern soils in the study area (Seils et al. 1992), developed on slopes ranging from 1% to 2% over most of the area and reaching 4% in the shallow drainageways. On these low slopes, erosion of the original 2 to 4 feet of Peoria loess in which the modern soil developed has been minimal. A weakly expressed fragipan in the B horizon inhibits water and root penetration and may become brittle in the dry season.

In the study area, there is up to 80 feet of drift over bedrock and below the modern soil; even on the uplands, there seems to be at least 20 feet of drift. Most of this material appears to be Illinoian till (Frye et al. 1972) derived from Pennsylvanian bedrock, capped by the Sangamon paleosol, and overlain by several feet of Peoria loess.

Bedrock Stratigraphy and Structure The study mine operated in both the Springfield seam at a depth of around 570 feet, and the Herrin seam at a depth of around 440 feet. The longwall panels were in the Herrin Coal. All bedrock above the mined coal seams is of Pennsylvanian age. The Herrin Coal is 5 to 7 feet thick in most of the mine, and may have several immediate roof lithologies. The typical roof sequence is 4 or more feet of Brereton Limestone separated from the Herrin Coal by several feet of black Anna Shale.

The bedrock above the Herrin Coal here is dominated by thick shale intervals. The only possible bedrock aquifers are the sandstones at 180 and 280 feet deep. The lower sandstone, which may be the Gimlet Sandstone, is generally thin and of less interest as an aquifer. The upper sandstone is the Trivoli, which is very persistent, ranges from 2 to 55 feet thick over the south side of the mine, and occurs both as a sheet up to 35 feet thick and a channel facies from 35 to 55 feet thick (Curtiss in prep).

Directly below the study area, the Herrin Coal and overlying strata are relatively undeformed and level; but to the south, the strata rise 90 feet in elevation over 4,000 feet horizontally (Curtiss in prep). This change suggests that an anticline or fault might be present to the south, perhaps related to the Cottage Grove Fault System. The study site is 4 miles north of the master fault of the Cottage Grove Fault System, and subsidiary faults and folds have been seen at this distance from the master fault (Nelson and Krausse 1981).

Mine Description and Instrument Layout Both panels extend about 1 mile east to west, and both were mined from east to west at a depth of about 380 to 400 feet. Panel 1 had an unsupported panel width of 668 feet, resulting in a panel-width-versus-mine-depth (W/D) ratio of 1.67. Panel 2 had an unsupported panel width of 618 feet, resulting in a panel-width-versus-mine-depth (W/D) ratio of 1.62.

The site was instrumented with one TDR cable at the centerline of the panel; two MPBX assemblies at the center of the panel; bedrock and drift piezometers over the chain pillars, the edge, the centerline of the panel, and north of the panel; and one pump well on the centerline. The monitoring plans also called for transverse and longitudinal monument lines, as well as control monuments north of the panel. Postsubsidence drilling was also undertaken to reestablish the pump well, add a bedrock piezometer, and characterize fracturing and rock mass changes.

The transverse monument line over panel 1 was extended south to the centerline of panel 3, and a shorter longitudinal monument line was developed on the centerline of panel 2; control monuments were established farther south, out of the influence of mining.

Results

Surveying and Subsidence Characteristics Panel 1 was surveyed for 19 months, starting when the panel face was approximately 400 feet away from the transverse line. Panel 1 was 668 feet wide by 7,893 feet long; its average mined-out height was 6.7 feet. The panel roof was located at a depth of 402 feet. The survey monuments began to show elevation changes when the longwall face approached to within 250 feet of the monument. The monuments continued to register substantial changes in elevations until the face was 500 feet past the transverse line at the mine level, when subsidence of 4.73 feet was measured at the panel centerline. The resulting ratio of subsidence to mined-out height was 70.5%. Vertical displacements measured during the 18 months after undermining showed an additional 1.3% subsidence, which increased the subsidence to 71.8%. The angle of draw for the static transverse subsidence profile at panel 1 was consistently 20°; there was no indication that the angle of draw changed with time.

The distance between panels 1 and 2 was 132 feet, representing two rows of chain pillars between the panels. Mining of both panels 1 and 2 produced subsidence of 0.29 foot over the chain pillars.

Over panel 2, subsidence of 4.40 feet was measured at the panel centerline at the time of completion of the panel. The resulting ratio of subsidence to mined-out height was 66.3%, in contrast to 74.8% induced at panel 1. About 6 months later, the increase in subsidence at the centerline of the panel was 0.12 foot, which resulted in a ratio of subsidence to mined-out height of 68%. The angle of draw determined at panel 2 for the static transverse subsidence profile was similar to that obtained for panel 1—about 20° (zero subsidence = 0.03 foot).

A 320-foot longitudinal line over the centerline of panel 1 was used to monitor the advance of the dynamic subsidence wave. The wave consistently started about 250 feet ahead of the panel face and extended behind it to 500 feet, totaling a length of 750 feet. Subsidence of 0.15 to 1.5 feet was measured when the panel face reached the survey monuments; more often, it was near 0.15 foot. The rate of wave advance was closely controlled by the rate of face advance.

Strain Profile For the transverse profiles, the maximum extensional strains were consistently found about 54 feet inside the panel edge, whereas the maximum compressional strains tended to be about 134 feet inside the panel edge. The corresponding ratios of distance from edge to depth were 0.135 and 0.335, respectively. The last set of transverse readings taken immediately after completion of the panel indicated a maximum extensional strain of 2.1% on the north side and 1.6% on the south side. Also recorded was a maximum compressional strain of 1.3% on the north side and 1.5% on the south side.

Dynamic extensional displacements tended to start about 200 to 250 feet ahead of the panel face. This initial strain, which remained practically constant and negligible, had a magnitude of less than 0.1% up to 120 to 160 feet away from the face; then it started to increase with decreasing distance to the face but without any linear relationship. Maximum dynamic extensional strains between 1.2% and 1.8% were developed from 20 to 80 feet behind the panel face. Far behind at a distance of 80 to 130 feet, the changes in longitudinal strains approached zero. Then maximum dynamic compressional strains of 1.3% to 1.4% were induced at 130 to 170 feet behind the face. For distances exceeding 350 to 450 feet behind the face, the strains approached and remained close to zero, reflecting the dynamic character of the subsidence wave.

Exploratory Drilling Although drilling through the overburden was more difficult after subsidence because of the loss of drilling fluid in fractures, core recovery was good to excellent before and after subsidence. The core recovery largely reflected drilling problems. The rock quality designation (RQD) shows small value decreases into the 90% to 99% range for some intervals because of subsidence fracturing in the postsubsidence core.

There was a clear increase in fracturing due to subsidence when the presubsidence and postsubsidence core logs were compared. When comparable depth ranges were matched, the increase was from 0.32 to 0.50 of a fracture per foot.

The change in the nature of the fractures is also distinctive. No fractures or discontinuities of more than a 45° dip, except those around nodules or on steepened bedding, occurred before subsidence. After subsidence, however, many high-angled (65–85°) fractures were found within shale, siltstone, and sandstone units. In the postsubsidence core, the interval with the largest increase in fracturing (178–188 ft) was within the Trivoli Sandstone; this interval shows the predominantly high-angled fracturing associated with subsidence.

Geophysical Logs A comparison of downhole geophysical logs for pre- and postmining showed that sandstone layers tend to exhibit a larger decrease in both shear and compressive wave velocities—a decrease as high as 35% within the Trivoli Sandstone. This decrease reflected not only the development of more fractures in this more brittle layer with respect to other adjacent layers, but also the occurrence of bed separation. In another sandstone layer between the depths of 272 and 285 feet, shear and compressive wave velocities decreased 18% and 14%, respectively. For the remaining depths, decreases of 1% to 15% in shear wave velocity and decreases of 1% to 13% in compressive wave velocity were recorded; more often, the decreases in both velocities were less than 8%.

Time Domain Reflectometry (TDR) A TDR cable 0.5 inch (12.5 mm) in diameter was installed in a 425-foot-deep, angled borehole at the centerline of panel 1. Readings were taken for 8 months, starting about 2 months before the instrument was undermined, at which time the panel face was 1,334 feet away. The last reading was obtained after the panel face was 2,564 feet past the instrument, and 3½ months after the completion of the panel.

Subsidence-induced changes in the cable were predominantly differential shear, as compared to extensional displacements. As one would expect, the frequency of displacements increased with the face advance towards the cable. The first differential shear displacement was recorded when the mine face was about 208 feet away from the instrument. A shear plane was detected at a depth of 173 feet within a layer of slightly silty and slightly fissile shale close to the contact with an underlying sandstone layer.

When the panel face was 79 feet away, the differential displacement along this first shear plane increased and progressed to a break in the cable at about a depth of 173 feet. No subsequent information was available for the units below the cable break. At the same time, the cable underwent an extensional displacement between the depths of 152 and 155 feet, where a thin coal layer separated shale layers.

Two days later, three new differential shear displacements at depths of 101, 117, and 141 feet were measured within a slightly silty and slightly fissile shale layer between 86 and 176.2 feet deep; the mine face was only 11 feet away from the instrument. On the same day, an extensional displacement was recorded in the glacial drift between the depths of 52 and 55 feet, where a standard penetration test (SPT) met refusal. The next day when the mine face was 18 feet past the instrument, a cable break was recorded at a depth of 141 feet; an extensional displacement was also detected at a depth of 76 feet. The reading taken 3 hours later indicated that the cable underwent a shear break at a depth of 101 feet. Three days later, readings showed that the cable had broken at a depth of 76 feet. The mine face at that time was approximately 63 feet past the instrument. After this cable broke in the glacial drift, displacement data for the rock mass were not available.

During the next 6.5 months of readings, only the upper portion of the glacial drift, where the TDR cable remained unbroken, could be monitored. Minor differential shear displacements, which were insufficient to break the cable, were recorded during this period. When the mine face was 160 feet past the cable, differential shear displacements were registered at depths of 32.5, 54.5, and 74.5 feet. Two more time-dependent differential shear displacements were detected later when the panel mining had already been completed: one at a depth of 36 feet and another at a depth of 12.5 feet. Differential shear displacements tended to form at depths with lower SPT values. SPT values ranged from 6 to 49 blows per foot; more often, they were higher than 15 blows per foot. The penetration of a split-spoon sampler met refusal at a depth of about 45 feet.

Multiple Position Borehole Extensometers (MPBX) Two six-anchor MPBXs were installed at panel 1. The anchors of the shallow MPBX were grouted at depths of 120, 140, 160, 180, 200, and 220 feet below the ground surface; whereas those of the deep MPBX were grouted at depths of 280, 300, 320, 340, 360, and 380 feet. The extensometers mechanically monitor vertical overburden movements at each of the six levels. MPBX readings were taken for 5 months, starting when the panel face was about 700 feet away from the borehole extensometers. The last set of readings was obtained when the face was 2,500 feet past the instruments.

Because the shallow and the deep MPBXs were located along the panel centerline and only 31 feet apart, the anchor displacements in these two extensometers were analyzed together. In addition, they were correlated with the subsidence data obtained at the top of boreholes and the results were used to determine the total anchor displacements.

Most of the displacements occurred during a period of 5 days, when the face was within 15 feet of the extensometers, and continued while the face paused and then advanced 75 feet past them. The anchor rods settled between 3.3 and 3.8 feet at the end of the 5 days. Initially, differential displacements between the ground surface and the shallowest anchor at a depth of 120 feet were very small. As the mine face advanced and the magnitude of settlements increased, however, extensional differential displacements between these two points became as much as 0.5 foot. This increase in differential displacements as the face advanced was the general tendency that predominated between most of the anchors. Most of the extension was induced within the glacial drift, which extended to a depth of 80 feet. In addition, a differential extension of 0.15 foot was measured between the depths of 200 and 220 feet. The description for this hole showed that, at a depth of 200 feet, there was a geological contact between a 25-foot-thick sandstone layer and an underlying 30-foot-thick shale layer. The extensional behavior may be associated with the difference in relative stiffness and subsequent bridging between these two rocks and, more importantly, with the relative position between them. The magnitude of differential displacements between other anchors was consistently lower than 0.10 foot during this period.

The rock mass between the depths of 80 and 175 feet, mainly shales overlying a sandstone layer, behaved as a rigid slab or beam during the period of large displacements. A similar "beam" performance was observed between the depths of 300 and 385 feet where the rock mass was composed of several layers of limestone, shale, claystone, and sandstone. Each of these lithologic units averaged less than 10 feet in thickness.

Additional settlements were measured during the 3 weeks after undermining, when the panel face progressed from 75 to 285 feet past the extensometers. Most of the displacements measured in this period occurred before the face reached 140 feet past the instruments. This period coincided with the period when the surface subsidence monuments underwent the most rapid subsidence, about 0.25 foot per day. The maximum cumulative settlement measured at the end of this period was close to 4.4 feet for all of the anchors. The change from a more irregular distribution of displacements with depth, as observed at the end of the previous period, to a new, practically uniform displacement pattern indicated the accommodation of the rock mass to a new equilibrium condition with the closure of fractures or bedding separations. Subsequent extensometer readings taken during a period of about 3.5 months after the undermining showed very small increases in displacements, usually less than 0.1 foot. There was no evidence that any anchor rods broke during active mining.

CONCLUSIONS

The overall vertical differential movements in the subsiding overburden were slight, indicating that the overburden dropped almost as an entire mass. The small differential vertical and horizontal movements were associated with interfaces between materials of contrasting strengths. Close monitoring of time domain reflectometry cables showed that the initial movements occurred in the upper part of the overburden as the longwall face approached. Then, small vertical and horizontal displacements worked their way up through the overburden as the area was undermined.

New fractures developed in the overburden as a result of subsidence. The fractures were high angle and more numerous near the mined-out coal seam and in stiffer units such as sandstones. These fractures throughout the overburden are not interconnected down to the level of the mine.

Ninety percent of the subsidence over the longwall panels occurred within the first 3 months of undermining. Residual subsidence at one longwall site continued for up to 3 years and represented 10% of the subsidence. At another panel, about 2% of the subsidence was recorded within 1.5 years after undermining.

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HYDROGEOLOGIC EFFECTS OF SUBSIDENCE DUE TO LONGWALL MINING IN ILLINOIS

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ABSTRACT

Hydrogeological impacts of active longwall mining were studied at two sites in Illinois, one in Jefferson County and the other in Saline County. These investigations were conducted at the same sites used for the overburden and agronomic studies. Hydraulic conductivities of the sandstone were determined before and after subsidence of a longwall panel. Piezometers and farm wells were monitored over and near the panels at both sites. At the Jefferson County site, which had the more transmissive sandstone aquifer, aquifer permeabilities increased one order of magnitude due to subsidence. Piezometric levels declined as a result of transmitted drawdown before undermining, then as a result of increased porosity due to fracturing produced by subsidence. Levels recovered rapidly at first and fully within 2 years. At the Saline County site, which had a poorer aquifer, impacts were similar except that recovery was limited. Researchers found that local aquifer enhancement through increased yield can occur, but only where the aquifer is transmissive enough for recovery.

INTRODUCTION

From 1988 to 1993, investigations into the effects of mining and subsidence on groundwater hydrology were conducted at two active longwall mines in southern Illinois. As part of the Illinois Mine Subsidence Research Program (IMSRP), these studies were conducted cooperatively by researchers from Northern Illinois University (NIU) and the Illinois State Geological Survey (ISGS).

Longwall mining differs from the traditional room-and-pillar mining in that it produces rapid, well defined subsidence of the overlying strata and ground surface. Accompanying the subsidence is the dilation and recompression of existing joints, new fractures, and bedding planes. These strains alter the hydraulic properties of the overlying strata and thus affect groundwater flow and resources.

In the United States, longwall mining has been practiced longest in the Appalachian Coalfield, and therefore most studies of its hydrogeologic effects have been made in this setting (Booth 1992). Although successful longwall mining operations in Illinois began in the late 1970s, the method has been widely adopted only recently, thus hydrologic studies are also recent. Prior to the IMSRP, the only hydrologic study over an Illinois longwall mine was conducted by Pauvlik and Esling (1987). IMSRP studies, the first to examine the effects of active longwall mining on bedrock hydrogeology in the Illinois Basin, were part of a longer term, comprehensive investigation that included rock characterization and subsidence monitoring studies by the ISGS (Brutcher et al. 1990, Kelleher et al. 1991, Mehnert et al. 1990, Van Roosendaal et al. 1990) and agronomic studies by the University of Illinois (Darmody 1990).

The studies cited generally indicated that the hydraulic properties (permeabilities and storage coefficients) of the strata are changed, primarily increased, by the creation of new fractures, and the opening and closing of existing joints and bedding planes. These changes in turn affect groundwater velocities, hydraulic heads and water levels, leakage between aquifers, and yields to wells.

The hydraulic changes apparently vary with the different intensities of deformation that develop at different levels in the overburden (Rauch 1987, Peng 1986). They found that, to some height above the mine (typically up to 20 to 60 times the mined thickness), the strata are extremely fractured and probably dewater into the mined panel. Above this zone, the intermediate levels of the overburden subside by bending and tend to continue to be a hydraulic confining zone (aquitard). Nearer the ground surface, the shallow aquifers deform more freely than the strata at depth and exhibit distinct hydrologic responses to the in situ subsidence: induced strains, rapid declines in potentiometric levels over and near panels, complete or partial recoveries after mining, and increased permeabilities.

Because the shallow, fracture-controlled, hydrologic response is a separate mechanism from that of drainage into the mine, there may be considerable effects on aquifers even when the mine is dry. Water from one part of the shallow groundwater system can discharge to other parts of the shallow system; for example, springflow may increase downgradient in hilly terrain (Tieman and Rauch 1987). Subsidence-related hydrogeological effects have also included loss of ponds, stream flow, and soil moisture due to increased downward drainage of groundwater (Singh and Bhattacharya 1987) as well as lower water levels in wells (Hobba 1981, Booth 1986, Tieman and Rauch 1987). Subsidence can also create problems with excess water, particularly where the water table is high in flat terrains (Kratzsch 1986).

In the Illinois Basin setting, with lower relief and less permeable strata than are present in Appalachia, deep room-and-pillar mines have usually been dry (Cartwright and Hunt 1981), and this mining method has had little effect on the minor bedrock aquifers. The impact of longwall mining on local groundwater resources can be expected to be greater and different, however, than the effects of room-and-pillar mining. Although groundwater resources in the Illinois coalfield are relatively poor in quality and quantity, they are locally important for agricultural and domestic uses. Shallow wells into drift and bedrock aquifers supply water to thousands of farms and homes, hundreds of municipalities, and numerous industries (Smith and Stall 1975).

Objectives

The broad goal was to observe and understand the hydrogeologic response to subsidence due to longwall mining in Illinois. The initial objectives of the study were as follows:

- determine the changes in permeability and storativity that occur at various distances from the active mining face and at various depths below ground;
- monitor changes in groundwater levels that occur in response to mining and mining-induced subsidence;
- measure chemical changes in groundwater above the study mine—changes that could indicate mixing of groundwaters and, hence, the impact of subsidence on aquifer connectedness, integrity, and flow patterns.

JEFFERSON COUNTY SITE

Site Description and Geology

The study site was in Jefferson County in south-central Illinois, about 12 miles southwest of Mt. Vernon in Sections 19 and 20, T4S, R2E. The mine operated in the Herrin Coal at a depth of about 700 feet. The Herrin Coal, ranging from 7 to 11 feet, is typically 8 to 9 feet thick in the study area. The overlying bedrock consists mainly of low permeability strata (shales, siltstones, some thin limestones) but includes a minor aquifer, the Mt. Carmel Sandstone. The aquifer is 80 to 90 feet thick below the study area and overlain by a shale-dominated confining interval and a thin (8–28 ft) cover of glacial drift.

The site contained four longwall panels, each more than 5,000 feet long, 600 feet wide, and 200 feet apart, separated by a twin row of pillars. Panels 1 and 2 were completed in 1988; the study began during the mining of panel 3 in 1988 and bracketed the mining of panel 4 in 1989. Periodic monitoring (Van Roosendaal et al. 1990) showed that subsidence, more than 6 feet over panels 3 and 4, was largely completed within 6 weeks of undermining.

The bedrock below the study area is relatively undeformed, flat-lying strata. The Pennsylvanian-age bedrock above the Herrin Coal consists of units of the Carbondale, Shelburn, Patoka, and Bond Formations (Greb et al. 1992). The immediate roof of the Herrin Coal is the Energy Shale, locally more than 100 feet thick.

The Mt. Carmel Sandstone of the Bond Formation is a widespread sandstone/siltstone unit in southeastern Illinois (Mehnert et al. 1994). The base of the Bond Formation, approximately 500 feet above the Herrin Coal, is at the base of the Carthage Limestone. A shale-dominated interval 70 feet thick lies between the top of the Carthage Limestone and the base of the Mt. Carmel Sandstone at the study site (fig. 1). The Mt. Carmel Sandstone at the study area is composed of channel facies dominated by thick sandstone units (Mehnert et al. 1994). Drill holes in the study area show the Mt. Carmel Sandstone to be around 85 feet thick, with roughly the bottom 50 feet predominantly sandstone with minor shale and siltstone interbeds; whereas the upper 35 feet contains both sandstone and silty shale, although siltstone generally predominates.

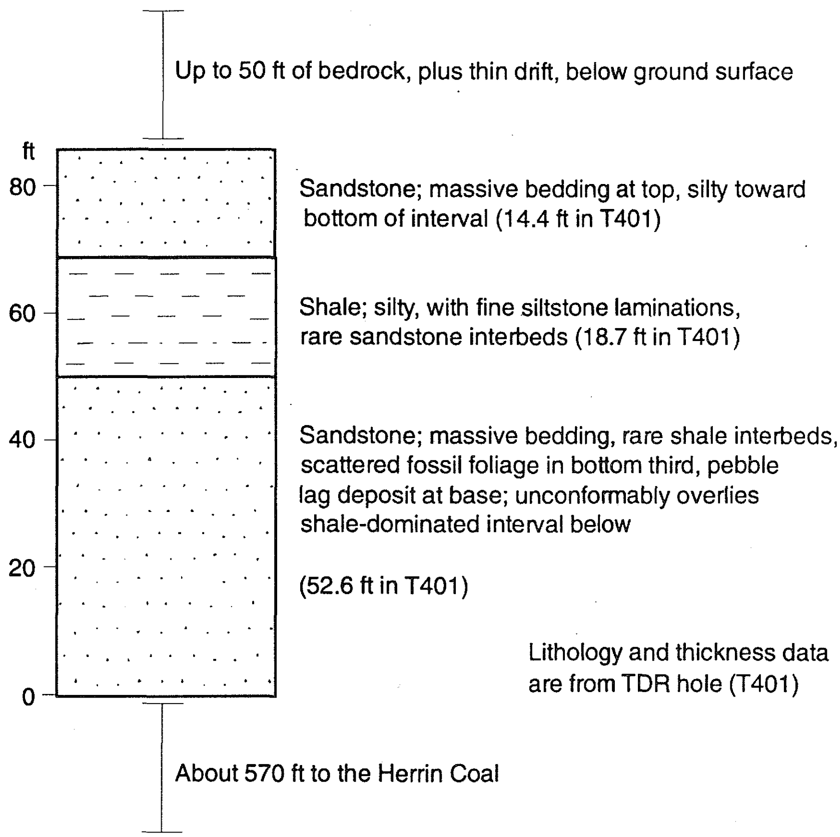

Figure 1 Mt. Carmel Sandstone lithology and position within the bedrock.

The Rend Lake Fault Zone crosses the mine, striking roughly N20°W adjacent to the study area. The longwall study panels, aligned east to west, were laid out to avoid these faults; the position of the fault just to the east of the study panels determined the eastern extent of panels 3 and 4. Because this fault dips westward, no fault effects were expected to be found in the subsided overburden.

Hydraulic Properties

Three hydrogeologic units of principal interest are present at the Jefferson County site: the surficial drift aquifer, the upper confining shale-dominated interval, and the Mt. Carmel Sandstone aquifer. The surficial drift aquifer is mainly till but includes some sand and gravel; it produces fresh water. The upper bedrock aquitard consists of the shale-dominated interval overlying the Mt. Carmel sandstone; bedrock wells in this aquifer produce brackish water.

The Mt. Carmel Sandstone aquifer, locally tapped by wells, produces slightly brackish water. Water levels at the site were monitored by five drift piezometers, seven bedrock piezometers, and one pump well, and later supplemented by two postsubsidence replacement piezometers. Other hydrogeologic information was gathered by packer tests on selected holes, slug tests, and pump tests run on piezometers adjacent to the pump well (fig. 2).

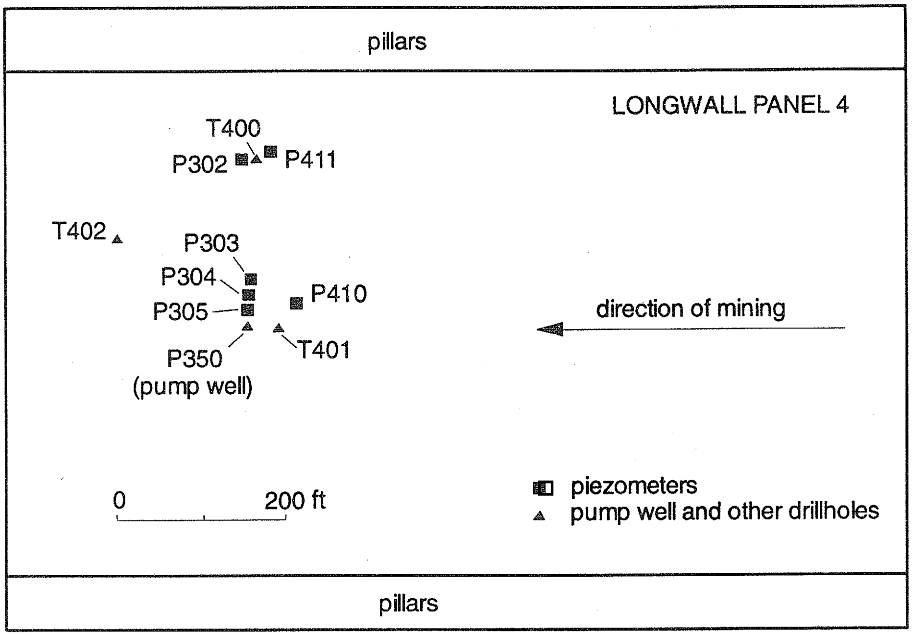

Figure 2 Instrument locations over panel 4.

Throughout the earlier investigations, the sandstone aquifer over panel 4 was unconfined. Hydraulic conductivities of the Mt. Carmel Sandstone before undermining were determined by slug tests in piezometers (P302, P303, P304), pumping tests in the pump well (P350), and packer tests in core hole T401 drilled at an angle to 720 feet deep (tables 1 and 2).

Overall, the tests indicate that the presubsidence hydraulic conductivity in the more permeable zones of the aquifer were in the of range 10^{-5} to 10^{-4} cm/s, and in the aquifer as a whole, about one order of magnitude less. Although there were some discrepancies in values obtained from different methods, the evidence generally suggests an increase in hydraulic conductivity of the sandstone of about one order of magnitude due to subsidence (Booth and Spande 1992).

Table 1 Slug test results for piezometers over panel 4 (modified from Booth and Pattee 1994).

Piezometer	Location	Mt. Carmel subunit	Screened depth (ft)	Hydraulic conductivity (Spande 1990)	Hydraulic conductivity (Pattee 1994)
P303	central	upper	102–112	1.8×10^{-5} cm/s	—
P302	north edge	lower	136–146	2.1×10^{-4} cm/s	—
P304	central	lower	142–152	3.0×10^{-4} cm/s	—
P306	off panel	lower	145–155	1.4×10^{-6} cm/s	5.1×10^{-7} cm/s
P410	central	lower	144–154	—	2.2×10^{-4} cm/s
P411	north edge	lower	145–155	—	1.4×10^{-3} cm/s

Table 2 Pump test results for panel 4 (modified from Booth and Pattee 1994).

Piezometer	Location	Mt. Carmel subunit	Presubsidence hydraulic conductivity (Spande 1990)*	Postsubsidence hydraulic conductivity (Pattee 1994)**	Postsubsidence hydraulic conductivity (Miller in prep.)†
P350††	centerline	all	3.3×10^{-6} cm/s	5.4×10^{-5} cm/s	9.4×10^{-5} cm/s
P303	central	upper	5.0×10^{-5} cm/s	—	—
P302	north edge	lower	9.7×10^{-5} cm/s	—	—
P304	central	lower	9.9×10^{-5} cm/s	—	—
P410	central	lower	—	4.4×10^{-4} cm/s	2.6×10^{-3} cm/s
P411	north edge	lower	—	1.0×10^{-2} cm/s	2.1×10^{-3} cm/s

* Neumann analysis; ** Hantush analysis; † Jacob analysis; †† pump well

Water Levels and Potentiometric Response

Water levels were monitored by using pressure transducers and recording drop line levels in piezometers over and near panels 3 and 4, and by recording drop line levels at intervals in farm and domestic wells over and around the site. The initial piezometric levels in the Mt. Carmel Sandstone were approximately 70 feet deep below ground surface (depending on the piezometer and initial date). Over panel 3, they declined about 20 feet (on the barrier) and 40 feet (on the centerline) in the 3 weeks preceding undermining, reached a minimum when the site was in the tensional zone of the advancing subsidence front, then recovered gradually in the months after undermining. During the next 2 years, values recovered at least to the levels initially measured.

The water table measured at intervals in wells in the drift over and near the panels did not respond to mining or subsidence, although rapid, very small fluctuations during actual ground subsidence were observed by the ISGS field technicians and by Darmody (1990) using pressure transducers in drift piezometers. Water levels in the upper bedrock (shale overlying the Mt. Carmel) fell rapidly, however, with undermining or adjacent subsidence. For example, a 62-foot-deep bedrock well on the edge of panel 3 dewatered, whereas the drift well at the same site remained unaffected.

Longer Term Investigations

In 1991, two replacement piezometers were drilled into the Mt. Carmel Sandstone over subsided panel 4, one approximately on the centerline (P410), and one in the surface tension zone at the edge of the subsidence trough (P411). Open fracturing (leading to lost circulation problems) was evident during the drilling of these holes, especially P411. Slug tests conducted in these piezometers in early 1992 showed water acceptance rates several times greater than the slug tests in the presubsidence holes.

Postsubsidence pump tests were run to evaluate well yield and determine permeability boundaries. Pattee (1994) compared presubsidence with postsubsidence pump test results (table 2) to evaluate changes in hydraulic conductivity. In the lower aquifer (comparison of P304 and P302 with P410 and P411 results), permeability increased about one-half of an order of magnitude in the compression zone and two orders in the tension zone. Results of a Jacob analysis of a more recent pumping test (Miller in prep.) indicate that hydraulic conductivity, compared with presubsidence values, generally increased in the aquifer. Related work supports the concept of a more permeable tension zone bounded by linear discontinuities.

Miller also compared earlier data and new data sets with various aquifer models and concluded that (1) the shale-dominated sequence above the Mt. Carmel was an effective confining unit, (2) the aquifer is internally divided into two hydraulically separate sandstone units by the intervening shale confining unit, and (3) the lower sandstone subunit is the more important aquifer, according to the comparison of well yields. Miller also noted a surprising degree of horizontal anisotropy in a postsubsidence test, in which the permeability was greatest north to south, apparently as a result of north–south flexure cracks due to the passing of the dynamic subsidence wave.

Conclusions from the Jefferson County Site

The fracturing and joint and bedding-plane dilation that accompanied subsidence increased the permeabilities by about one order of magnitude in the sandstone, and by several orders at localized zones in the lower, tighter sequence. From the various hydraulic tests, it is clear that subsidence changed the Mt. Carmel Sandstone locally from a poor aquifer into a potentially more productive aquifer with a complex hydraulic configuration. Test results indicate that higher pumping rates are sustainable with lower drawdowns. Increased fracture permeability appears to be high in the tensional zones along the edges of the panel. This zone, which surrounds a rectangular area of moderately increased permeability in the central subsidence trough, is surrounded by a native zone of unchanged permeability.

SALINE COUNTY SITE

Site Description and Geology

The second study site was in northwestern Saline County, about 10 miles northwest of Harrisburg, in Sections 16, 17, and 18, T8S, R6E. The mine extracted the 5- to 6-foot-thick Herrin Coal at a depth of about 400 feet. The overlying bedrock is dominated by thick shale intervals interspersed with a few thin beds of coal, impure limestone, and siltstone. The only possible bedrock aquifers are the sandstones at the 180- and 280-foot depths. The lower unit, which may be the Gimlet Sandstone, is generally thin and less important as an aquifer. The upper sandstone is the Trivoli Sandstone, which is continuous and ranges from 2 to 55 feet thick over the southern half of the mine, occurs both as a sheet up to 35 feet and a channel facies from 35 to 55 feet thick (Curtiss in prep.). In the study area, the Trivoli Sandstone is only a sheet facies (fig. 3) and laterally variable in lithology. Above the bedrock is a 60- to 90-foot thick drift deposit that is mainly Illinoian till but includes some sand and gravel lenses.

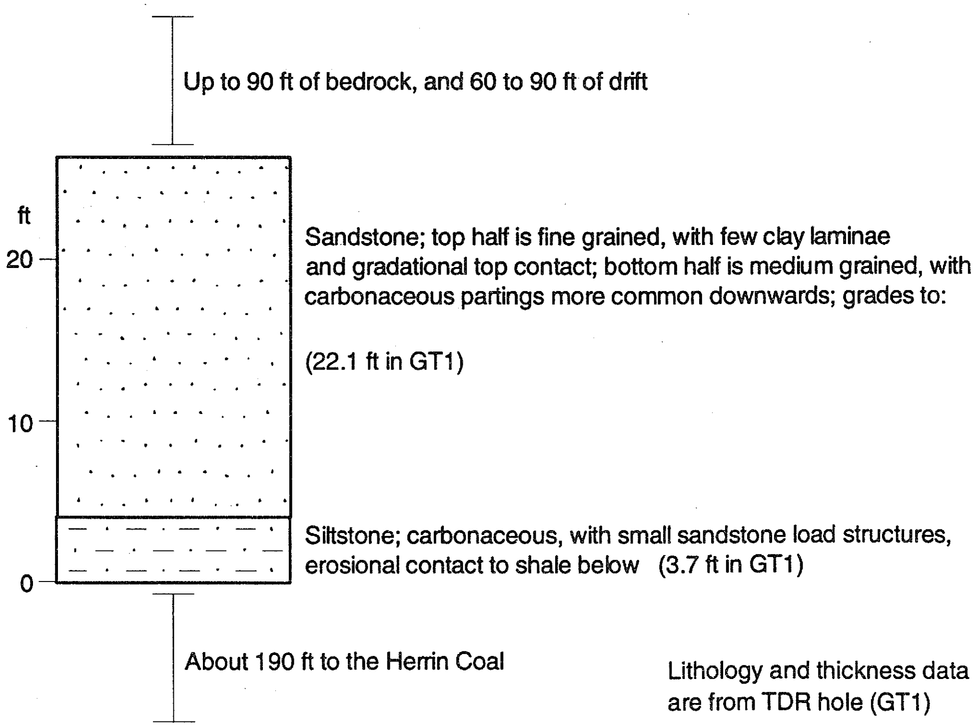

Figure 3 Trivoli Sandstone lithology and position within the bedrock.

The study began prior to the start of the first longwall panel, which was mined from late 1989 into 1990. The ISGS (Van Roosendaal et al. 1990, Kelleher et al. 1991) measured surface subsidence of about 4.5 feet, and reported that above the 20-foot caving zone immediately over the mine, there was relatively little differential vertical displacement or major bedding separation of the overburden at the center of the panel.

Hydraulic Properties

The water levels at the site were monitored by four drift piezometers, eight bedrock piezometers, one pump well, and later supplemented by a postsubsidence bedrock piezometer (BPPS). Other hydrogeologic information was gathered by packer tests on selected holes, slug tests, and pump tests run on piezometers adjacent to the pump well (fig. 4).

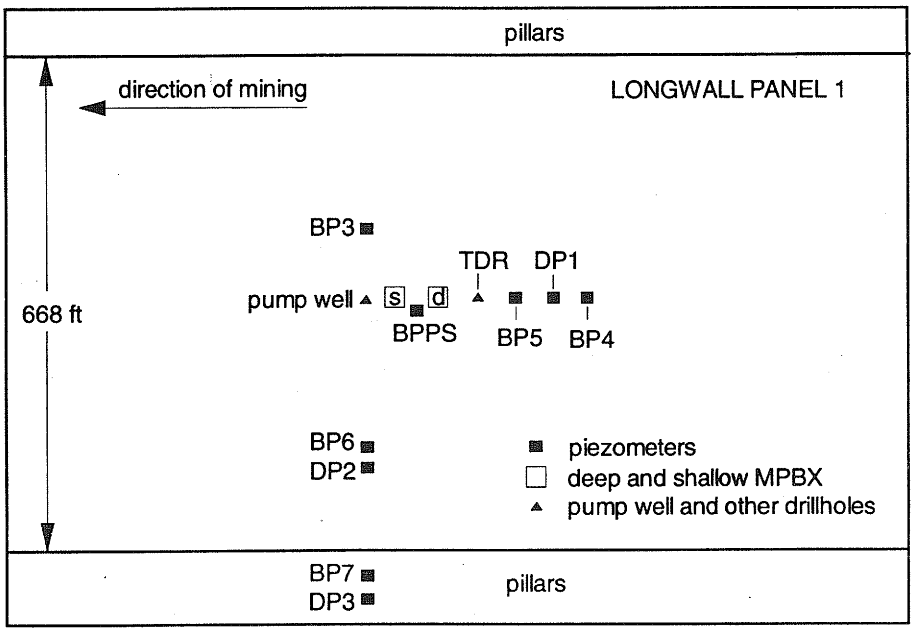

Figure 4 Instrument locations over panel 1.

Because of damage to piezometers and to the test well shortly after the area was undermined, hydraulic property data from this site were limited. Slug tests in different Trivoli piezometers over the panel centerline yielded hydraulic conductivity values of around 2.5×10^{-5} cm/s before subsidence and around 4×10^{-5} cm/s after subsidence—a very modest increase. The only directly comparable data are for BP7, over the pillars between panels 1 and 2; slug tests showed progressive increases in conductivity as each panel was mined, but a net increase of well less than one-half of an order of magnitude (table 3).

Packer tests of bedrock were conducted at 10-foot injection intervals in two boreholes drilled on the panel 1 centerline: a 426-foot-deep hole before subsidence, and a 276-foot-deep hole after subsidence (fig. 4). Both tests showed that most of the bedrock would not accept water; but postsubsidence tests of the Trivoli Sandstone showed increased permeability due to fracturing, dilation of joint and bedding planes, and increased interconnectedness of fractures.

Water Levels and Potentiometric Response

Changes in water levels in drift and bedrock piezometers were recorded as mining progressed. Drift piezometers 1, 2, 3 and the drift control piezometer were located over or adjacent to panel 1 (fig. 4) and varied in depth between 53 and 76 feet within the drift (Van Roosendaal et al. 1994). Hydrographs for drift piezometers over and adjacent to panel 1

Table 3 Hydraulic conductivity values for bedrock piezometers (from Curtiss in prep.).

Piezometer	Type of test	Date	Timing relative to mining panels	Conductivity value (cm/sec)	Unit
BPC	Slug	1-4-93	after 2	7.88×10^{-7}	Trivoli Ss
BP3	Slug	12-14-89	during 1	2.51×10^{-5}	Trivoli Ss
BPPS	Slug	3-11-91	after 1	2.72×10^{-5}	Trivoli Ss
BP4	Slug	8-25-89	before 1	4.82×10^{-5}	Gimlet Ss
BP4	Slug	11-8-89	before 1	4.01×10^{-5}	Gimlet Ss
BP6	Slug	8-25-89	before 1	4.70×10^{-5}	Trivoli Ss
BP6	Slug	11-8-89	before 1	4.65×10^{-5}	Trivoli Ss
BP6	Slug	12-14-89	during 1	4.56×10^{-5}	Trivoli Ss
BP7	Slug	12-14-89	during 1	2.33×10^{-5}	Trivoli Ss
BP7	Slug	5-23-90	after 1	3.55×10^{-5}	Trivoli Ss
BP7	Slug	3-11-91	after 2	6.35×10^{-5}	Trivoli Ss

showed 6- to 10-foot drops due to undermining, whereas the control well and nearby wells showed erratic or unchanged levels (Curtiss in prep.). The range of influence on drift piezometers ahead of mining can only be estimated because of the scarcity of early data. The mining of panel 2 adjacent to panel 1 indicated that tensile and compressional events influenced water levels 300 feet away, but no response was seen at 600 feet away.

All bedrock piezometers were placed in the Trivoli Sandstone, except BP4, which was placed in the underlying Gimlet Sandstone 70 feet below the Trivoli Sandstone. These two sandstone units are separated from each other and from the bedrock surface by aquitards. The maximum depth of the Trivoli Sandstone piezometers ranged from 143 to 196 feet; initial drops for several bedrock piezometers exceeded 100 feet. Each bedrock piezometer showed similar patterns where the pattern is complete, but most of the bedrock piezometers over panel 1 were damaged within 6 weeks after being undermined (Van Roosendaal et al. 1994). The range of influence ahead of mining was considerably farther for bedrock piezometers than for drift piezometers. In the Trivoli Sandstone, declines in water levels occurred over the panel when the longwall face was at least 2,800 feet away. The rate and regularity of decline in the bedrock piezometric levels were directly related to the face advance rates.

Conclusions from the Saline County Site

The increased hydraulic conductivity in the mass of subsided bedrock was due to two mechanisms: (1) regularly distributed voids due to extension acting on existing joints and bedding planes (dilation of rock mass), and (2) development of new tensional and shear fractures.

The primary changes to the two bedrock aquifers were an opening up of existing discontinuities, and the development of new tensional and shear fracturing due to the passing extensional wave. These changes significantly increased storativity within the bedrock, which accounts for substantial drops in water level in the upper bedrock, as registered by the piezometers. Hydraulic tests indicated that the sequence at the Saline County site was generally tight; the Trivoli Sandstone experienced slight to moderate increases in permeability and fracture continuity, but remained poorly permeable overall. Slug tests in the Trivoli suggest some horizontal heterogeneity within the aquifer. The lack of a longer term recovery suggests that the aquifer was inadequately recharged because of low transmissivities, internal lithologic variability, tight confining cover, and continued upgradient mining.

GENERAL CONCLUSIONS

The potentiometric responses before and during mining conform to the general model that is becoming clear from studies elsewhere and from the earlier phase of the IMSRP investigation. At both sites, the thick, tight lower confining layers have prevented drainage from the near surface sandstone into the mine or lower aquifers. The water level drops thus appear to be a result of the opening of increased fracture and bedding plane voids during subsidence. This opening of voids creates storage capacity for groundwater, lowers the water levels, and causes water to move toward the area of lowered water levels (drawdown). The steepness of the gradient of the drawdown, and hence the nature of the drop in head, depends on the permeability of the unit. The response is thus later, more localized, and more intense in less transmissive units.

The possibility of physical enhancement of the low-yielding sandstone aquifers by the improvement of well yields as a result of subsidence depends on two conditions being met:

1. Subsidence increases the permeability and storativity of the aquifer through fracturing and bedding separation. This has certainly been the case at the Jefferson site, where all hydraulic tests indicate significant enhancement of the aquifer properties in the Mt. Carmel Sandstone. There has been only a modest permeability increase at the Saline site, however, where the fracturing and bedding separation in the bedrock was not as intense.

2. The affected aquifer is adequately recharged after mining. Increased permeability and storativity alone cannot improve well yields if the water levels remain depressed.

The sandstone aquifer at Jefferson County had substantial water level recovery, in fact to heads higher than those first measured (indicating the aquifer had already been affected by adjacent mining). This recharge is probably occurring primarily by lateral migration through the aquifer, which is relatively transmissive, and secondarily by leakage through the overlying shale.

The lack of recovery of the Trivoli Sandstone at the Saline County site reflects the poor "rechargeability" of the aquifer, which is thinner and more variable in lithology across the site than the Mt. Carmel Sandstone at the Jefferson site. The Trivoli Sandstone has lower overall permeability, so that potential for lateral recharge through the aquifer is diminished. At the Saline County site, the recharge flows are not only hindered laterally but also restricted by overlying tight shales.

The overall conclusion is, therefore, that aquifer enhancement can indeed occur, but is critically dependent on local geological conditions. The most favorable conditions are those in which the aquifer already possesses more than marginal transmissivity and has the potential for recharge either laterally through the aquifer and/or vertically from overlying aquifers with which it is in effective hydraulic communication.

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MODELING THE HYDROGEOLOGICAL EFFECTS OF LONGWALL MINING IN ILLINOIS

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Summarized by Colin J. Booth

ABSTRACT

Concurrent studies in the Illinois Mine Subsidence Research Program (IMSRP) showed that the conceptual model of aquifer conditions was uncertain and ambiguous; therefore, the project focused on clarifying the conceptual hydraulic model. The critical conditions of the sandstone aquifer at the longest studied site in Jefferson County were shown to be the separate layering into upper and lower sandstone benches, the return to a properly confined condition after mining, and the sharp zonation of permeability created by subsidence, particularly the high permeability region in a widened tension zone. The first of these conditions is site-dependent. The third condition should be a general feature of longwall subsidence. The return of the aquifer to a confined condition depends on site characteristics but should be a feature of many longwall settings. These conditions have been simulated on readily available modeling software for personal computers.

INTRODUCTION

Original and Modified Objectives

The original objective of this study was to develop a numerical computer model to simulate and predict the effects of longwall mining on groundwater flow at sites in the southern Illinois setting. The model would be designed to predict the behavior of the hydraulic head and related flow features in the shallow aquifer region above the mine, and empirically incorporate changes in ground elevation and hydraulic properties due to subsidence. It was not intended to simulate the immediate roof behavior or drainage of groundwater into the mine. The model would be based on established partial differential equations of groundwater flow and developed in FORTRAN with an additional version in BASIC. Calibration would be based on sites currently under study in the IMSRP. Since the project started, however, several external developments have forced changes in the study:

Advanced personal computers have developed rapidly. Since the original proposal was made, the power, computing speed, and storage capacity of standard office computers have increased massively. The hardware explosion has made it feasible for users of personal computers to run powerful modeling programs previously accessible only on mainframes.

Concurrently, modeling software became readily available (and easily usable) for personal computer users. Major standard modeling programs such as the USGS MODFLOW, originally designed for mainframes (McDonald and Harbaugh 1988), are now commercially available for personal computers. These programs no longer require the user to program in FORTRAN, or even to have access to a FORTRAN compiler. For example, the *Graphic Groundwater* version by Micro-Innovations (Esling and Larson 1993) follows the mathematics of MODFLOW but is completely rewritten in C++ and operates entirely through a graphic menu/mouse interface. Furthermore, because of increased computing power, these programs are now capable of simulating a wide range of boundary conditions and hydraulic stress regimes, including those for underground mines, without the need for code modification. In effect, the FORTRAN development stage of this proposal became obsolete. The subsidiary objective of developing a hydrogeologic model in BASIC not only became obsolete, but impossible. BASIC, a DOS-manipulation language for simple utility programs, is not capable of operating such sophisticated software.

While the task of running computer models became simpler, the problem of interpreting hydrogeologic data in a conceptual model became more complex. Concurrent IMSRP field studies revealed more uncertainties, ambiguities, and complexities. It is generally accepted that one of the greatest problems in mathematical and computer modeling is the original conceptual model of hydrogeologic conditions and processes; all further modeling efforts depend upon a well-defined problem. In particular, three hydrogeological issues became of chief concern in this study:

1. precise delineation of the impact of longwall subsidence on the hydraulic properties and movement of groundwater in the overlying aquifer. Related IMSRP field studies were indicating anomalies in the configuration of permeability changes and in time-dependent potentiometric changes—anomalies that needed to be resolved.
2. resolution of ambiguities in the hydraulic test data, especially discrepancies between permeabilities determined by pumping and slug tests.
3. interpretation of the site conditions, for example, whether aquifers were semiconfined or confined, whether leakage was significant or double porosity a factor, and how different types of boundary conditions affected such hydrogeologic parameters.

It therefore became evident that the most useful direction for this project was a conceptual model of the hydrogeologic conditions, rather than the development of a computer code that would immediately be obsolete. To that end, this project overlapped considerably with and supported the other field-oriented, hydrogeological studies under the IMSRP.

BACKGROUND

Hydraulic Response to Longwall Mining

Longwall mining produces rapid subsidence of the overburden and ground surface. The hydraulic properties of the overburden strata are altered by the creation of fractures, the opening and closing of joints and bedding planes, and the dislocation of conductive and confining horizons. Consequently, hydraulic heads, groundwater flow, leakage, and other groundwater characteristics are altered in the area of subsidence and the immediate vicinity. The effects differ according to location and time of occurrence in the subsidence stress regime, but the overall result of the fracturing and the dilation of joints and bedding planes is an increase in the permeability and storage coefficient of the bedrock strata. The observed effects of subsidence on the bedrock aquifers typically include rapid, localized declines in potentiometric levels during mining, partial recoveries after mining, and residually increased permeabilities. Although the lowest zone above an active longwall panel tends to be heavily fractured and dewaters into the mine, this zone is typically overlain by thick confining units that prevent the hydraulic effects of mine drainage from reaching the shallow aquifers. The shallow aquifers thus respond primarily to in situ subsidence strains.

The IMSRP field characterization studies have supported the concept that the bedrock hydraulic response corresponds well to the sequence of tension and compression observed in the subsidence stress regime. At the site of subsidence, increased porosity due to dilation of joints and bedding planes causes declines in potentiometric heads. The resultant potentiometric low induces a surrounding potentiometric depression and inward-focussed hydraulic gradient. Therefore, potentiometric levels ahead of the advancing subsidence front also decline, reaching their minima as the site undergoes maximum tension. The water levels partially recover when bedding planes and joints close up and water flows in from other parts of the aquifer during the compressional phase.

These potentiometric effects spread farther in the more transmissive strata than in the poorly transmissive strata, in which they are more localized and more intense. In the Illinois coalfield, however, the generally low transmissivities of strata, even of the aquifer units, tend to limit potentiometric effects to within a few thousand feet of the subsiding mine face.

Within the subsidence trough, differences in stress–strain responses would be expected to cause systematic spatial variations in hydraulic effects. In particular, the outer edge of the subsidence trough undergoes only the tensional phase of the subsidence wave, not the later compressional phase, which is restricted to a smaller inner area. This outer zone of residual tension, characterized by permanently dilated fractures, should thus have a greater residual increase in permeability than occurs in the interior compression zone. The tension zone should therefore be a corridor of preferential groundwater flow, anomalous potentiometric levels, and increased vertical leakage. The IMSRP field studies by Booth and Pattee (1994) have supported this concept of permeability configuration.

Review of Modeling Studies

Few applications of numerical flow models have been made to examine the hydrological effects of underground coal mining. Stoner (1983) applied finite-difference modeling to the groundwater system affected by room-and-pillar mining in Pennsylvania. Booth (1984) developed a finite-difference model of groundwater flow above a Pennsylvania longwall mine, but calibration was crude and the code was not developed enough for general practical application. Schmidt (1985) applied a boundary integral model to simulate a dewatering operation for a room-and-pillar mine in a fracture-zone setting in West Virginia. Several models have simulated two-phase (water and gas) flow in the coal seam (Contractor and Eftekharzedeh 1985, Contractor 1988), and Owili-Eger (1989) reported on proprietary two-phase models to simulate mine inflow in a variety of situations.

An ideal comprehensive model would include subsidiary simulations of the following:

- the stresses at all affected positions and times from a specified mine operation in a specified setting;
- the strains (e.g., fracture aperture changes) that would result from these stresses;
- the changes in hydraulic properties that would result from these strains;
- the changes in potentiometric heads, gradients, flow rates, and leakages caused by the changes in hydraulic properties.

Different models focus on different parts of this problem. No comprehensive model has been developed to adequately predict the changes either in hydraulic properties or in the specific stresses and strains that result from mining. Bai and Elsworth (1991) produced a continuous, deterministic groundwater model that attempted to link the several stages (described above) through functional relationships, such as a simple cubic law relating fracture aperture to fracture permeability, and poroelastic models relating stresses, permeability changes, and pressure changes. The primary hydrological stress was drainage into the mine. The complexity of actual field variations in hydrogeology was not considered.

HYDROGEOLOGICAL SITE STUDY

This report concentrates on the IMSRP study site in Jefferson County, Illinois, where hydrogeological conditions relating to the mining of the last two longwall panels of a four-panel section have been studied since 1988. The panels, approximately 5,000 feet long and 600 feet wide, were mined in the Herrin Coal at a depth of approximately 725 feet. Mining of the panels produced subsidence troughs with a maximum subsidence of about 6 feet in depth. Over panel 4, the overburden is a mainly poorly permeable bedrock sequence with a minor aquifer, the Mt. Carmel Sandstone, occupying the interval between about 70 and 155 feet below ground surface. The sandstone is overlain by a confining unit of shale and 15 to 30 feet of glacial drift. Local wells penetrate the drift, shale, and (off site) sandstone.

IMSRP studies concentrated on the effects of mining on the hydrogeologic behavior of these shallow aquifer units. As discussed in more detail in the IMSRP reports by Booth and Spande (1992) and Booth and Pattee (1994), the sandstone aquifer exhibited a four-stage potentiometric response:

1. advance decline in heads transmitted through the aquifer from the subsiding zone;
2. sharp drop in head in the subsiding zone due to increased fracture porosity and leakage;
3. rapid partial recovery as the site moved into the compressional phase;
4. long term recovery by recharge through and into the aquifer, to above initially measured levels.

At the other IMSRP study site in Saline County, there has so far been no long term recovery, probably because of limited recharge potential of the aquifer. At the Jefferson site, the overlying shale had sharp subsidence-related head drops and eventual postsubsidence recovery, whereas the water table in the drift aquifer had at most a minor response to subsidence-related changes in topography.

Hydraulic Testing and Analysis over Panel 4

Constant Head Packer Tests Pressure injection straddle-packer tests were conducted in the Mt. Carmel Sandstone over the center of panel 4 in cored boreholes T401 (presubsidence) and T402 (postsubsidence). The T401 results showed that the Mt. Carmel Sandstone had hydraulic conductivities between 3×10^{-7} and 1×10^{-5} cm/s (Booth and Spande 1992), with a geometric mean of 4.7×10^{-5}. The T402 results had a geometric mean of 9.1×10^{-4} cm/s over the somewhat thinner sandstone interval, indicating an increase of more than one order of magnitude. T402 was approximately 100 feet from T401 and had evident bedding dislocation and fracturing due to subsidence.

Falling Head Slug Tests in Piezometers Presubsidence hydraulic conductivities in the lower (P304), middle (P303), and upper (P302) sections of the sandstone over the panel were 3.0×10^{-4}, 2.1×10^{-4}, and 1.8×10^{-5} cm/s respectively, and 1.4×10^{-6} cm/s in the lower sandstone piezometer (P306) north of the panel. Spande (1990) suggested that the apparent upward decrease in permeability corresponded to the upward grain fining observed in cores.

Postsubsidence slug tests were performed in lower sandstone piezometers P410 and P411 in the inner (compression) and edge (tension) zones of panel 4. The results (2.2×10^{-4} cm/s in P410, 1.4×10^{-3} cm/s in P411) are probably low estimates because slug inputs were not instantaneous and discrete open fractures were present, especially in P411. There has been at least one order of magnitude increase in permeability in the tension zone, and probably considerably more, if test difficulties and aquifer heterogeneity are taken into account.

Pumping Tests Numerous pumping tests have been conducted in P350 at the centerline of panel 4 (Spande 1990, Pattee 1994, Miller in prep.). The 1988–1989 suite of presubsidence tests were mainly brief and produced varying determinations of hydraulic conductivity, partly attributable to development of the aquifer. The last and longest (test 5: 239 minutes) produced a conductivity value of 3.3×10^{-6} cm/s by recovery analysis. Results from presubsidence observations in piezometers gave conductivities in the range of 5×10^{-5} to 1×10^{-4} cm/s. Postsubsidence tests in 1990 produced more consistent values. The comparable test 11, which lasted 258 minutes, indicated a conductivity of 3.7×10^{-5} cm/s—again, one order of magnitude greater. These tests were analyzed by the Neumann method because of the unconfined aquifer conditions.

Pattee (1994) conducted several pumping tests in well P350 and also observed drawdowns in P410 and P411. By this time (1992), the aquifer had returned to a confined condition, and the results were analyzed by the Hantush method for leaky confined aquifers. For test 11 (the longest at more than 24 hours), conductivities for the pumping well were 5.4×10^{-5} cm/s (very similar to Spande's postsubsidence results), and 4.4×10^{-4} cm/s for P410, and 1.0×10^{-2} cm/s for P411. These piezometer results are higher than the values from the slug tests (noted above) but perhaps more reasonable, given the qualitative observations of high-permeability characteristics of these boreholes.

As noted in the Booth and Spande 1992 report to IMSRP, the results differ from test method to method, most likely because of scale factors:

- Different vertical zones of the aquifer are sampled between packer tests with 10- and 20-foot injection intervals, slug tests with 10-foot test intervals, and pumping tests that sample the whole aquifer.
- Different regions of the aquifer are sampled by the tests. The pumping tests, especially the longer tests, sample much wider regions than the slug and packer tests, and thus

incorporate greater heterogeneity. They are also less influenced by disturbed conditions around the boreholes.

In general, the packer test and slug test results are more similar to each other than to the pumping test results.

RECENT MODELING

The studies at the Jefferson County site by Spande, Pattee, and Booth identified several major ambiguities and uncertainties in the conceptual hydraulic model. Therefore, the project was redirected toward resolving these ambiguities, a task that formed part of the master's thesis of Miller (in prep.). The following is partly summarized from the earlier field results and Miller's recent work.

Heterogeneities

The Mt. Carmel Sandstone is clearly heterogeneous. Its hydraulic conductivity varies spatially between test holes over a range of two orders of magnitude over distances of a few hundred feet. Natural hydrogeologic boundaries certainly exist. The edge of the sandstone paleochannel lies about 1 mile to the west and less than 1 mile to the north (Pattee 1994) and would most likely be a no-flow or low-permeability boundary; whereas recharge boundaries probably occur between 1 and 2 miles farther south, where the sandstone thickens rapidly then subcrops at the bedrock surface. Permeability discontinuities also occur because of subsidence features; especially, the tension zone is a zone of increased permeability. Hydrogeologic discontinuities cause deviations from ideal type curves in the drawdown data obtained from pumping tests. Alternative interpretations of these deviations are leaky aquifer, unconfined, and double-porosity conditions.

Leaky Aquifer Condition

The possibility that water was leaking through the overlying shale into the sandstone was supported by several lines of evidence, some ambiguous. The packer tests indicated horizontal permeabilities in the shale of the order of 10 to 4 cm/s; however, excess injection pressures may have caused bedding plane separation with resultant overestimated permeability. Hydrochemical analyses of Mt. Carmel water over panel 4 by Spande (1990) and later by Pattee (1994) showed increases of salinity after subsidence. The increases were interpreted by these researchers as evidence of increased leakage of water from the shale into the sandstone during subsidence. Additionally, the pumping test data collected in 1992 by Pattee fitted well with Hantush type curves for leaky aquifers.

Double Porosity Condition

Even in the natural state, the sandstone possesses both primary intergranular porosity and secondary fracture (including bedding plane and joint) porosity. Subsidence increases the secondary porosity through the separation of beds and joints and the formation of new fractures. Primary and secondary systems of permeability correspond to these separate systems of porosity. In many aquifers, the primary and secondary systems are fully interconnected and respond essentially as one hydraulic system in which the separate components are indistinguishable. Wherever there is a marked discrepancy between hydraulic properties (i.e., the intergranular porosity provides the dominant storage properties while the fractures provide the dominant permeability), the hydraulic response of the double porosity system is different from the response of a single system. The pumping test data provide some evidence for the hypothesis that subsidence might have created a double porosity system.

Aquifer Structure

The sandstone aquifer had clearly become unconfined (i.e., the potentiometric head had dropped below the top of the aquifer) in the period shortly before mining and remained so for the early postmining tests. By the later tests (1992 and after) it had become confined and, in fact, improved sufficiently in yield that it remained confined throughout the pumping tests. It had been observed in the cores and geological logs that the sandstone aquifer consisted of two benches separated by a shale-siltstone unit. It was not clear whether the benches were functioning as a single confined aquifer, or whether the intervening unit effectively separated them into two aquifers. In the latter case, the more permeable lower bench would dominate well yield, whereas the upper bench might be functionally continuous with the higher shale that overlies it and is similar to it in permeability.

Miller (in prep.) compared several different analytical methods to interpret pumping test data collected earlier by Spande (1990) and Pattee (1994), as well as more recent data collected by himself. His conclusions were as follows:

- the shale overlying the Mt. Carmel Sandstone continued to be an effective confining layer, and therefore, the aquifer was not responding as an unconfined or extensively leaky unit;
- the double porosity model was an unlikely explanation for the observed pumping test response, despite some resemblances in the data curves;
- the Mt. Carmel Sandstone was functioning as a layered aquifer: the upper sandstone unit, which had a transmissivity between 2628 and 3200 gpd/foot, accounted for about 40% of the flow of the aquifer; the whole 83-foot interval had a transmissivity of 4560 to 5200 gpd/foot; and the two sandstone units were locally separated by the intermediate confining layer;
- lateral boundaries (discontinuities in hydraulic properties) best explained the various pumping test responses.

Numerical Simulation of Pumping Response

To examine these conceptual models of aquifer condition, Miller (in prep.) has used the MODFLOW/EM version of the USGS finite-difference groundwater flow model to simulate pumping effects (as drawdown). The site was simulated as a plan view quadrant centered on pumping well P350. The lower Mt. Carmel Sandstone was represented by a single layer discretized into a grid of 38 rows by 38 columns with cell spacing ranging from 2 to 700 feet. The northern and eastern boundaries were set at 2,341 feet with a constant head condition, whereas the southern and western boundaries were defined by flow-system symmetry as no-flow boundaries. The model employed the basic MODFLOW package to define time steps and pumping periods, the block-centered flow package to simulate pumping from P350, the general head boundary package to simulate the constant head boundaries, and the SIP solution routine.

The principal domain configuration was three permeability zones extending east to west and representing the interior portion of the panel, the tension zone, and the undisturbed region beyond the subsidence trough. Miller conducted more than 100 runs of the model, varying values of hydraulic properties, positions of permeability discontinuities, and values of anisotropy to achieve calibration against the known pumping test response. Approximate calibration was achieved with

- a horizontal anisotropy factor of 7.5—the major permeability being north to south;
- an interior panel region that is bounded 72 feet from the centerline well and has transmissivities of 92 and 685 gpd/foot and storativity of 2.5×10^{-5};
- a 72- to 271-foot-wide tension zone with transmissivities of 10,200 and 76,700 gpd/foot and storativity of 2.5×10^{-3};
- an undisturbed zone that lies beyond 271 feet and has transmissivities of 8 and 61 gpd/foot and storativity of 7×10^{-5}.

It should be pointed out that Miller's results are tentative; further work may change hydraulic values and configurations. The results are included here primarily to illustrate that recent versions of modeling software are capable of simulating aquifer conditions in the longwall mining environment. Specifically, standard modeling software has (1) been used to test different conceptual models of aquifer conditions, which were obtained by comparison of analytical models of aquifer pumping tests; (2) supported field tests that indicated an increase in hydraulic conductivity of approximately two orders of magnitude in the tension zone as a result of subsidence; and (3) suggested some possible hydrogeologic conditions that merit further investigation, particularly the degree of horizontal anisotropy and the location of the permeability boundaries (which may be nearer to the panel center than ground definitions suggest).

Current Modeling

In contrast to the MODFLOW/EM simulation of pumping described above is the *Graphic Groundwater* model (1993) currently being used to simulate the site at a larger scale. Although the results are not ready for this report, they will be summarized and provided to the ISGS coordinators of the IMSRP literature. Readily available software such as MODFLOW/EM, which can be used on standard personal computers, is capable of simulating the hydrogeological conditions in the longwall mining environment.

CONCLUSIONS

IMSRP studies at the Jefferson County site showed a sandstone aquifer with many hydrogeological ambiguities. The purpose of this project was to clarify the conceptual hydraulic model. Work in conceptual, analytical, and numerical modeling indicates that the sandstone aquifer is layered and heterogeneous, with permeability boundary conditions created by the subsidence process.

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HIGH-EXTRACTION COAL MINING IN ILLINOIS: EFFECTS ON CROP PRODUCTION, 1985–1987

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ABSTRACT

Underground coal mining methodology is moving toward techniques that cause immediate planned subsidence of the overlying land. The effects on agricultural productivity have not been documented. This study in the Illinois Mine Subsidence Research Program was conducted to (1) determine the measurable subsidence effects associated with planned subsidence mining, (2) measure the impact of subsidence on corn yield, and (3) compare the effects of longwall and high-extraction retreat mining methods. Five locations in southern Illinois were included in the 3-year study, which involved 37,760 acres in 1985, 44,160 acres in 1986, and 52,480 acres in 1987. These areas represented unmined control areas as well as mitigated and unmitigated subsided areas over longwall and high-extraction retreat mines.

Subsided areas were identified on aerial photographs taken of the study locations each spring; 7.5% of the study area had measurable subsidence effects due to longwall mining and 3.3% due to high-extraction retreat mining. Corn was harvested each year on selected subsided and nearby unsubsided reference areas. The weighted average yield reduction was 4.7% for longwall mining and 1.8% for high-extraction retreat mining. Results for the individual years varied with the weather: the greater the precipitation, the greater the reductions in yield. The results also reflect the yearly variation in mining activity, crop sample areas, and overall study areas. In addition, the mitigation of subsidence effects in place at the time of the study also influenced the results, but the potential for mitigation for either mining type was not included in this research.

INTRODUCTION AND BACKGROUND

With traditional room-and-pillar mining methods, enough coal is left unmined in pillars to support overlying strata and prevent subsidence effects on the surface. Room-and-pillar mining recovers only about one-half of the coal and does not absolutely guarantee that subsidence will not occur. The unplanned subsidence that may result from this type of mining is difficult to manage at the surface because the small closed depressions can form at any time after an area is mined.

In the 1950s, some mine operators began using a different mining method called high-extraction retreat. This method involved the planned removal of as many supporting pillars as possible after the rooms were mined. In the 1960s, a widely used European mining method, called longwall, was adopted in the United States. This method removes all the coal along a broad front and results in subsequent subsidence of the mined-out area. Longwall and high-extraction retreat remove more coal from the mine production area than is possible with the room-and-pillar method, while allowing the surface to subside more or less uniformly over the mined-out area. Most of the subsidence takes place within a few months, and very little settlement occurs after the first few years.

Because the land drops more or less uniformly, surface drainage may be disrupted less with high-extraction techniques than with room-and-pillar mining. Proponents claim that planned subsidence mining can be undertaken without significant effects on the land. The subsidence damage that occurs is usually more easily repaired than that resulting from unplanned subsidence.

Subsidence primarily affects agriculture by altering the natural topography of the land surface. The productivity of farmland can be impaired by alteration of subsurface soil drainage, soil chemistry and structure, and surface drainage. Crops can drown if surface water stands too long in closed depressions that formed as a result of subsidence. Both the time of formation and duration of ponding are important to crop response. Seasonal patterns of rainfall distribution can greatly influence the impact of subsidence and ponding. Another factor is soil type. Ponding is more likely to occur on some particular soil types. The most important factor, however, is the topography (contours and elevation) of the land before mining takes place. If the premine topography is such that no closed depressions form, the impact of subsidence (the postmine topopgraphy) on crop yield will be less significant. In general, the more nearly level the landscape, the more likely that subsidence will create closed depressions.

The goal of the Illinois Mine Subsidence Research Program (IMSRP) was to develop guidelines to maximize coal extraction while preserving the agricultural productivity of land in Illinois. Because the effects of mine subsidence on crop yields had not been documented, an initial research priority was to establish the actual impact of coal mine subsidence due to high-extraction mining operations. In the first IMSRP agronomic study, which began in 1985, aerial surveys and field sampling were used to assess the relative impacts of longwall and high-extraction retreat mining on corn yields. This research was conducted in consideration of the importance of agriculture and coal mining to Illinois. The specific objectives were to

- use aerial photography to determine the extent of subsidence effects associated with planned subsidence mining;
- compare the effects of longwall mining with those of high-extraction retreat;
- measure the impact of subsidence on corn yield over three growing seasons.

METHODS AND MATERIALS

Mine Land Analysis

The study areas were located in Franklin, Jefferson, and Williamson Counties over high-extraction retreat or longwall mines. Each study area included surrounding unmined areas for comparison. Mine maps, topographic maps, and aerial photographs served as guidelines for selecting individual study areas. The study areas were square mile survey sections (59 sections in 1985, 69 in 1986, and 82 in 1987). All of the study locations were on the Illinoian till plain. Slopes ranged from nearly level to 18%. Two to three sets of aerial photographs of the study areas were taken each year during the spring and summer; the spring flights were taken to give a view of bare soil under moist field conditions, and the later flights, to show crop response.

The study areas included all or parts of seven mines in 1985 and nine mines in 1986 and 1987. Some mines combined longwall and high-extraction techniques, and others used only one mining method. The estimated area of each mine was calculated by using only the areas within the actual longwall or high-extraction retreat panels. Mine maps with the entries, longwall panels, high-extraction retreat panels, and room-and-pillar areas identified were traced onto drafting film. The mine maps, topographic maps, early season photos, and late season photos were compared, and observed mine subsidence effects were marked on the early season infrared photos. The photographs were viewed stereoscopically to determine where previous topography was altered by subsidence as indicated by increased wetness, relief changes, or both. Subsidence-induced effects (SIE) classes and the factors considered in assigning them are given in table 1.

These tonal anomalies and topographic alterations were checked against premine aerial photographs to verify that they occurred subsequent to mining. The areas were also carefully checked to rule out other possible causes, such as natural soil patterns, construction features, field boundaries, or land use changes. Areas of suspected subsidence features delineated on the spring photos were checked against the same areas in the summer photos. Areas marked on the spring photos were enlarged or reduced to reflect crop response that was observed

Table 1 SIE classes, as assigned on aerial photographs.

SIE class	Evidence
None	No change from premining topography or tone on aerial photos
Slight	Topographic change without dark infrared signature (marked yellow on photo)
Moderate	Dark infrared signature (marked orange on photo)
Severe	Ponding or black infrared signature (marked red on photo)

later; for example, many slight SIE areas marked in yellow on the spring photos showed no crop response in July. After the photos were edited, a dot-grid sampling technique was used to quantify features in the study area. The centers of 10-acre cells regularly arranged in a grid on each square mile section served as the sample sites. This gave 64 sample sites per square mile. The categories of information recorded for each grid point included land use class (agriculture, forest, water, or urban/other), mine name, panel orientation, soil type, and slope.

Yield Estimates

Corn (*Zea mays* L.) was chosen as the indicator crop because it is the most important crop in the state and grown extensively in the research areas. Sites were selected to give representative samples of corn yield for all classes of subsidence-induced effects over all mines in the study areas. Sites were chosen after careful inspection of the aerial photos. Each site consisted of a corn field that included a marked SIE area and a control area. This approach was adopted to ensure that variables in paired sample sites were the same; that is, to hold constant such variables as corn hybrid, planting date, soil fertility, herbicides, soil types, and other farm management factors.

At each site, one corn sample was taken from the affected area and one from an adjacent unaffected control area. More than one pair of samples were harvested in exceptionally large fields that had more than one type of soil or form of management. Sampling was done by conventional agronomic methods. A sample consisted of all ears on two adjacent 25-foot corn rows. The corn was air-dried, shelled, weighed, and analyzed for moisture. Yields were adjusted to 15% moisture.

The difference between yields for the control and subsided areas at a site served as an estimate of the yield reduction for the subsidence class assigned at that site. Yield reductions were calculated using the following formula:

$$\%\ \text{yield reduction} = 100\ (\text{control yield} - \text{subsided yield})/\text{control yield}$$

All the yield reductions for a SIE class calculated with this formula were then averaged to give the final estimate for each class. A total of 40 samples at 15 sites in 1985, 83 samples at 28 sites in 1986, and 79 samples at 31 sites in 1987 were harvested in late September and early October of each year. The reduction in yield estimates reflects conditions over the study area for the particular year of sampling. Soil fertility and crop quality data were also collected. Other costs that might be associated with subsidence, such as replanting and differential harvest losses, were not considered. All differences reported as significant were tested at a confidence level of 95%.

RESULTS AND DISCUSSION

Characterization of the Study Area

Land use The land uses in the total study area were similar over the years. The study areas included 37,760 acres in 1985, 44,160 acres in 1986, and 52,480 acres in 1987. Land use for the 3 years of the study averaged 73% for agriculture, 19% for forest, 3% for water, and 5% for urban and other.

Soils With a few minor exceptions, the soils in the study areas were rated as prime or important for agriculture (USDA, SCS 1983), and prime soils accounted for about 53% of the total study area. The soils of the study area were representative of the most common soils on the southern portion of the Illinois Till Plain in southern Illinois (Fehrenbacher et al. 1984); therefore, the results of the study should be valid for that portion of the state. The study area soils were rated for properties that would influence their sensitivity to subsidence. These properties included soil drainage group, susceptibility to flooding or ponding, and physiography. The soils on floodplains or nearly level till plains, or in slowly permeable and poorly drained soil-drainage groups, are highly sensitive to subsidence.

Mining types Acreages of mining types in the study areas are given in table 2.

Table 2 Acreages of mine types in the study areas.

	Area (acres)			% total		
Mine type	1985	1986	1987	1985	1986	1987
Unmined	14,610	11,750	13,770	38.7	26.6	26.2
Unmined within mine	3,820	5,490	6,030	10.1	12.5	26.2
Room-and-pillar	7,170	9.640	11.170	19.0	21.8	21.3
Longwall	1,160	1,590	2,100	3.1	3.6	4.0
High-extraction retreat	10,210	15,070	17,070	27.0	34.1	32.5
Unclassified	790	620	2,340	2.1	1.4	4.5
Total	37,760	44,160	52,480	100.0	100.0	100.0

Weather

Soil moisture reflects the ability of a soil to store water, the amount and intensity of precipitation, air temperature, solar radiation, and wind. Overall, 1985 was a wet year in the study area; precipitation was about 2 inches in excess of normal amounts. The excess precipitation was evident in the soil moisture content, which was more than adequate from January through June 1985. Southern Illinois, where soil temperatures warm up early in the spring, normally precedes the rest of the state in corn planting. In 1985, corn was planted late in the study area because the soil moisture was excessive. The late planting delayed the corn's development, as indicated by the percentage of silking in the area, which was well behind the state's average in July. By late in the season, however, corn in the study area had essentially caught up with the state's average for maturation, as indicated by the percentage of the corn dented (Illinois Cooperative Crop Reporting Service 1985, 1986, 1987).

The 1986 growing season was drier and more nearly "normal" than it was in 1985. There was about a 2.5-inch deficit in rainfall over the study area. Soil moisture was adequate throughout the year, and crop performance was ahead of 1985. The 1987 season was the driest of the three seasons. There was about an 11.8-inch deficit in precipitation over the study area. Soil moisture was particularly short in the last part of the year, and crops matured well ahead of the usual time (Illinois Cooperative Crop Reporting Service 1985, 1986, 1987).

Because subsidence-induced effects (SIE) on crop production are primarily related to changes in soil–water relationships, increases in precipitation increase problems related to excess water. The 1985 growing season in the study area was the wettest, so the subsidence-induced effects recorded that year were predictably more extensive than the effects in other years. Overall, the weather variability was nearly ideal for the 3 years of the study, including a wet year (1985), a dry year (1987), and a normal year (1986).

Corn Yields

Yield reduction was estimated by subtracting the yield in an affected area from the yield in an adjacent unaffected control area. Yield-reduction differences were not significant for a given SIE class between mine types or years. This means that an area rated as a moderate SIE class, for example, had the same relative reduction in yield whether it was over longwall or high-extraction retreat mining or whether the yield was measured in 1985, 1986, or 1987. In addition, no significant reduction in yield was found for the slight SIE class in any year, although significant reductions in yield were noted for the moderate and severe SIE classes. The moderate class averaged a 43% reduction in yield, and the severe class averaged a significantly greater reduction of 95% in yield (table 3). These values are for the SIE areas that consitute about 7.5% of the entire mine area.

Table 3 Subsidence-induced reduction (%) of corn yield in the study area.*

SIE class	1985	1986	1987	Average
Slight		Not significant †		
Moderate	52	56	22	43
Severe	95	99	91	95

* Yield reduction was estimated by subtracting the yield within an affected area from an adjacent unaffected control area. This was done at a total of 24 sample pairs in 1985, 55 in 1986, and 48 in 1987.

† For each year, the difference in yield reduction between moderate and severe classes was significant. No significant reduction was found for the slight class, nor was there a significant (5% level) difference in yield reduction between mine types or years.

Subsidence Effects

The SIE frequency was inversely proportional to slope, i.e., the less the slope, the greater the probability of moderate or severe SIE. Most subsidence effects were found in nearly level areas and none were found on slopes exceeding 12 %. Nearly level areas are more sensitive to subsidence because of the greater probability that closed depressions will form, and because of the closer proximity to the water table on the broad, slowly permeable landscapes included in the study. Of the total moderate plus severe SIE classes, 53.6% was in the 0 to 1.5% slope class (table 4).

Table 4 Distribution of moderate plus severe subsidence effects related to soil slope.

Soil slope range (%)				
0–1.5	1.5–4	4–7	7–12	>12
Frequency of moderate plus severe SIE (%)				
53.6	27.6	13.0	5.8	0

A chi-square test was used to check that the difference in SIE frequency over longwall and high-extraction retreat mines was not due to an unequal distribution of original soil slopes. For the 1986 data, no interaction was noted in slope and mine type. For the 1985 and 1987 data, a small interaction was noted: longwall mines were relatively more prevalent than high-extraction retreat mines in areas of nearly level soils. This effect was significant at the 5% level but not at the 1% level, which indicates that the overall difference in SIE frequency between the two mine types was real and was not due primarily to slope effects.

Another factor that influenced the frequency of SIE on soils was the distribution of soils and mines. In general, the more extensive the soil, the higher the probability was that it would be undermined; and the more nearly level the soil and the more restricted the soil drainage, the greater impact of subsidence.

Impact of Mining Methods

In this study, subsidence effects of longwall mining were much more evident than those of high-extraction retreat mining. Individual subsided longwall panels are more obvious than high-extraction retreat panels, especially on level divides or in bottoms. The lines of coal pillars left between longwall panels often stand as noticeable ridges between panels. These between-panel pillars are usually partially to completely removed in high-extraction retreat mining. When these pillars are partially or not removed, however, ridges may remain between blocks of panels. Where the pillars are removed, a much larger area subsides and the edges of the subsided area are less well-defined. In addition, high-extraction retreat mine borders often follow manmade features such as fence rows, railroads, or highways.

Both types of mining make previously wet soils wetter, especially where the topography is subtle. The orientation of longwall panels and the edges of high-extraction retreat mines may be important for determining the severity of the subsidence effects, although the data from this study are inconclusive. For both mine types, panels on a nearly level slope had the greatest SIE frequency, again indicating the impact of subsidence on nearly level ground.

Subsidence effects also vary with weather conditions. The 1985 growing season was particularly rainy in southern Illinois, and the effects observed may be representative of a wet year. The 1986 growing season had very favorable soil moisture and may represent a normal year. The 1987 season was rather dry. In an unusually dry year, crops may respond favorably to increased soil wetness due to subsidence. In addition, crops initially affected by excessive wetness early in the season may show no ill effects later on.

This study did not address other possible consequences of subsidence. For example, fields with SIE may have been planted later or parts replanted because of wetness, reducing yield and increasing management costs. These variables were controlled by using a large number of samples spread over the entire research area and by pairing every sample with a control from the same field.

A summary of the subsidence-affected areas related to mine type is given in table 5. These results reflect all effects observed in the mine type areas in the study year and represent all the factors that influence subsidence, such as weather, time since subsidence, and previous mitigation efforts. In general, the extent of land in an SIE class was inversely related to its severity. That is, most land was in the "none" and "slight" classes of subsidence effects, and only a small amount was in the "severe" class.

This evaluation included only land directly over the mine panels, most of which should have subsided; but noticeable effects were limited to a relatively small portion of the area. This is because most subsidence troughs do not completely pond water, and in addition, the mining companies attempt to mitigate subsidence effects as quickly as possible. The effects measured, therefore, were in areas that had subsided too recently for mitigation, or where mitigation was not effectively applied. A significantly higher frequency of slight, moderate, and severe SIE classes was recorded for the longwall mine type than for the high-extraction retreat type. The moderate and severe classes were significantly greater for both mine types in 1985 than in the other years, as expected for that wet year. A chi-square test revealed that the

Table 5 Summary of subsidence-affected areas, 1985, 1986, 1987, according to mine type.*

	Longwall				High-extraction retreat			
Mine type	1985	1986	1987	Avg	1985	1986	1987	Avg
None	64.6	70.9	65.5	64.7	91.9	92.0	90.2	91.2
Slight	23.3	24.5	32.9	27.8	3.8	4.3	7.5	5.5
Moderate	9.5	1.9	5.2	5.2	4.0	3.4	1.8	2.9
Severe	2.6	3.2	1.4	2.3	0.3	0.3	0.5	0.4

* Within each SIE class, differences between mining types were found to be significant at the 5% level. No significant difference was found between years for high-extraction retreat mining. A significant difference was found between years for longwall mining.

difference between mine types was significant. These results, coupled with the yield estimates, indicated that on a per-acre mined basis, the longwall method had a greater negative impact on agriculture than did the high-extraction retreat method.

The weighted average reduction in yield per acre was calculated by multiplying measured subsided areas by their associated yield reductions (table 6). The overall reduction in yield was 4.7% for longwall mines and 1.8% for high-extraction retreat mines. Because the weather during the 3 years of the study included one wet, one dry, and one normal year, these results should be representative. These estimates include only the land directly over the mine panels and do not reflect replanting costs, harvest losses, or other costs.

Table 6 Overall reduction of corn yield (%) in 1985, 1986, and 1987.*

Mine type	1985	1986	1987	Average
Longwall	7.4	4.2	2.4	4.7
High-extraction retreat	2.4	2.2	0.9	1.8

* Weighted average reduction in yield calculated by multiplying measured subsided areas by their associated yield reductions.

CONCLUSIONS AND RECOMMENDATIONS

These results are based upon the conditions of weather (e.g., precipitation), field management, and any mitigation measures in effect at the time of the studies in 1985, 1986, and 1987. The study did not address the long-term possibilities for mitigation or the permanence of the yield reductions and possible mitigation effects. Most importantly, the results reflect the weather during the three growing seasons. Weather variability was ideal during the study. The 1985 season was wet, 1987 was dry, and 1986 was a "normal" year. Subsidence-induced reduction of corn yield was near the average for the three years in 1986, greatest in 1985, and least in 1987.

Longwall mining has had significantly more impact than high-extraction retreat mining on crop production, according to the results of this study. Individual longwall panels tend to be more evident on the landscape; they are well-defined by a line of coal pillars left between the panels. The high-extraction retreat operation removes as many of these between-panel pillars as possible, thus eliminating the pronounced high divides on the ground surface between panels. High-extraction retreat mining causes subsidence of a larger, less well-defined area than does longwall mining. These large areas are less susceptible to ponding. In addition, the average maximum amount of subsidence over high-extraction retreat panels is about 1 to 1.5 feet less than that over longwall panels (Bauer and Hunt 1982).

Another factor that can influence the impact of subsidence is panel orientation. Data from this study were not sufficient to find a statistically significant relationship. It was generally observed, however, that mine panel edges perpendicular to natural drainageways tend to function as dams, whereas panel edges parallel with drainageways have less impact.

Recommendations to minimize the impact of subsidence on crop production are as follows:

- minimize the relative length of mine panel perimeters and the number of between-panel pillars by keeping the panels and the subsided areas as large as possible;
- orient panels so that edges run parallel to natural drains.

These recommendations are most important in areas of subtle topography, low relief, and high water tables.

The results of this study indicate that the overall impact of subsidence on crop production in terms of yield was slight during 1985, 1986, and 1987. Although the impact on a single field or farm may have been great, when determined for a total mine area, the maximum yield reduction was less than 10%. The most severe crop reductions occurred in only about 2% of all subsided areas.

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EFFECTS OF LONGWALL MINE SUBSIDENCE ON AGRICULTURAL SOILS AND HYDROLOGY

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Summarized by Billy A. Trent

ABSTRACT

The impact of planned coal mine subsidence on agricultural soils and groundwater resources was evaluated in this study, as part of the Illinois Mine Subsidence Research Program. When soils subside, surface drainage is altered, which can result in ponding. Soils that stay wet for for several days may undergo physical, chemical, and hydrological changes deleterious to crops. Soils were studied over one high-extraction retreat mine and two longwall mines in three Illinois counties; a detailed investigation of soil profiles was performed before and after subsidence.

Results indicated that hydraulic conductivity increases in some soils. Water tables responded to subsidence by initially dropping, then recovering to original elevations. An exception to this was found in the soil with a perched water table above a fragipan. In this case, the increased hydraulic conductivity of the fragipan after subsidence caused the perched water table to disappear. The changes in the land surface caused by subsidence include alteration of surface flow paths, ponding, and cracking. The ground surface near the mine panel edge developed subsidence cracks that function as preferential flow paths for groundwater and solutes.

INTRODUCTION

Crop production problems may be caused by drainage regimes changed by planned mine subsidence. The permeability, flow direction, and drainage of surface agricultural soils above planned subsidence mine panels were described and analyzed before and after subsidence. The possible effects on agriculture includes impedance of tillage; alteration of soil drainage with concomitant changes in the soil chemistry, morphology, and temperature; and the most obvious effect, alteration of internal and surface drainage. Surface water that stands for a long time in closed depressions formed by subsidence can be deleterious to crop growth. Not only the duration, but the timing of ponding can be critical in the cycle of crop/plant development. Thus, the seasonal patterns of rainfall distribution can greatly increase the impact of subsidence (Darmody et al. 1988). Some years will show much greater impact of ponding.

Altering the natural topography of the land surface may alter soil properties, which are dependent on soil type (Darmody et al. 1988). Poorly permeable and poorly drained soils on nearly level landscapes are more sensitive to subsidence; conversely, well-drained soils on steeply sloping or rolling landscapes are not as sensitive to subsidence. There are few natural analogs to subsidence as a factor in soil genesis. The closest equivalents would be seismipedoturbation, or the changes to soils caused by earthquakes or by natural subsidence due to sinkhole formation. This research was a unique chance to study this factor of soil formation and management because the effects of mine subsidence on soil morphology were undocumented. Some farmers believe that the response of soils to subsidence is an initial increase, followed by a decrease, in soil hydraulic conductivity and subsequent ponding. This research was designed to address that issue.

Soils studies began in 1986 at a site in Williamson County over a high-extraction retreat mine; IMSRP overburden studies were conducted in the same location so that data could be correlated. Later, studies of soils, overburden, and hydrology were conducted over longwall panels in Jefferson and Saline Counties. Sample sites were generally arranged at the mine panel centerlines, panel edges, barrier pillars separating two panels, and nearby unmined reference sites. The locations along the centerline were expected to undergo maximum subsidence, whereas the locations near the edge were expected to undergo some subsidence and maximum tensional forces.

At each study site, soil pits were excavated to a depth of 6 feet to sample and characterize soil morphology. Piezometers at different depths as well as neutron and gamma attenuation access tubes were installed at each site. Soil temperature and moisture were also recorded. A series of horizontal and vertical control points were established on two of the faces of each pit. Soil samples were retrieved to determine particle size distribution, bulk density, and micromorphology. Hydraulic conductivity was determined adjacent to each pit. Analyses in the field and in the laboratory were by standard methods (Black 1965, Page 1982). Soil profile descriptions were by techniques given by Soil Survey staff (1975). At the third site in Saline County, a dye and tracer investigation was added to the study to further investigate the movement of water through the soil before and after subsidence.

WILLIAMSON COUNTY SITE

Site and Mine Characteristics

Six soil pits were excavated at the Williamson County research site, arranged along two transects with three pits each, following two ridges that were oriented normal to the panel. The east transect was in a wooded area at the head of the panel, and the west transect was in a cultivated field near the midpoint of the panel. Two pits were on the panel centerline, two near the panel edge within the maximum tensile areas, and two off site to serve as controls. The maximum subsidence was expected to occur at the centerline locations; some subsidence and the maximum tensional forces were expected to occur near the edge. The landscape at this site was rolling with about 30 feet of local relief, thus ponding was not expected. However, the soils contained a brittle fragipan that restricted root growth and water movement, and was expected to crack. After subsidence, two additional pits were excavated to expose the tension cracks observed near the east transect.

Three piezometers were installed adjacent to each pit and terminated at different depths above, within, and below the fragipan. The piezometers were monitored monthly. Nails were inserted at 4-inch intervals in the west and north face of each pit and the elevations of these were surveyed subsequent to subsidence to monitor subsidence-induced soil distortion. Soil temperature and moisture recorders were installed at each site. Saturated hydraulic conductivity was determined at three depths at each site (Black 1965). Presubsidence soil physical and hydrologic properties were collected to compare with postsubsidence conditions.

Morphological characteristics, moisture content, bulk density, and penetrometer resistance were found to vary by vegetation cover at the site. In general, the soils under forest vegetation were drier and had stronger fragipans with stronger accessory properties such as restricted hydraulic conductivity than the soils in crop-covered sites.

The weather in the region of the study area was unusually dry during the study period (Illinois Department of Agriculture 1988). The area experienced deficits of precipitation of 1.13 inches in 1986, 6 inches in 1987, and 3.6 inches through May 1988. The soil at the site was a moderately well drained Ava silt loam that has a fragipan developed under forest vegetation (Fehrenbacher and Odell 1959). Topography at the site was rolling with 1% to 15% slopes. The slope at the individual study sites ranged from 2% to 4%. The Ava series is considered prime farmland when located on slopes of less than 6% (Soil Survey Staff 1983).

The mining method at the Williamson County research site was high-extraction retreat. Pillars under the east transect were removed in March 1987, and subsidence began about March 25, 1987. The pillars beneath the south edge of the panel were not removed because of mining constraints; therefore the pit located along the panel edge was not subsided. Consequently, the centerline pit was, in effect, close to the high-tension panel edge position. The mine company ceased operations on May 18, 1987, and never removed any pillars below the west transect area.

Results

Because the coal mining operation was terminated at the Williamson County site, the mine panel at this site was not developed as planned. Fewer pillars were removed than expected, and only a portion of the east transect was undermined. Only one of the six soil test pits excavated was undermined; it subsided 3.6 feet. Another pit adjacent to the undermined area subsided 0.3 feet. Cracks appeared at the soil surface and subsided areas were evident after mining. The ground was relatively dry at that time and a few cracks 0.5 to 12 inches wide and 3 to 6 feet deep could be traced for about 100 feet.

Measurements of soil hydraulic conductivity before and after subsidence indicated an increase in hydraulic conductivity in only one case. The fragipan horizon in the soil pit that was undermined had a statistically significant ($\alpha = 0.05$) increase in conductivity; this horizon showed no cracks. Where the soil was cracked, however, water moved rapidly into and through the subsidence cracks. Another change noted at the subsided pit was a drop in the water level in the deep piezometer. This drop may be attributed to natural fluctuations, but the piezometric levels of the two other sites also fell, then later recovered. Perhaps the cracking of the fragipan allowed the perched water table to fall. Complicating this observation is the variability of vegetation covering the sites. However, the measured change in hydraulic conductivity at the subsided pit supports the hypothesis that the piezometric drop was due to subsidence. In summary, subsidence had very little agricultural impact at the Williamson County site. Only a few cracks were visible in the soil at the surface.

JEFFERSON COUNTY SITE

Initial work at the Williamson County site indicated that the location of areas exhibiting the effects of subsidence may be unpredictable. Therefore, the experimental design at the Jefferson County site was modified to increase the size of areas monitored. The soil pits were enlarged to ensure that the subsidence cracks would pass exactly through our monitored area. This was done by means of a soil variability study (extensive grid sampling), as well as a seismic technique that integrated a larger soil area.

Site and Mine Characteristics

The study area for this site was located over a longwall coal mine in Jefferson County, Illinois. Land use was intertilled crops. The soils of interest in the study area were in the Bluford series, which consists of slowly permeable and somewhat poorly drained soils considered prime for agriculture (Soil Survey Staff 1983). A weakly expressed, brittle fragipan in the Bt horizon was expected to crack after subsidence. Tile drainage is not effective in these soils because of their slow hydraulic conductivity; unless conductivity is greatly enhanced by subsidence, water ponded on the surface is unlikely to be removed by infiltration. The gently sloping landscape at this site had about 16 feet of local relief, indicating that a potential outlet for surface drainage existed. The weather at the research site was unusually warm and dry during 1988 (Illinois Department of Agriculture 1988).

Six soil pits were excavated in May 1988 to a depth of 6 feet. They were arranged in two north–south transects, one toward the east end of the panel and one toward the west end. There were three pits in each transect, one located over the panel centerline, one near the panel edge, and one outside the barrier between the subject mine panel and the existing panel to the south. Three piezometers were installed at different depths at each pit; soil temperature and moisture recorders were also installed. Vertical and horizontal control points were established on the north and west face of each pit. Soil samples were retrieved to determine particle size distribution, bulk density, and micromorphology. Hydraulic conductivity was determined in situ at three depths adjacent to each pit and in soil cores retrieved from selected horizons.

The coal seam thickness ranged from about 8.5 to 10.5 feet. Subsidence began on the east transect in late July 1988 and reached the west transect about 1 month later. Before subsidence took place, a grid of each transect area was surveyed and a topographic map of the grid

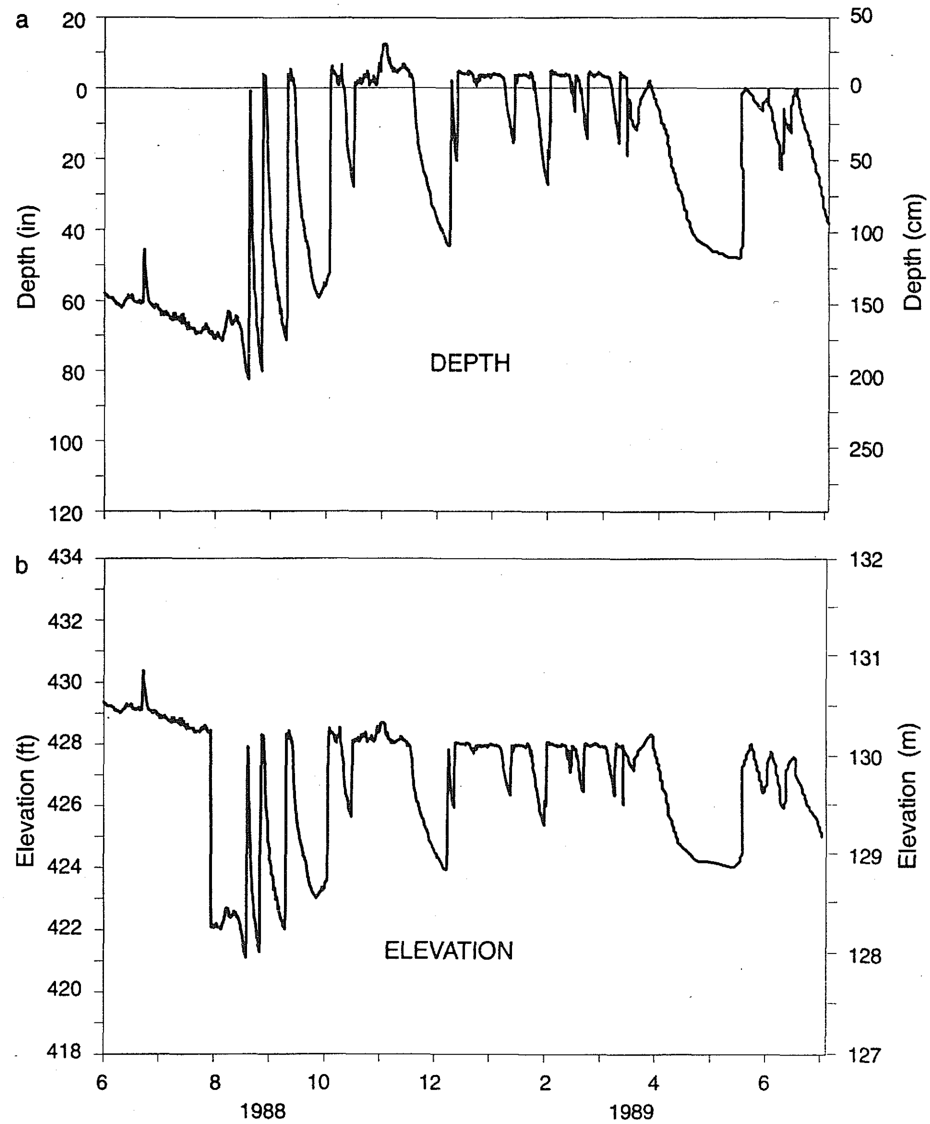


Figure 1 Piezometric response to subsidence that occurred in September 1988. Note that the apparent rise in piezometric surface shown in "a" is simply the maintenance of a constant elevation "b."

areas constructed. After subsidence, the same areas were surveyed again to produce another pair of topographic maps. The elevations shown in the pre- and postsubsidence maps were subtracted to develop a map of the elevation change caused by subsidence. The maximum measured subsidence was 5.2 feet on the east transect and 6.2 feet on the west transect. The barrier pillar subsided 0.8 feet. Subsidence cracks 0.5 to 12 inches wide developed in the soil along the south side of the study area. A ponded area of about 0.2 acres developed at the west transect.

Results

No obvious effects of subsidence were noted in the soils, but the water tables responded to subsidence by maintaining constant elevation as the ground subsided (fig. 1). Although the hydraulic conductivity increased after subsidence, the rate remained slow (fig. 2). The largest increase in conductivity was in the Bt (fragipan) horizon. This horizon had very slow initial conductivity and had fragic (or brittle) properties. The horizon most likely responded to the deformation caused by subsidence by shattering.

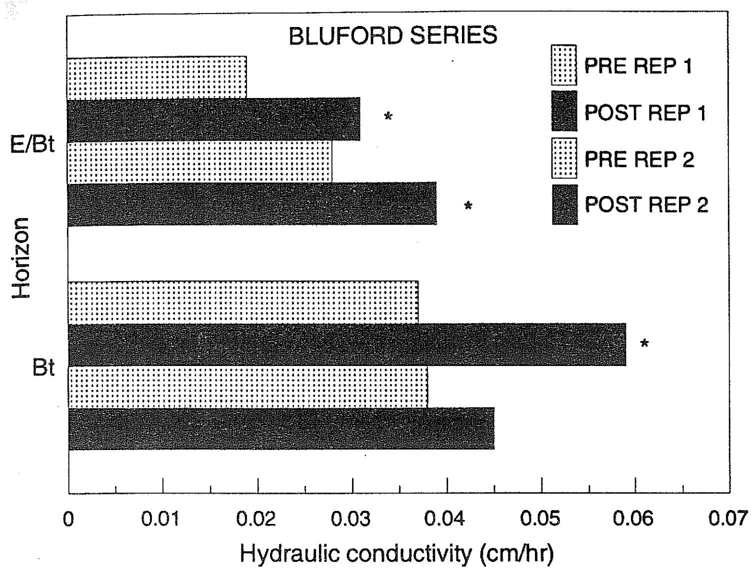


Figure 2 Effects of subsidence on hydraulic conductivity at the Jefferson County site. Significantly different values are indicated by an asterisk.

The first obvious piezometric response to mining occurred when the mine face was 410 feet beyond the site, 18 days after it was undermined. The piezometric surface rose above the soil surface after subsidence; the water table attempted to maintain constant elevation as the surface dropped. When the mine was active, the water table dropped because mining increased the storage capacity of the overburden rocks. On the weekends, the water table recovered because all recently created voids were filled with water and no new voids were being developed. The maximum change was 6.7 feet in 8 hours. The deeper piezometers recorded higher piezometric surfaces, which indicated that the water filled in from below, not from above as normal rainfall infiltrating surface materials. In addition, precipation and piezometric fluctuations did not correlate. Despite the fact that no cracks were observed in the four pits reexcavated after subsidence, water table fluctuations were beyond those predicted by presubsidence evaluation and may reflect subsidence-generated macropores through which water could move more freely. Because subsidence occurred in the fall when water tables normally rise, some of the observed rise could be due to normal (seasonal) water table fluctuations.

SALINE COUNTY SITE

This field study was undertaken to characterize the soil cracks resulting from coal mine subsidence and to determine whether greater preferential flow of water through soil occurs as a result of the cracks. Rhodamine B dye and bromide tracers were used to determine whether subsidence fractures remain in the soil and contribute to increased preferential flow. Soil cracks typically form near the edges of the elongated depression produced by subsidence from longwall mining. The transverse cracks close as the dynamic subsidence wave passes. Longitudinal cracks may remain open, however, until surface processes close them (Van Roosendaal et al. 1992) (fig. 3).

Site and Mine Characteristics

The study site was located in northwestern Saline County. The soils in the study site were being used for row crop and small grain production. The Herrin Coal seam that underlies the research site was being mined by the longwall method at a depth of 400 feet. Three pedons (research sites) were selected to investigate the subsidence effects. Two of the pedons were located above the mine panel edge and centerline. An undisturbed or control pedon was located slightly outside the subsidence-affected zone (fig. 4).

Methods and Materials: Dye Study

The subsidence-induced cracks were characterized using an absorbing dye and an anionic tracer. In August 1989, the three pedons received a solution of saturated Rhodamine B dye and bromide. The solutions were applied in 3×3-foot bottomless tanks driven into the soil to a depth of 4 inches. Rhodamine B dye was used to show whether subsidence cracks remain

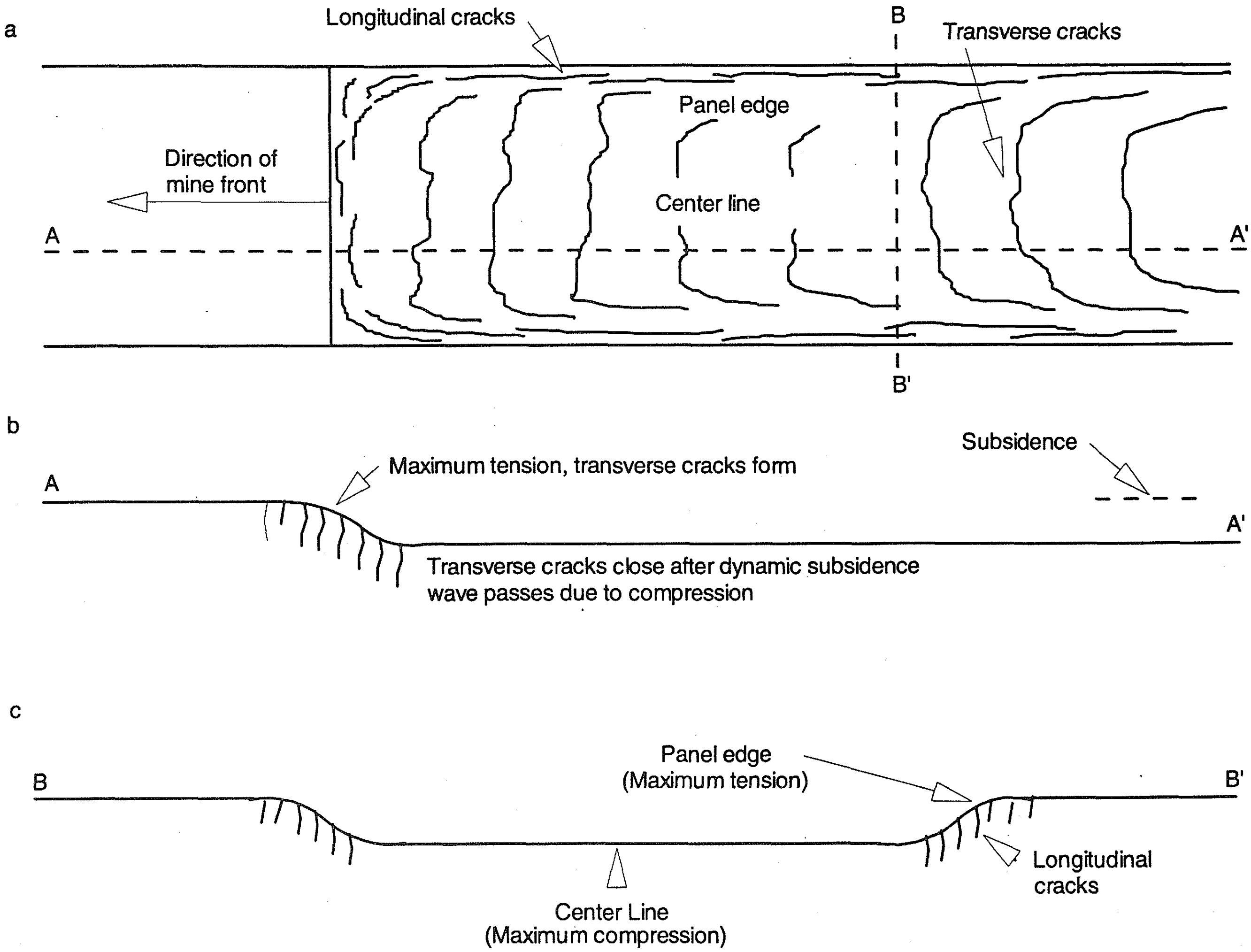


Figure 3 Formation of subsidence cracks above a longwall mine panel.

after their apparent closure at the soil surface. The dye has a strong visual contrast to the soil matrix and has been used successfully by others (Anderson and Bouma 1973, Sollins and Radulovich 1988). Bromide was used as a conservative tracer to compare water flow between pre- and postsubsidence (Germann et al. 1984, Onken et al. 1977). Subsidence occurred in December 1989. In August 1990, the procedure was repeated in adjacent pedons. Most of the topsoil (or Ap horizon) was scraped off at each site before driving the tanks into the soil—a measure taken to prevent leakage of the solution outside the tanks into the friable Ap horizon, and to prevent excessive adsorption of the dye by organic matter. The tanks were carefully filled to avoid physically dispersing the exposed soil surface.

One week after dye was applied, the tanks were removed and 10-foot-deep trenches were dug on two sides. The trenches facilitated excavation of horizontal planes below the tanks. Incremental planes were exposed, smoothed with a scraper, and vacuumed to remove debris. Photographs of each layer were taken of a centered 28×20-inch sampling area. After each layer was photographed, the soil was sampled for bromide determination. A grid was used to compare preferential movement of bromide and dye (Seils 1992). Ten to 12 planes were sampled and photographed per plot. Image analysis was used to quantify the dye patterns. Each plane was analyzed for percentage of dye area and number of dyed objects. Three samples were collected from each horizon of the three study pedons to evaluate changes in bulk density. Saturated hydraulic conductivity was determined.

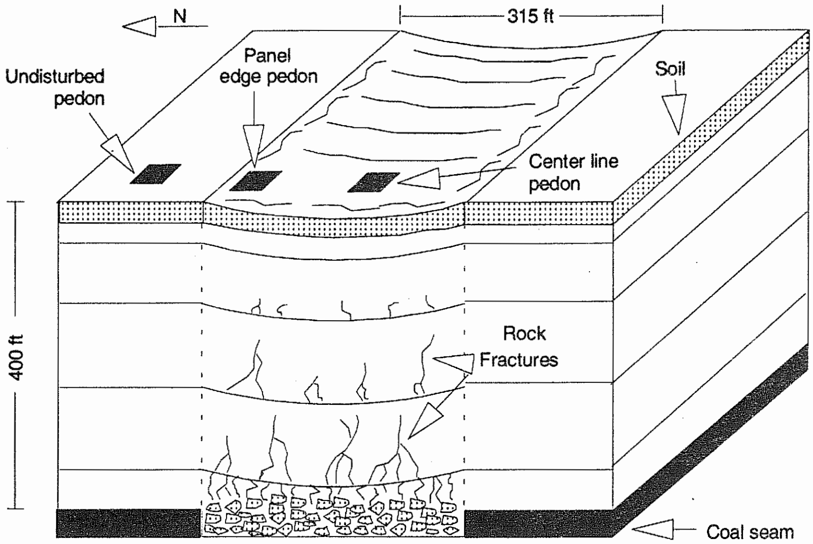


Figure 4 Experimental layout at the Saline County soils subsidence research site.

Dye Study Results

Dye patterns of all trials revealed greater preferential flow deeper in the profile. Below the E/Bt horizon (60–80 cm), flow was restricted to prism faces and larger macropores. During excavation, it was observed that the faces of larger aggregates were heavily stained, whereas the interior contained little dye. The dye that did penetrate the interior of aggregates was due to flow via macropores.

Van Roosendaal et al. (1992) showed that the panel edge is subjected to tensional forces during subsidence because of the induced relief as the panel subsides. Soil cracks that form along this zone occur at angles between 45° and 90° relative to the advancing mining front. As subsidence proceeds, a more significant fracturing occurs in these lower depths because of the greater bulk density, shear strength, and stronger consistence with depth. These soil properties as well as the absence of compressional forces prevent the cracks from closing. In this study, the plot at the edge of the panel showed easily recognizable dyed subsidence cracks. The cracks were more clearly defined with depth. Fractures were observed at the surface along the panel edges immediately after subsidence. At the time of the solution application (8 months after subsidence), however, the surface fractures could not be seen. Near the surface, the cracks lost their distinctiveness after time because the soil is more friable, which allows for infilling of the fractures by natural processes.

In the postsubsidence experiment, the solution at the panel edge infiltrated in the shortest time (less than 1 day) as compared with the infiltration time at the other plots (4 to 7 days). It is evident that the panel edge zone lacked sufficient compressional forces to completely close the fractures during the period of the study. Dye patterns of the centerline did not reveal cracks. Cracks form along this zone parallel to and behind the advancing mining front. As the mining front advances beyond a given point in the centerline, the compressional forces that are generated tend to close the cracks. The lack of soil cracks along the centerline may be because the sample area did not include a subsidence crack, or more likely, the cracks closed completely because of compressional forces in this zone. Surface cracks were found to be about 3 feet apart at the panel edge. No cracks were observed at the centerline during postsubsidence excavation.

Both the control and the subsided plots showed an increase in the number of dye stains during postsubsidence sampling. Differences between pre- and postsubsidence soil conditions likely contributed to the increase in dye stain numbers for all three plots. The greater soil moisture recorded during the postsubsidence period would have allowed the infiltrating dye to stay in suspension longer, decreasing the sorption of the dye on the soil particles. A result of this was a greater number of stained pores deeper in the profile.

All plots showed few differences in the percentage of dye coverage between pre- and postsubsidence. Also, there was no discernible relationship between subsidence and increases in hydraulic conductivity of the panel edge and centerline pedons. These results are quite site-specific because the fast rate of drainage of the solution tank along the panel edge indicated that an increase in hydraulic conductivity did occur in certain areas.

Evidence of little difference in dye coverage for the coal panel plots indicated that subsidence did not increase total macroporosity through the whole soil matrix as measured. Although the total flow paths were not significantly altered, subsidence cracks at the panel edge zone contributed to an increase in preferential flow, as evidenced by the dyed cracks and the unusually fast rate of drainage of the solution. This increase in preferential flow along the panel edge could influence the movement of dissolved substances through the soil materials. The resulting soil fractures could facilitate the movement of contaminants, such as agricultural chemicals, into the groundwater.

The contribution of subsidence fractures to bypass flow would increase with increasing soil moisture (Hoogmoed and Bouma 1980, Germann et al. 1984, Edwards et al. 1988). Also soil fractures do not need to extend to the surface for flow to occur in them. Quisenberry and Phillips (1976) showed that preferential flow occurred below a tillage layer where macropores were disrupted. At the Saline County study site, there was a stained large horizontal macropore directly above the E/Bt horizon, indicating resistance to root penetration in this zone, where water could flow laterally toward the fractures along active and decayed root channels.

All plots, both subsided and control, showed greater bromide levels after subsidence. Figure 5 shows an increased concentration of tracer Br in the groundwater after subsidence. Like the dye stains, this was also attributed to greater soil moisture at the time of postsubsidence application of the bromide tracers. Thus, a conclusive statement about the relation between transport and subsidence is not possible.

Both image analysis of dye stain patterns and comparisons of bromide profiles were inconclusive in predicting deeper water flow due to coal mine-induced subsidence. However, visual observations and the solution drainage rate show that subsidence cracks along the panel edge zone appear to have increased the possibility of preferential flow. This was apparently the result of flow through the subsidence cracks, not of changes in macroporosity of the overall soil matrix. The significance of increased preferential flow depends on soil water conditions.

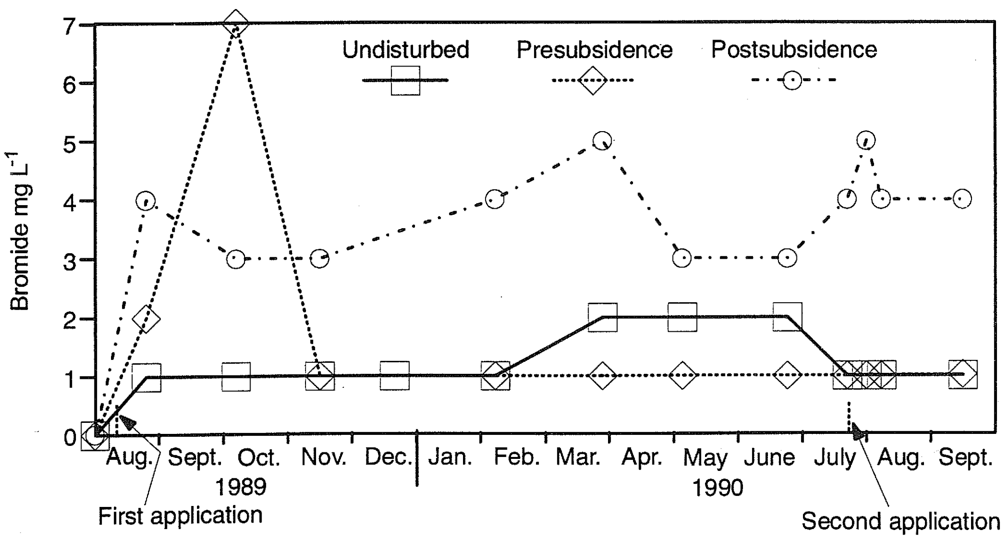


Figure 5 Groundwater bromide concentrations following pre- and postsubsidence solution application. Samples were taken from 7-meter-deep lysimeters.

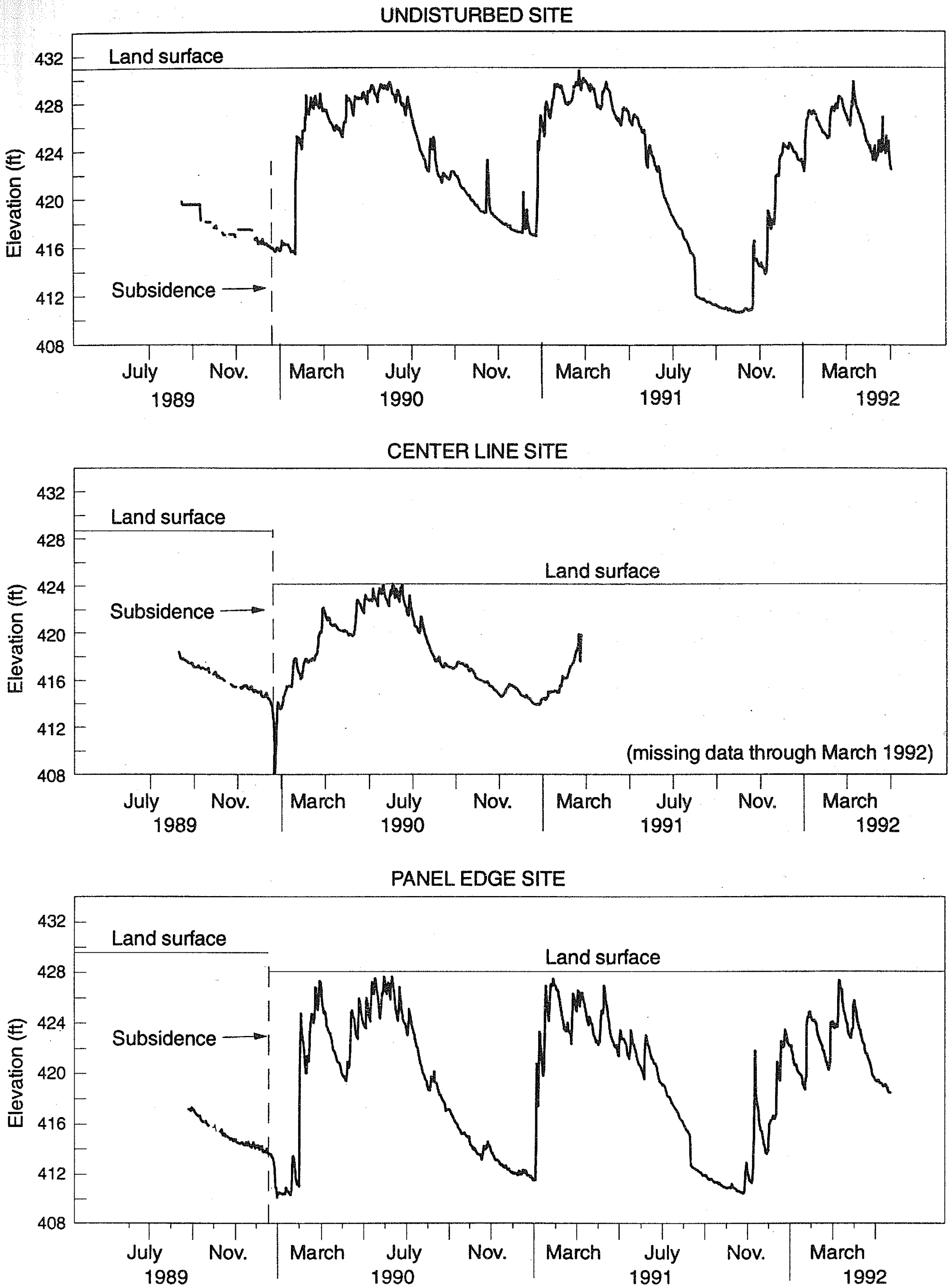
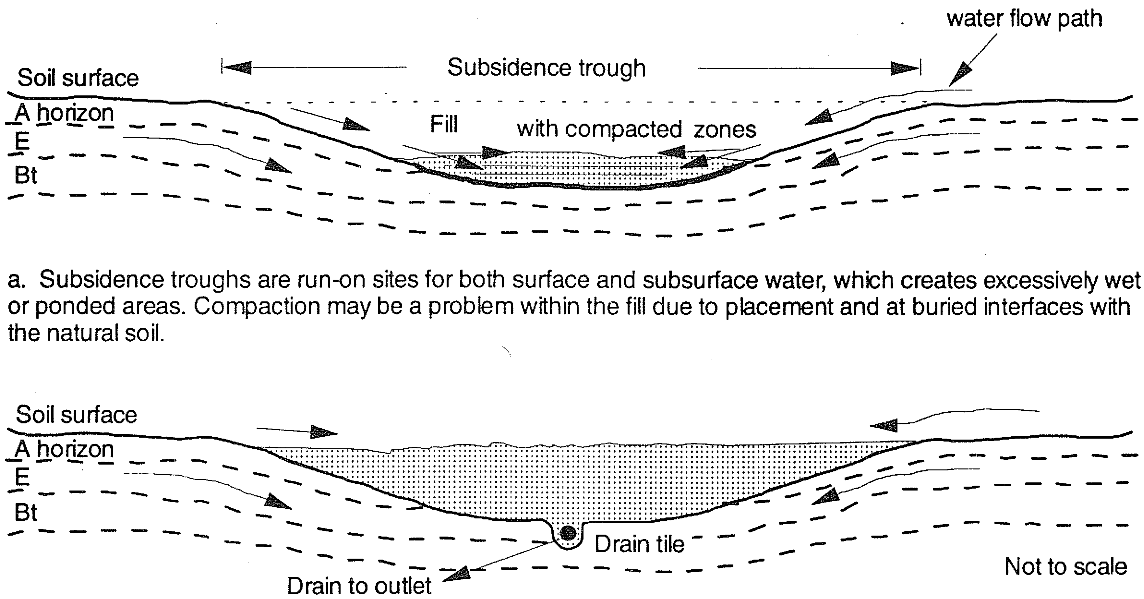


Figure 6 Piezometric elevations at undisturbed, centerline, and panel edge study sites in Saline County.



a. Subsidence troughs are run-on sites for both surface and subsurface water, which creates excessively wet or ponded areas. Compaction may be a problem within the fill due to placement and at buried interfaces with the natural soil.

b. Adding sufficient fill, installing drain tiles, minimizing soil compaction, and tillage to eliminate compaction in fill and at the fill-soil interface should increase mitigation success.

Figure 7 Cross section of an idealized subsidence mitigation trough.

Groundwater response to subsidence was superimposed on normal seasonal variation. The subsidence event occurred at the time of normal recharge. However, a drop in groundwater level was noted as subsidence occurred at the panel centerline position. After subsidence, the water table at the centerline almost reached the surface due to the change in elevation. The piezometric surface at the panel edge also dropped at the time of subsidence, but quickly recovered. Graphs of these piezometers are shown in figure 6. No closed depressions formed at the Saline County site as they did at the Jefferson County site. Therefore, the water tables never overtopped the soil surface. Groundwater elevations of the site 2 years after subsidence were approximately the same as before subsidence. Large-scale investigations of surface groundwater quality changes beneath mined panels would aid in determining whether subsidence cracks contribute to increased solute movement into the groundwater.

OVERALL CONCLUSIONS AND RECOMMENDATIONS

There are a few general conclusions to be gained from the results of the soils subsidence research. With the exception of a perched water table over a fragipan, water tables initially dropped after subsidence, then recovered to almost their original elevations. If closed depressions form, they may cause ponding at the surface. The increase in hydraulic conductivity associated with subsidence may intensify this condition. If no closed depressions form, the impact of the decrease in water table depth may not be significant except in wet years.

Results of this research can be used to improve the efficacy of subsidence mitigation. The rise in water tables relative to the land surface makes drainage critical. Typically, fill is applied to subsided areas to raise the grade and to encourage runoff. Subsurface drain tile (fig. 7) can be installed to improve the discharge of subsurface water and prevent saturation of soils. Given an outlet, this will improve discharge of subsurface water that may cause excessive wetness.

The implications of this subsidence research for groundwater contamination are not clear. The Br tracer moved more rapidly after subsidence, as shown by the deep lysimeters. The paths taken by water moving through soil are not obvious; and no increase in potential for contamination could be identified, based upon the dye study. This remains an unanswered question for further research.

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EFFECTIVENESS OF CROPLAND MITIGATION AFTER LONGWALL MINE SUBSIDENCE

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ABSTRACT

Longwall coal mining in southern Illinois occurs beneath some of the best agricultural land in the United States. This region is characterized by highly productive, nearly level, and somewhat poorly drained soils. Subsidence from longwall coal mining changes surface topography and thus alters surface and subsurface hydrology. These changes can adversely affect agricultural land by creating wet or ponded areas that can be deleterious to crop production. Although most subsided areas show few effects of subsidence, some subsided fields have total crop failure. Coal companies are required by law to mitigate subsidence damage to cropland. The objective of this study was to test the effectiveness of mitigation in restoring grain yields to premined levels. Sites in southern Illinois were selected to represent conventional mitigation techniques applied to the predominant soils in the area. Corn (*Zea mays* L.) and soybean (*Glycine max.* [L.] Merr) yields from mitigated and nearby undisturbed areas were compared for 4 years. There was no significant ($\alpha=0.05$) difference in soybean yields averaged over the 4 years; however, average corn yields were significantly lower in mitigated areas than in reference areas. Soil fertility levels were similar and did not account for yield differences. The impacts of subsidence and mitigation were variable and site specific. Results were also related to weather. In wet years, yields in mitigated areas tended to be lower than yields in undisturbed areas. This research demonstrated that mitigation of subsidence damage can be successful.

INTRODUCTION AND BACKGROUND

High-Extraction Mining Methods

The underground coal mining industry of the Eastern Interior Coal Basin is moving toward high-extraction mining methods, including longwall, as surface mineable coal is depleted. Conventional room-and-pillar underground mining leaves much of the coal in place to support the mine roof. In contrast, longwall mining extracts all the coal in a panel, a practice that results in immediate subsidence over the panel. Consequently, subsidence from longwall mining is predictable and damage to buildings or other civil structures can be prevented or moderated (DuMontelle et al. 1981). Subsidence effects on agricultural land have been documented in Illinois (Darmody et al. 1989, Guither 1986, Veith 1987), the United Kingdom (Selman 1986), and Australia (Ham 1987). The effects include soil erosion, disruption of surface drainage, creation or enlargement of wet or ponded areas, and reduction of crop yields.

Southern Illinois is characterized by nearly level to gently rolling topography, shallow water tables, and extensive areas of poorly drained, slowly permeable soils (Fehrenbacher et al. 1984). Land use is primarily agriculture, and many of the soils of the area are classified as prime; this landscape is particularly sensitive to subsidence. Although most longwalled areas have little or no damage from subsidence, some localized areas are severely affected. In southern Illinois, for example, most severe subsidence effects are limited to approximately 1 to 3 acres in the much larger subsided panel. Corn yield reductions of up to 95% have been documented in these limited areas (Darmody et al. 1989). In the same study, Darmody et al. (1989) found a 4.7% average reduction in overall corn yields on subsidence-affected land in Jefferson, Franklin, and Williamson Counties, Illinois, when yield reductions were averaged over the entire mine panel area.

Mitigation Techniques

Coal companies are required by law to repair or mitigate areas adversely affected by subsidence. The regulations require the companies to restore the premining land use. Mitigation techniques include cutting drainage ditches or grass waterways, recontouring the landscape by adding fill, or a combination of these methods. Ditching, the least complex technique, involves creating or deepening ditches to expedite removal of surface water. Recontouring is more complex and involves raising the grade of a subsided area to prevent ponding. Fill material is either dug from new or existing ditches, borrowed in the construction of a pond, or taken from high spots in the field. Topsoil is first removed from both the borrow and the subsided areas; then stockpiled. The topsoil is returned to both areas after the fill is put in place. Fill depths typically range from ½ to 3 feet. For this study, mitigation techniques were classified into three types: ditch, fill, and ditch-plus-fill.

Cropland reclamation after underground mining is not well documented. However, numerous studies on cropland reclamation after surface coal mining have identified soil compaction (caused by large earthmoving equipment used in subsoil and topsoil replacement) as a major factor limiting crop productivity (Fehrenbacher et al. 1982). Soil compaction increases soil density and reduces fractional air volume (Gupta et al. 1989). Consequently, plant growth is altered because of poor soil aeration, low nutrient and water availability, slow permeability, and mechanical impedance to root growth (Indorante et al. 1981). Fehrenbacher et al. (1982) found significant differences in corn yields and root densities brought about by different soil replacement techniques. Their research demonstrates the importance of proper soil replacement techniques. Although the equipment used in subsidence mitigation tends to be smaller than that used in surface mine reclamation, the potential for soil compaction still exists.

Research Objectives

The effectiveness of cropland mitigation after longwall mine subsidence had not been documented prior to this research. The objectives of this research were to (1) measure the effectiveness of mitigation in restoring corn and soybean yields to premined levels, (2) compare soil physical and chemical properties in mitigated and undisturbed areas to identify factors that may be limiting crop yields, and (3) identify effective reclamation methods and make recommendations to improve future mitigation.

MATERIALS AND METHODS

Research Sites

Seventeen research sites in Jefferson and Franklin Counties, Illinois, were selected from an earlier study that identified longwall and high-extraction retreat mining subsidence-affected areas (Darmody et al. 1988). Crop yields and soil physical properties were not measured at all sites in all years because corn or soybeans were not available at each site each year. The research sites were areas currently being used for row crop production and included a wide variety of soils and mitigation techniques. The soils were classified as highly sensitive, moderately sensitive, or somewhat sensitive to subsidence damage because of their natural drainage and landscape position (Darmody et al. 1988).

Each site consisted of the mitigation area, usually about 1 to 2 acres, paired with an undisturbed reference area in the same field. The fields were planted to corn or soybean and fertilized and managed by individual farmers. Management factors such as planting dates and crop varieties varied from site to site; however, these variables were constant within a paired mitigated and reference site.

Sampling Methods

Four soil fertility samples were collected during harvest at mitigated and reference areas. A sample consisted of a composite of five cores taken from the plow layer (9 in.). Phosphorus and potassium levels were determined using a Mehlich 3 extraction procedure and inductively coupled plasma (ICP) spectrometry. Soil pH was determined by a 1:1 water paste method. Organic matter was estimated by a modified organic carbon combustion method at 350° C.

Corn and soybean were hand-harvested in the fall in 1988, 1989, 1990, and 1991. Yields were based on the grain weight from sampling units of four 20-foot-long rows from mitigated and reference areas. Yields were corrected to 15% moisture for corn and to 13% moisture for soybean.

Soil physical properties were determined from three undisturbed soil cores, which were collected at selected mitigated and reference sites with a Giddings hydraulic coring machine. The cores were divided into segments and the plow layer and the E horizon were discarded (0–17 in.). The samples were sealed to keep them moist until analysis. Saturated hydraulic conductivity was determined by a standard constant head laboratory technique (Klute and Dirksen 1986). After hydraulic conductivity determinations, the cores were placed in low pressure suction funnels and desorbed from saturation to field capacity. Bulk density was determined by the core method (Blake and Hartge 1986), and particle size analysis was by the hydrometer method (Gee and Bauder 1986).

Soil strength to a depth of 43 inches was measured in situ with a constant rate cone penetrometer (Hooks and Jansen 1986). Nine readings were taken in each mitigated and reference area when the soil was at or near field capacity. The data profiles were separated into five segments for statistical grouping. A mean penetrometer resistance value was calculated for segments three, four, and five. The means of paired segments were compared using a least significant difference (LSD) (α=0.05) test. Segment one was discarded because of disturbance from annual cultivation. Segment two was discarded because it coincided with the E horizon of the natural soil that was drier than the same segment in fill.

RESULTS AND DISCUSSION

Soil Fertility

Soil fertility could be affected by subsidence mitigation in two ways. First, recontouring could expose less fertile subsoil and remove fertile topsoil. Second, fill material could be deficient in major or minor plant nutrients or organic matter, or could contain excessive amounts of sodium. These problems are typically prevented by removing topsoil before fill is added and then replacing it upon completion of the work.

Soil test results showed that soil organic matter content was similar in the mitigated and reference areas. These results were expected as a result of the replacement of topsoil. The pH of the mitigated areas was 6.8, slightly lower than the reference areas pH of 7.0; this is not a significant difference. Both values are close to the recommended range of 6.0 to 6.8 (Hoeft et al. 1994). Phosphorus and potassium levels were slightly higher in the mitigated areas than in the reference areas. This difference may be attributed to soil variability or to the addition of fertilizer to the mitigated areas. The phosphorus slightly exceeded recommended levels on both reference and mitigated sites, whereas potassium was somewhat lower than recommended. Nitrogen was not measured; however, nitrogen deficiencies were not observed. At some sites, measured soil fertility levels of both major and micronutrients were lower than recommended for optimal yields. However, because soil fertility levels at mitigated areas were similar to nearby reference areas, differences in soil fertility should not account for yield deficiencies in mitigated areas.

Crop Response

Yields averaged over all sites for corn and soybean are presented in table 1. Corn yields were significantly lower in mitigated areas in 1990 and 1991 and when averaged over the 4-year study. Soybean yields were significantly higher in 1989 and significantly lower in 1991 but were not statistically different when averaged for the 4 years.

The growing season was unusually dry in 1988 and unusually wet in 1990. The 1989 and 1991 seasons had approximately normal precipitation (Illinois State Water Survey 1992). During the drier 1988 growing season, crops in the mitigated areas may have benefited from the extra water collected and held by subsidence troughs. In contrast, a wet spring in 1990 precluded planting or caused low seed germination in these areas. Corn plant counts were significantly lower in 1990. Corn ear counts were significantly lower in 1990 and 1991, and significantly lower in the mitigated areas, as averaged for the 4-year study. Hence, both low plant stands and plant stress resulting in low ear counts account for lower yields in mitigated areas. The better response of soybean to mitigation is attributed to a later planting date under typically better soil moisture conditions and to the inherent stress tolerance of soybean.

Crop yields at individual sites varied widely in a given year (table 2). At some sites, productivity was returned to premined levels; whereas at other sites, mitigation did not totally correct the problem. Table 3 shows crop yields for different mitigation methods. Ditch-type

Table 1 Crop yields (bushels/acre) at subsidence mitigation research sites.

Crop	Treatment	1988	1989	1990	1991	Mean
Corn	Reference	95	125	112	106	110
	Mitigated	96	116	79	74	89
	Difference	+1	-9	-33 *	-32 *	-21 *
	n ¶	6	7	11	4	28
Soybean	Reference	26	29	28	31	29
	Mitigated	25	36	24	25	27
	Difference	-1	+7 *	-4 *	-6 *	-2
	n ¶	7	3	3	10	21

* significantly different, LSD (0.05); corn = 12.4, soybean = 2.9

n ¶ mean of sites

Table 2 Crop yield (bushels/acre) extremes at each research site.

Crop	Year	Site	Reference	Mitigated	Difference
Corn					
Worst case	1988	8	105	84	-21 *
	1989	2	158	107	-51 *
	1990	3	122	23	-99 *
	1991	8	111	62	-49 *
Best case	1988	6	84	116	-32 *
	1989	13	74	91	+17
	1990	11	79	75	-4
	1991	1	111	109	-2
Soybean					
Worst case	1988	9	36	28	-8 *
	1989	6	30	35	+5
	1990	14	32	15	-17 *
	1991	15	37	20	-17 *
Best case	1988	2	32	32	0
	1989	7	33	42	+9 *
	1990	8	33	36	+3
	1991	11	39	44	+5

* significantly different at the 5% level

Table 3 Overall yields (bushels/acre) for different mitigation methods.

Treatment	Corn	Soybean
Reference	110.2 a*	28.7 a
Ditch	96.7 ab	28.0 a
Fill	76.0 b	28.8 a
Ditch-plus-fill	89.4 b	23.3 b

* means within columns followed by the same letter (i.e., a or b) are not significantly different ($\alpha = 0.05$)

mitigation was the most successful, as there were no statistically significant yield differences with either crop. The fill and ditch-plus-fill methods did not successfully restore corn yields; however, soybean yields were successfully restored by all but the ditch-plus-fill method.

Differences in mitigation success may be primarily due to the severity of the subsidence problem that the mitigation was designed to correct. Where subsidence problems are relatively minor, ditching is the preferred method. Where subsidence causes the greatest problem, ditch-plus-fill is used. Mitigation success is thus directly related to the severity of the initial subsidence problem. The difference in success rates among different crops is due to the difference in sensitivity to moisture stress of corn and soybean. Soybean plants usually can tolerate more adverse conditions than can corn plants.

Soil Physical Condition

Soils at selected research sites were characterized to identify factors that may be limiting yields. Typically, mitigated sites were characterized by massive or platy soil structure in the fill material. Soil texture of fill and natural soil ranged from silt loam to silty clay.

Low hydraulic conductivity values were observed in both mitigated and reference areas and were attributed in part to the medium to fine textured soil and fill material. Both reference and mitigated sites showed variability in hydraulic conductivity with depth. In mitigated areas, massive structure and compaction left by earthmoving equipment contributed to low hydraulic conductivity. Inclusions of foreign material (e.g. wood, weeds) in the fill also slowed hydraulic conductivity.

Higher hydraulic conductivity values in reference soils were attributed to natural soil structure and voids left by soil fauna or plant roots. At many sites, there was only a slight difference in hydraulic conductivity between reference and mitigated areas. All values were within the moderately low to moderately high Soil Conservation Service (SCS) conductivity class (Soil Survey Staff 1993). There was no detectable correlation between mitigation method and hydraulic conductivity. In summary, mitigation can lower the hydraulic conductivity of the soil, but the change may not be significant because of the low permeability of the natural soil.

The lack of soil structure in fill material did not significantly change the bulk density from reference soils. This is due in part to similar textures of soils in mitigated and reference areas. Average bulk density values for both fill and ditch-plus-fill mitigation tended to be only slightly lower than those for reference soils. Hence, soil compaction, as identified by higher bulk density, did not appear to affect yield differences between mitigated and reference areas. It is possible that the sampling density was not great enough to allow the detection of changes in bulk density. Although the structure was massive in filled areas, it was not highly compacted throughout. Compaction was confined mainly to traffic interfaces, which may not have been sampled.

Penetrometer resistance measurements were taken in late spring when soil water content was approximately at field capacity. Because of the continuous sampling, this technique is more sensitive than bulk density is to compaction. Soil compaction from reclamation was detected at sites 1, 2, 3, 8, and 15 (fig. 1). Prominent points (sites 2 and 15 at 18 in.) in the

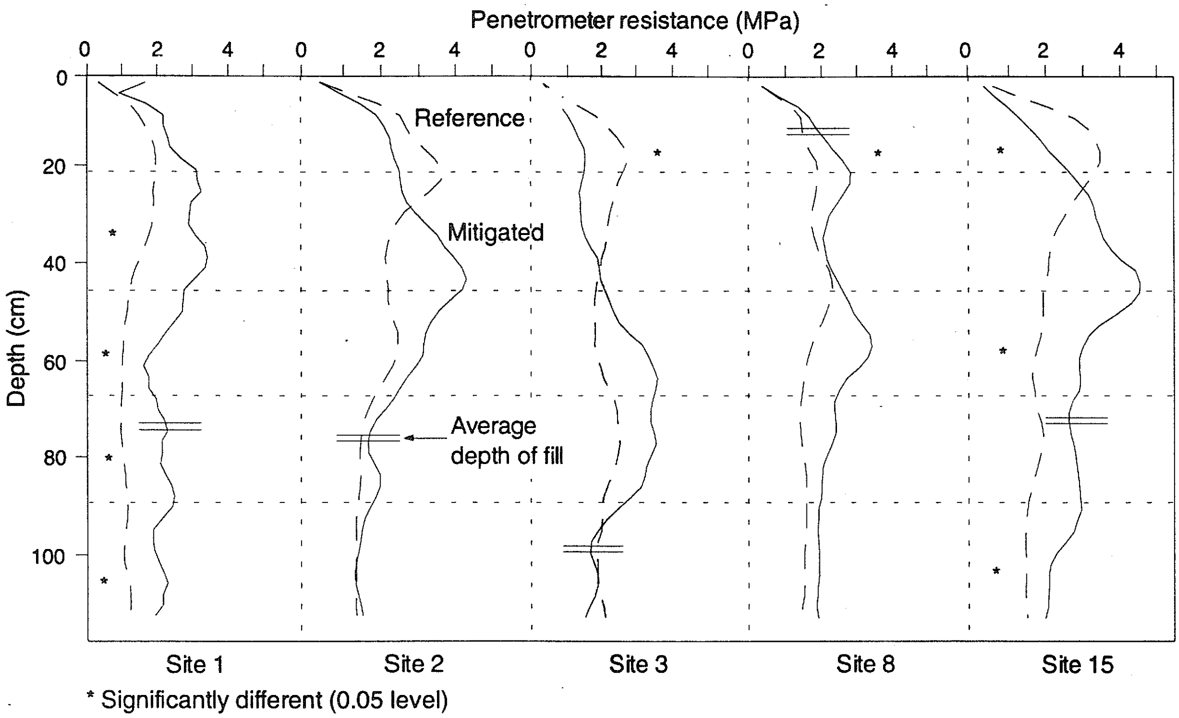

Figure 1 Penetrometer resistance profiles of mitigated and reference areas.

penetrometer profile identify traffic or scraper lift faces. These interfaces disrupt internal drainage, and as a result, saturation of the soil may be prolonged. However, mitigated and reference segment means were not statistically different ($\alpha = 0.05$). The exception was Site 1 with higher soil strength below the depth of tillage.

Root-restricting soil strength values depend on soil texture, structure, moisture content, and method of measurement and therefore do not lend to direct comparison from other studies. Penetrometer resistance values in the range of 2 to 2.5 MPa (290 to 363 psi) have been identified as potential root-restricting values (Taylor and Burnett 1964). In this study, these values were exceeded at some sites and may have caused root restriction. In most cases, however, the penetrometer resistance values from mitigated areas were statistically indistinguishable from those taken in the reference areas. Lower yields in mitigated areas cannot be simply attributed to poor physical conditions.

SUMMARY AND CONCLUSIONS

Successful mitigation of land adversely affected by longwall mine subsidence in southern Illinois is primarily dependent on adequate water drainage. Level topography and poorly drained soils make this task difficult. Results from 4 years of crop yield sampling show that currently used mitigation techniques applied to subsidence-affected areas can be effective in restoring soybean but not corn yields to premined levels. Corn yields were reduced an average of 19% in mitigated areas, as compared with the yield in undisturbed reference areas. However, mitigation does improve corn yields in subsided areas. Corn yield reductions of 42% to 95% have been reported for recently subsided areas (Darmody et al. 1989).

This research showed that all types of mitigation (ditch, fill, and ditch-plus-fill) can be successful. However, rainfall and other factors at a site may interact to cause significant yield reductions, regardless of mitigation method. Ditching was found to be more successful than ditching-plus-fill, or fill only. Site-specific factors such as the amount of subsidence damage, and hence the amount and type of mitigation necessary, and field/landscape characteristics may bias the ditching success rate. For example, ditching may be performed when subsidence impact is less and fill is not needed. The disadvantage of ditch mitigation is that waterways in fields take land out of production and require maintenance.

There were no significant differences in soil fertility and only small differences in soil physical properties between mitigated and reference soils. These small differences in soil properties are unlikely to affect crop yields. Field observations support the conclusion that temporary, excess moisture is the factor limiting crop growth in mitigated areas.

This research indicated that the following practices may contribute to successful mitigation:

- reduce soil compaction by working only when the soil is dry;
- minimize traffic and use only low ground pressure equipment;
- apply deep tillage to alleviate compaction interfaces;
- provide surface water removal with ditches and waterways;
- add sufficient fill to prevent ponding.

In addition, installation of subsurface drainage may be beneficial. Subsided areas may function as basins that collect and store excess water even if filled. Drainage tiles are not commonly used in southern Illinois because of low permeability and siltation problems in high sodium soils (Drablos and Moe 1984). If an outlet is available, a subsurface tile drain may be effective. A surface inlet may be necessary if the fill is compacted. Further research is necessary to develop this idea.

Mitigated areas are not extensive and a small yield decrease on 1 to 2 acres in a large field will not significantly reduce overall field yields. Mitigation is important, not only from a productivity standpoint, but also to minimize weed problems and maintain normal planting and harvest patterns. As longwall coal mining in this region of productive agricultural soils increases and expands into the even more productive soils on the Wisconsinan till plain, the need for effective reclamation is increasingly important to maintain agricultural viability.

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MODELING AGRICULTURAL IMPACTS OF LONGWALL MINE SUBSIDENCE

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Summarized by Robert G. Darmody and Billy A. Trent

ABSTRACT

Minimizing subsidence impacts on agricultural land by avoiding sensitive soils or modifying the mine plan are options that coal companies should consider. A model for predicting agricultural impacts of subsidence would give mine designers and regulating agencies another tool for evaluating mine plans. This project was a logical successor to previous agronomy studies in the Illinois Mine Subsidence Research Program, which first documented subsidence impacts and the effectiveness of mitigation.

A predictive model of agricultural soil subsidence sensitivity (SSS) was developed solely from empirical data from all previous IMSRP agronomy research. The SSS model integrated soil properties such as depth to seasonally high water table, soil hydraulic conductivity, natural soil drainage class, slope, and probability of flooding to assign a subsidence sensitivity class to soils of a given area. The GIS (Geographical Information System) program, GRASS, was used to optimize the utility of the model. Using the model with a subsidence topographic model should allow mine companies to optimize a mine plan to predict and minimize subsidence impact. Hypothetical mine plans could be tested with the model to determine which plan would minimize the impact of subsidence on agricultural soils. The model gives the location and an estimate of how the soils would respond to subsidence.

The model was applied to a proposed longwall mine in Illinois. Crop yield loss, predicted using corn (*Zea mays* L.) yields as a reference, was 6.8% for the proposed longwall panel area but ranged from 4.1% to 9.5% for individual mine panels. The model also predicted that mitigation of the affected areas would reduce that yield loss to 1.2% for the longwall area and to 0.5% to 1.7% for the individual panels.

INTRODUCTION

Subsidence subsequent to mining forms depressions that may cause ponding in agricultural fields and impact crop yields. Ponded areas may cause problems, including difficult cultivation, poor stand establishment, loss of nutrients, poor root development, and increased diseases. These problems can be evaluated quantitatively by measuring yield reduction at harvest. Previous studies in other parts of the state showed an estimated crop yield reduction of 4.7%, compared with crop yields measured at nearby sites that were under the same farm management. Corn yields were measured at subsidence sites selected from aerial photographs (Darmody, Steiner et al. 1988, Darmody, Jansen et al. 1989). This estimate was for the entire mine area. Specific sites within the area identified as having severe subsidence effects had an average loss of 95%. Sites identified as having moderate effects had 43% reduction, and sites with slight effects had an insignificant 2% yield reduction.

Coal companies are required to restore the land to its premining capability. Research in Illinois indicates that mitigation is successful in restoring soybean (*Glycine max* L.) yields, but not successful in fully restoring corn (*Zea mays* L.) yields (Hetzler and Darmody 1992). Corn yields in mitigated sites averaged 19% lower than yields in adjacent undisturbed sites during a 4-year study period (Darmody et al. 1992). Soil properties that contribute to deleterious effects of longwall mining are primarily related to hydrologic aspects of the soil (Darmody, Jansen et al. 1988, Darmody, Bicki et al. 1989). These include water table depth, flooding probability, slope, natural drainage, and hydraulic conductivity. Unfortunately, many soils in

Illinois, particularly those on the Illinoian till plain, have many of these properties that make them sensitive to subsidence (Fehrenbacher et al. 1984). Longwall mining to date has been largely in the portion of the state that includes soils relatively insensitive to the deleterious effects of subsidence. The work reported here involves the development of a predictive model of the sensitivity of agricultural soil to subsidence. This model should be helpful to both the coal industry and regulatory agencies. Prediction is particularly important as longwall mining moves into the extensive areas of highly sensitive, nearly level soils in Illinois (Darmody and Vance 1994).

The objectives of this research were to (1) develop a predictive model of agricultural soil sensitivity to subsidence (SSS) associated with longwall mining, and (2) apply the model to a proposed longwall mine plan.

METHODS AND MATERIALS

Research Area

The study area was a proposed longwall permit area in Macoupin County, Illinois (fig. 1). It was in the Honey Creek watershed and included many of the soils of Macoupin County. Because of the proximity of the creek, however, the study area was more sloping than much of the county. The physiography of the southern portion of the study area is dominated by the creek valley and its associated sloping soils; whereas the northern portion of the study area is on the nearly level, poorly drained Illinoian till plain (Fehrenbacher et al. 1984). The U.S. Department of Agriculture Soil Conservation Service (SCS) produced a digital soils map of the area and used it as a base for the map generated with the SSS predictive model.

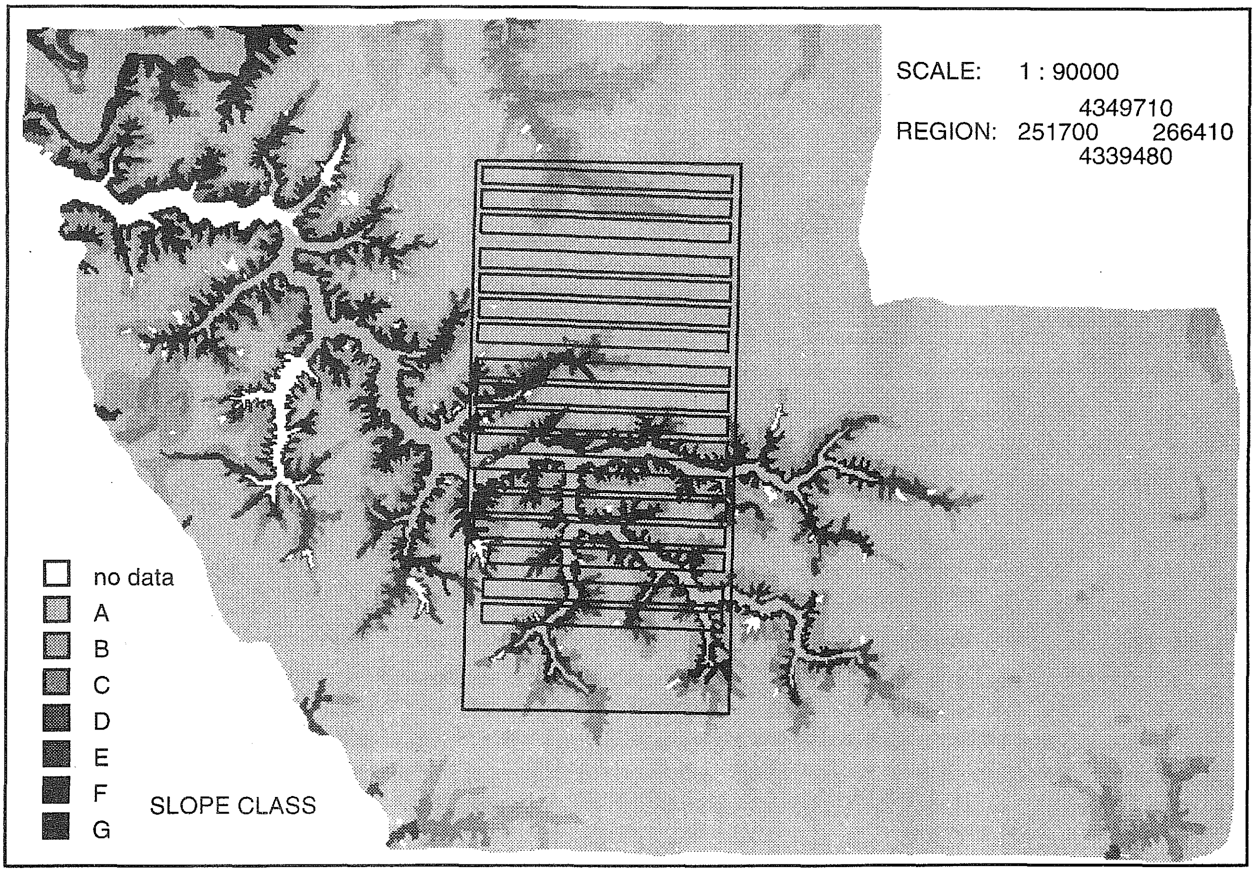

Figure 1 Longwall mine subsidence modeling study area (permit area outlined). Map shows soil slope classes from A (nearly level 1–2%) to G (strongly sloping 30%).

The proposed longwall mine plan was provided by the Illinois State Geological Survey (R.A. Bauer, personal communication, 1993). The plan consisted of a longwall permit area with 17 panels that were approximately 10,000 feet long and 600 feet wide, and oriented east to west. They were numbered for research purposes from 1 to 17, south to north.

Subsidence Yield Reduction Computation

Soil properties that influence sensitivity to subsidence were given a weight to assign an SSS score to each soil map unit in the county (tables 1 and 2). The properties used were depth to seasonally high water table, slope, probability of flooding, natural soil drainage, and hydrologic group (Drablos and Moe 1984, Darmody, Bicki et al. 1989, Hodges 1990, Darmody, Jansen et al. 1988). SSS scores ranged from 0 to 20. Assignment of SSS classes to soil mapping units was based on their scores. A SSS score of <6 was assigned to SSS class A, indicating none to slight subsidence impact; a score of 6 to 10 was assigned to class B, indicating slight impact; scores 11 to 15 were class C, indicating moderate impact; and scores >15 were class D, indicating severe subsidence impact.

Table 1 Properties used to assign subsidence sensitive scores to soils.*

Slope class	Drainage group	Flooding		Hydrology group	Water table depth (cm)		Subsidence score
		Frequency	Duration		Perched	Apparent	
A	3A, 4A, 4B	Frequent	Brief to longer	D	<0	<30	4
	2A, 3B, 3C, 4C	Frequent	Very brief	C	—	30–60	3
B	2C, 2B	Occasional	Brief	B	0–30	60–180	2
	1C	Occasional	Very brief	A	31–180	—	1
C		None	—		>180	>180	0
D	—	—	—	—	—	—	-3
>D	—	—	—	—	—	—	-4

* table 2 for property definitions

Table 2 Definitions of soil property criteria classes.

Slope class	Drainage group		Hydrology (runoff)	Flooding frequency
	Drainage	Permeability (in./h)		
A = 0–2%	A = poorly	1 = rapid (>2)	A = low	Occasional = <50%
B = 2–5%	B = somewhat poorly	2 = moderate (0.6–2)	B = low moderate	Frequent = ≥50%
C = 5–10%	C = well + moderately well	3 = moderately slow (0.2–0.6)	C = high moderate	Very brief = <2 days
D = 10–15%	—	4 = slowly	D = high	Brief = ≥2 days

The crop yield impact associated with each SSS class was determined from previous research on the impact of longwall subsidence on corn yields in Illinois (Darmody, Jansen et al. 1988). The proportion of the yield reduction found in that earlier study associated with each SSS class was determined (table 3). The effectiveness of subsidence mitigation for restoring corn yields was estimated from the results of a previous research project (Darmody et al. 1992). Reference corn yields for each soil map unit were taken from the Soil Survey of Macoupin County (Hodges 1990).

GIS Software

The geographical information system (GIS) software package GRASS (USACERL 1991) was used to generate the maps and tabular data concerning soil properties, SSS information, and crop yields. This software is in the public domain and available from the U.S. Army CERL. The Soil Conservation Service (Tom D'Avello, personal communication, 1993) provided the digital soil map of the Honey Creek watershed; it was used as the base map from which all the other maps were derived. The mine plan map was hand-digitized.

Table 3 Generalized impact of subsidence on crop yields.*

Subsidence risk class	Yield reduction (%)		Extent (%) of soils in each class				Average yield loss (%)	
	Subsided	Mitigated	0-to-slight	Slight	Moderate	Severe	Subsided	Mitigated
None-to-slight	0	0	90	10	0	0	0.2	0.0
Slight	2	0.4	82	15	3	0	1.6	0.3
Moderate	43	8.6	56	35	8	1	5.1	1.0
Severe	95	19	47	40	6	7	10.0	2.0
Average	35	7	69	25	4	2	4.2	0.8

* data derived from Darmody, Jansen et al. (1988) and Darmody et al. (1992)

RESULTS AND DISCUSSION

SSS scores for the soils of the longwall permit study area ranged from 1 to 18 (least to most impact) with a weighted average score of 12.3, lower than the weighted average SSS score of 13.8 for the watershed. (Both scores fall into SSS Class C: moderate impact.) Scores tended to be higher in the northern portion of the study area, away from the creek valley and toward the nearly level Illinoian till plain. The northern portions of the study area on the Illinoian till plain were primarily in the moderate and severe classes, whereas the southern portion of the study area included some land classified as none-to-slight and slight. The proposed mine was placed in an area of the watershed that had a nearly average SSS score. If the mine had been located farther east in the watershed, the SSS scores would have been higher and subsidence would have had a greater impact on agriculture. Figure 2 shows the distribution of SSS classes for the permit area.

Most of the soils in the study area are well adapted for corn growth. The weighted average predicted corn yield was 112 bushels per acre (fig. 3). The most productive soils had a predicted yield of 141 bushels per acre and were in the northern part of the study area. Some areas, particularly in the southern portion of the study area, are not suitable for corn growth and are shown in white on figure 3. In the longwall study area, the unmitigated impact of subsidence predicted, based only upon the soils suitable for growing corn in the study area, was a 6.8% reduction in corn yields (table 4). The predicted corn yields averaged 105 bushels per acre and ranged from 42 to 133 bushels per acre after subsidence (fig. 4).

Table 4 Predicted corn yields for the total longwall permit area.

Condition	Total corn yield bushels	Weighted average corn yield	
		bushels/acre	%
Unmined	488,031	112	100.0
Subsided	454,931	105	93.2
Mitigated	482,216	111	98.9

Subsidence impact would not be expected to be uniformly distributed over a given panel, as shown in the model. The resolution of the available topographic data would not permit displaying individual portions of a panel. This apparent deficiency in the model is accommodated, however, by adjusting the impact over the entire panel, according to known impact distributions from previous studies (table 3).

Mitigation of the subsidence effects was predicted to lessen the impact on corn yields. The weighted average loss in corn yields after subsidence mitigation, when only the soils suitable for growing corn in the study area were included, was predicted to be 1.2%. The predicted corn yields averaged 111 bushels per acre and ranged from 43 to 139 bushels per acre after subsidence mitigation (fig. 5).

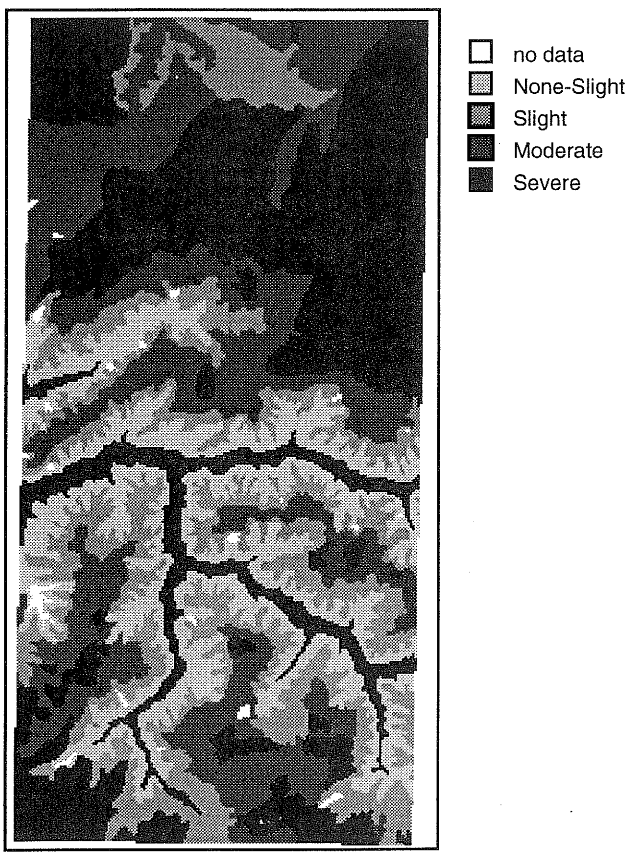

Figure 2 Soil subsidence sensitivity (SSS) classes for the longwall permit area.

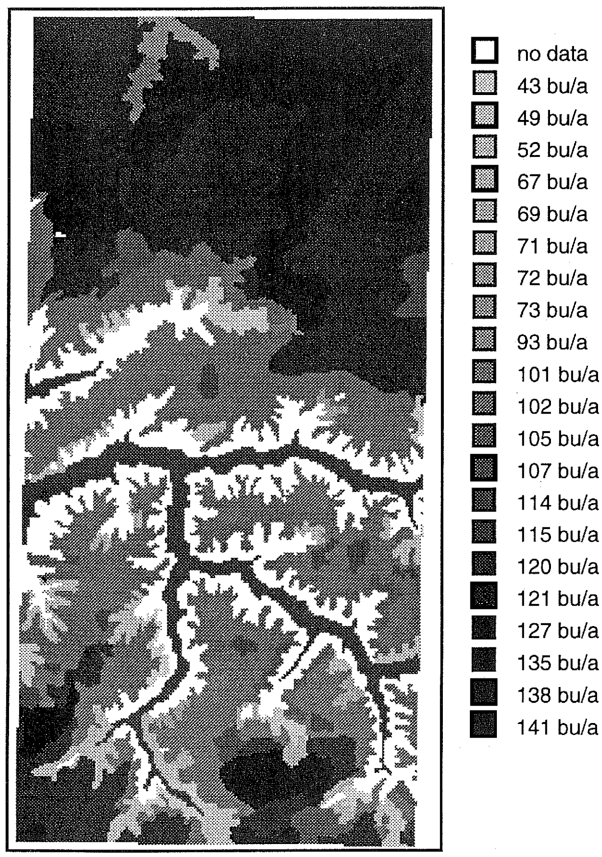

Figure 3 Premining corn yields for the longwall permit area.

The predicted impact of longwall mining was calculated for each mine panel (table 5). Because the northern and southern portions of the proposed mine were so different, a discussion of the impact on panel 1 in the south near Honey Creek and panel 14 in the north on the Illinoian till plain follows. The most obvious difference between the two panels was in slope. The classes of slope over panel 1 ranged from A (0–2%) to G (>30%); whereas panel 14 had only slopes classified as A (fig. 1). Sloping ground tends to be less susceptible to subsidence because there is less of a tendency for runoff to collect in closed depressions (Darmody, Bicki et al. 1989). Another way the two panels differed was in depth to seasonally high water table. Water tables tended to be uniformly shallow over panel 14, but variable and often deep over panel 1 (fig. 6). Well-drained soils have relatively high hydraulic conductivity and a seasonally high water table deeper than about 3 feet. Poorly drained soils have relatively low hydraulic conductivity and a water table at or near the surface seasonally. Darmody, Bicki et al. (1989) found that water tables tend to remain at the same elevation after subsidence, and if they are shallow, increase the probability of subsidence. Soils with a shallow water table are more sensitive to subsidence because their surface may drop below the water table after subsidence.

The differences in topography and soils between the panels was reflected in different SSS scores. Panel 1 had a weighted average SSS score of 9.9, whereas panel 14 had a score of 16.0. Predicted corn yields were quite different on the two panels. The undisturbed corn yield from panel 1 was a total of 12,241 bushels or 103 bushels per acre. The premining corn yield from panel 14 was 21,664 bushels or 130 bushels per acre. Subsidence was predicted to reduce the corn yields to 11,653 bushels or 98 bushels per acre for panel 1 and to 19,812 bushels or 119 bushels per acre for panel 14. These analyses excluded non-corn-producing areas of the panels. This is a corn yield reduction of 4.8% for panel 1 and 8.5% for panel 14.

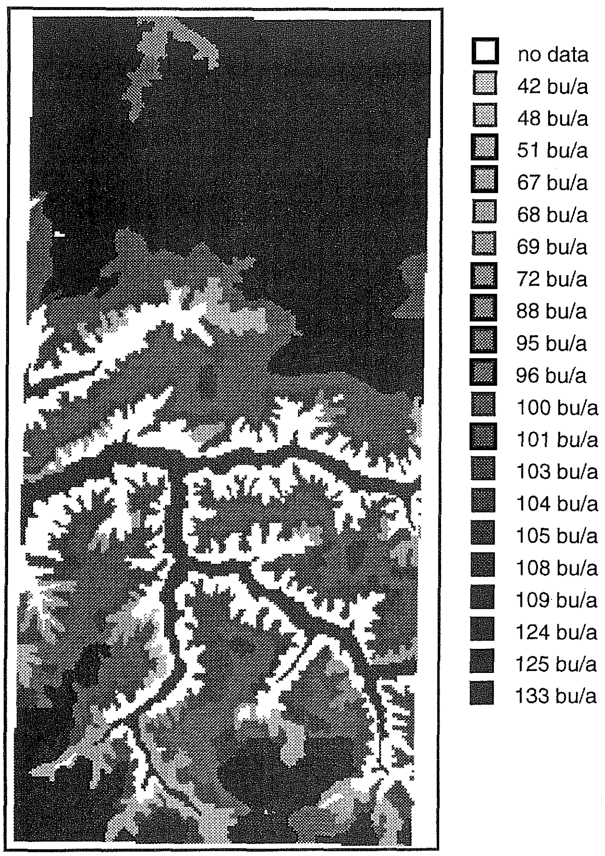

Figure 4 Predicted corn yields after subsidence without mitigation.

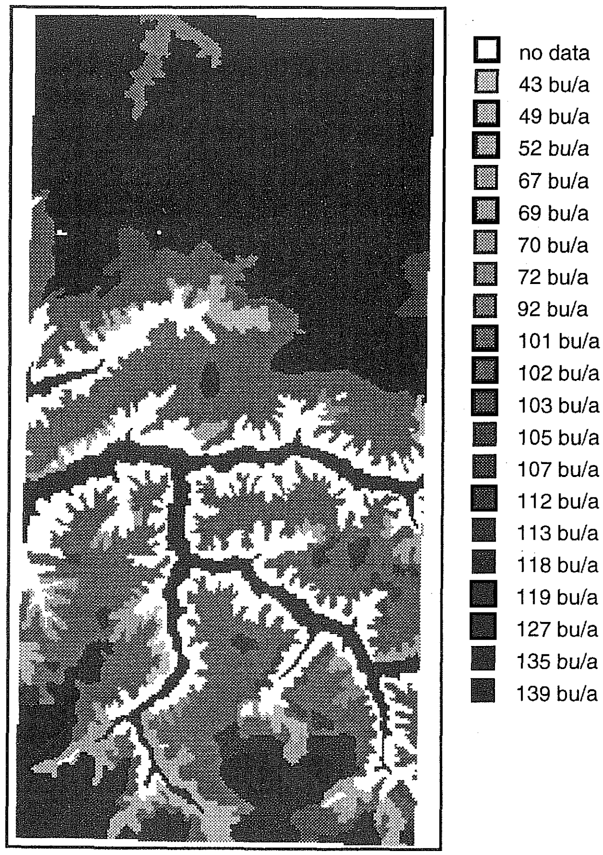

Figure 5 Predicted corn yields after subsidence with mitigation.

Mitigation was predicted to reduce subsidence impact. The mitigated corn yield was predicted to be 12,150 bushels or 102 bushels per acre for panel 1 and 21,301 bushels or 128 bushels per acre for panel 14. This is a corn-yield reduction of 1% for panel 1 and 1.5% for panel 14.

SUMMARY

The SSS model is a useful tool for predicting the impact that longwall mine subsidence will have on agricultural production. Different mine plans can be tested to predict the impact mining will have on crop yields. This can be done to estimate mitigation costs, test different mine plans to minimize impact, or predict loss in corn yields.

The predicted impact, as measured by corn yield loss, for the proposed mine in Macoupin County was 6.8% for the permit area and ranged from 4.1% to 9.5% for the individual panels (table 5). Mitigation was predicted to lessen the impact to 1.2% loss of corn yield for the permit area and from 0.5% to 1.7% for the individual panels.

The GIS program GRASS is readily available from the U.S. Army CERL and The model requires digital soil maps that are increasingly available from the USDA SCS.

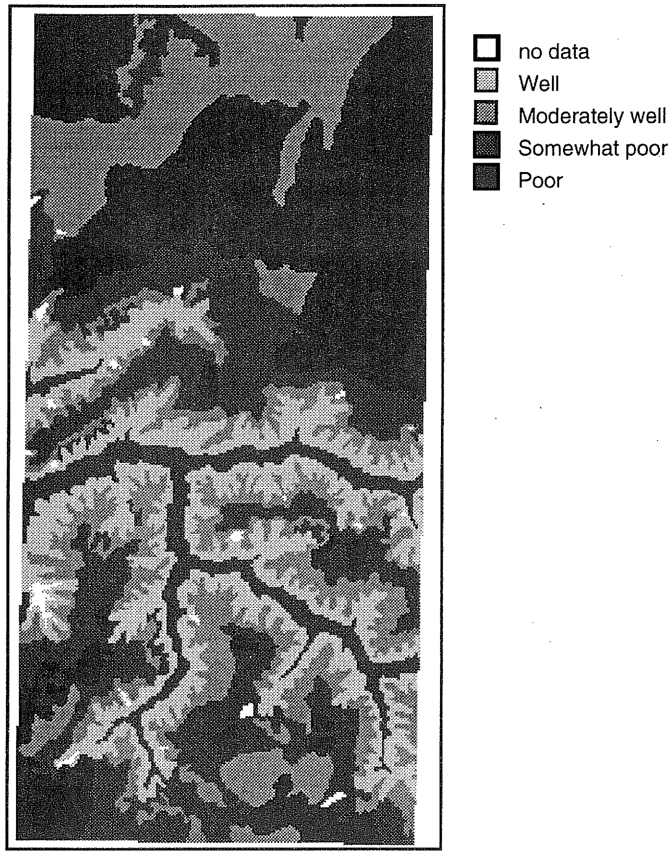

Figure 6 Natural soil drainage in the longwall permit area.

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Table 5 Predicted corn yields before and after longwall mine subsidence in the study area.

Panel	Average SSS score	Average class	Initial yield		Subsided yields			Mitigated yields		
			Total	bu/ac	Total	bu/ac	% loss	Total	bu/ac	% loss
1	9.9	3.4	12,241	103	11.653	98	4.8	12,150	102	0.7
2	10.7	4.1	12,854	102	12,136	96	5.6	12,740	101	0.9
3	8.7	2.9	10,531	101	10.042	96	4.6	10,460	100	0.7
4	10.4	3.6	13,712	105	13,019	99	5.1	13,611	104	0.7
5	8.9	2.5	11,047	100	10,590	96	4.1	10,988	99	0.5
6	8.6	2.7	10,590	105	10,091	100	4.7	10,521	104	0.6
7	8.9	3.6	10,186	106	9,526	99	6.5	10,078	105	1.1
8	10.0	2.9	12,611	101	12,086	97	4.2	12,540	100	0.6
9	12.9	5.6	15,477	108	14,393	101	7.0	15,300	107	1.1
10	11.8	4.9	13,590	103	12,664	96	6.8	13,444	102	1.1
11	15.1	7.5	18,733	114	17,245	105	7.9	18,464	112	1.4
12	16.9	9.3	19,952	122	18,060	111	9.5	19,607	120	1.7
13	16.5	9.0	20,751	128	18,853	116	9.1	20,394	126	1.7
14	16.0	8.4	21,664	130	19,812	119	8.5	21,301	128	1.7
15	15.7	8.3	21,019	128	19,256	118	8.4	20,683	126	1.6
16	13.4	5.7	20,760	129	19,555	121	5.8	20,542	127	1.1
17	13.6	6.1	18,144	124	17,012	116	6.2	17,923	123	1.2
All	12.3	5.3	263,861	114	245,993	106	6.8	260,746	113	1.2
Permit	12.3	5.4	488,031	112	454,931	105	6.8	482,216	111	1.2

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APPLICATION OF SURFACE GEOPHYSICS TO DETECTION AND MAPPING OF MINE SUBSIDENCE FRACTURES IN DRIFT AND BEDROCK

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ABSTRACT

Electrical resistivity and seismic surveys were made before, during, and after mining in Saline County, Illinois, to test the usefulness of these techniques for mapping the lateral extent and depth of subsidence surface fractures and in monitoring water table changes. The geophysical methods included vertical electrical resistivity soundings, resistivity profiles, azimuthal resistivity surveys, seismic refraction and reflection profiles. Postsubsidence resistivity soundings and seismic refrac-tion profiles were made over portions of three panels in Jefferson County to test the applicability of these methods at another site. As this study showed, resistivity soundings may be inverted for minimum estimates of fracture penetration depth, and common offset seismic reflection profiles may be used to identify fractured bedrock horizons. Repeated resistivity soundings allowed minimum estimates of fracture depth. Common offset seismic reflection surveys helped researchers identify a fractured bedrock unit. These surveys were performed at the same locations as other overburden, hydrology, and agronomy projects in the Illinois Mine Subsidence Research Program.

INTRODUCTION AND BACKGROUND

Geophysical techniques measure physical property changes in earth materials over wide areas, as opposed to well or borehole data that indicate changes at individual points. Few studies have applied surface geophysical methods to mine subsidence, particularly in Illinois. In the Illinois Basin, Burdick et al. (1986) successfully used resistivity to locate shallow abandoned mine voids; Henson et al. (1989) used high-resolution seismic reflection techniques to map sedimentary facies that could lead to roof instability during mining. Most other longwall mine geophysical studies have been in the Appalachian coalfields (Wilson et al. 1988, He and Wilson 1989, Rudenko et al. 1989). None of these studies, however, used geophysical techniques to identify subsidence-induced changes in drift materials or to characterize hydrogeological changes accompanying subsidence.

In this study, electrical resistivity and seismic surveys were used to map fractures and monitor water levels over subsiding longwall coal mine panels in Saline and Jefferson Counties, Illinois. Inversion of resistivity soundings made during subsidence of panel 2 in Saline County revealed a shallow high-resistivity layer corresponding to fractured unsaturated drift. Resistivity soundings could not detect the presence of these fractures below 5 feet, however, nor could soundings map the lateral extent of drift fractures or provide information on bedrock fracturing. Azimuthal resistivity variations were consistent with predicted directions of drift fractures over panel 2, and repeated azimuthal surveys indicated that shallow drift fractures along the centerline closed within 8 months of subsidence. Interpretation of seismic refraction surveys was hampered by the development of strong lateral velocity variations in fractured materials; however, these surveys revealed no widespread water table fluctuations during subsidence. Reductions in both resistivity and P-wave velocity were measured over static tension zones along the sides of panel 2 in Saline County and panel 3 in Jefferson County. These measurements, if confirmed, may indicate long-term fracturing and downward water seepage along tension zones. Common offset seismic reflection surveys identified disrupted reflections below the bedrock surface over the southern margin of panel 1 in Saline

County 8 months after subsidence. A thin limestone at a depth of 125 feet exhibited enhanced postsubsidence permeability and may have been the source of these reflections. Fractures in the subcropping bedrock surface (at a depth of 85 ft) were not detected.

SALINE COUNTY SITE

The study site in northwestern Saline County consisted of a narrow strip a few hundred feet wide across longwall mine panels 1 and 2. Approximately 6 feet of the Herrin Coal was mined from a depth of 370 feet. The maximum surface subsidence along the panel centerlines was 4.5 feet (Kelleher et al. 1991).

Hydrogeology

Four deep drift piezometers, six bedrock piezometers, and one pump well were installed over and adjacent to panel 1; no piezometers or wells were installed over panel 2. The Trivoli sandstone, 175 to 200 feet deep, is the principal aquifer in the study area. During and after subsidence, piezometric levels in the Trivoli declined sharply and showed little or no recovery, although postsubsidence packer tests showed a slight increase in hydraulic conductivity.

Piezometric levels in the basal drift also declined rapidly during subsidence; however, these levels recovered completely within 1 year. Short-term, local water level fluctuations in the drift occurred in response to subsidence over panel 1, then shallow water levels gradually recovered to presubsidence levels (Seils 1992). Water levels measured in domestic wells around the panels (Booth and Spande 1991) and piezometers screened in upper levels of the drift over panel 1 (R. Darmody, personal communication, 1992) indicated that the water table lies within 20 feet of the surface through most of the year.

Subsidence Fractures and Geotechnical Measurements

Surface displacements, strains, subsidence rate, and subsurface movements were monitored throughout the subsidence of panels 1 and 2 (Kelleher et al. 1991, Van Roosendaal et al. 1992). Fractures were aligned parallel with the panel sides over the static tension zones and parallel with the mine face near the panel centerlines (fig. 1). Arcuate (curved) fractures occurred elsewhere (Van Roosendaal et al. 1992). Fractures aligned with the mine face near panel centers closed within a few weeks, as these areas passed from dynamic tension into compression. Eight months after subsidence, static tension zone fractures over panel 1 remained open to a depth of at least 5 feet (Seils et al. 1992). Van Roosendaal et al. (1992) used surface strain measurements and downhole inclinometer readings to estimate a maximum penetration depth of 27 to 31 feet for fractures visible at the surface in the static tension zones of panel 2.

Data Collection and Results

Electrical Methods ▪ *Resistivity soundings* An overview of the electrical resistivity methods used in this study may be found in Telford et al. (1976). The basic electrode configuration

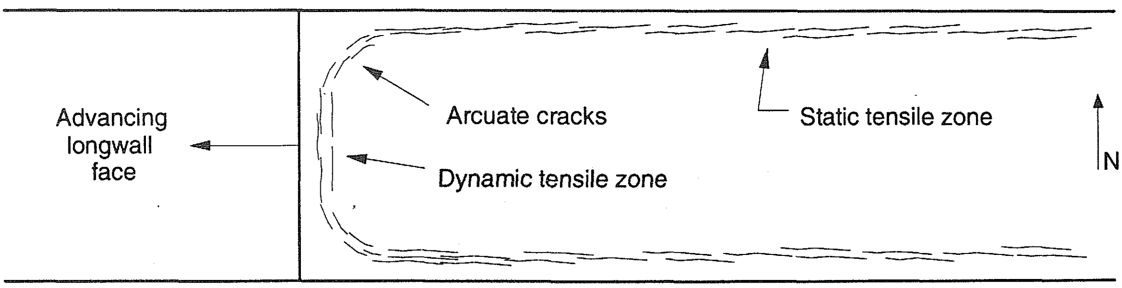

Figure 1 Typical pattern of open tension cracks over a longwall panel (after Van Roosendaal et al. 1992).

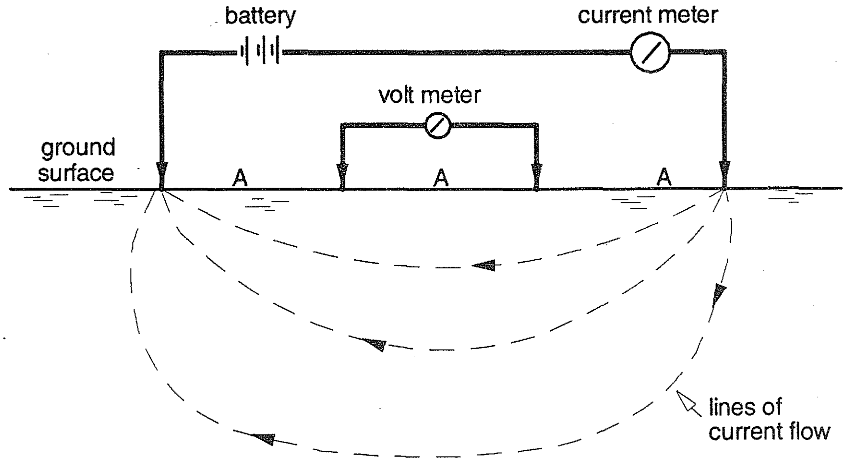

Figure 2 Schematic representation of the electrical resistivity method.

used was the Wenner array, as shown in figure 2. Twenty-five Wenner array vertical electric soundings were made over selected portions of panels 1 and 2 before, during, and after subsidence.

Soundings were inverted with a least-squares computer inversion procedure (Interpex 1988) to yield multilayer geoelectrical models. Most resistivity soundings over panels 1 and 2 were modeled with four geoelectrical layers (fig. 3), although the presence of a thin, conductive upper soil layer required five-layer models in a few cases. The interpretation of these layers is based on a soil boring made at the center of panel 1 and a roadcut approximately ½ mile northwest of the panels (Frye et al. 1972). The uppermost layer of the four-layer model represents moderate-to-high resistivity topsoil and loess (1–3 ft thick). This overlies 15 to 20 feet of relatively conductive clayey Wisconsinan lake deposits. Water levels from piezometer and seismic refraction surveys indicated that this unit is probably continuously saturated below a depth of 15 to 20 feet. The lowermost 20 to 40 feet of drift is composed of saturated gravelly tills and outwash. Resistivities of the underlying Pennsylvanian shale bedrock were confirmed through comparison with electric logs for the area. In many soundings the lower saturated drift cannot be distinguished from the bedrock.

Geoelectrical layers one through three were reasonably well determined for most soundings; uncertainty in resistivity averaged about 10% and depth uncertainty averaged 35%. The thickness of the lowest layer and the resistivity of the bottom unit (usually bedrock) were poorly constrained; uncertainties were as great as 50%. Consequently, resistivity soundings were not used to identify fracturing or other subsidence-induced changes in the bedrock. Soundings were also not used to estimate water levels because seismic refraction surveys generally provided more accurate water table depths than those provided by piezometers.

■ ***Effect of fracturing on resistivity*** Repeated soundings were made during subsidence over the centerline of panel 2 and at a point 490 feet east of the centerline. These soundings exhibited major increases in resistivity at short spacings during passage of the mine face (fig. 4). Soundings made later at these locations showed no significant differences from presubsidence soundings. These temporary increases in resistivity may reflect shallow air-filled fractures that developed during passage of the dynamic tension zone. In the case of two soundings made east of the monument line near the end of the syn-subsidence (during subsidence) period, this high resistivity zone appeared to penetrate only about 2 feet, which corresponded exactly to the base of a preexisting layer. The air-filled fractures may have occurred only in the loess, which is about 2 feet thick at this location. Another possibility is that fractures were already closing because the mine face had passed this location about 1 week earlier. At the centerline, inversion of a syn-subsidence sounding also revealed a shallow high-resistivity layer approximately 5 feet thick. These anomalous high resistivities vanished 5 days later after passage of the mine face, presumably as fractures closed. Pre- and postsubsidence sounding models from surveys over the north static tension zone and barrier

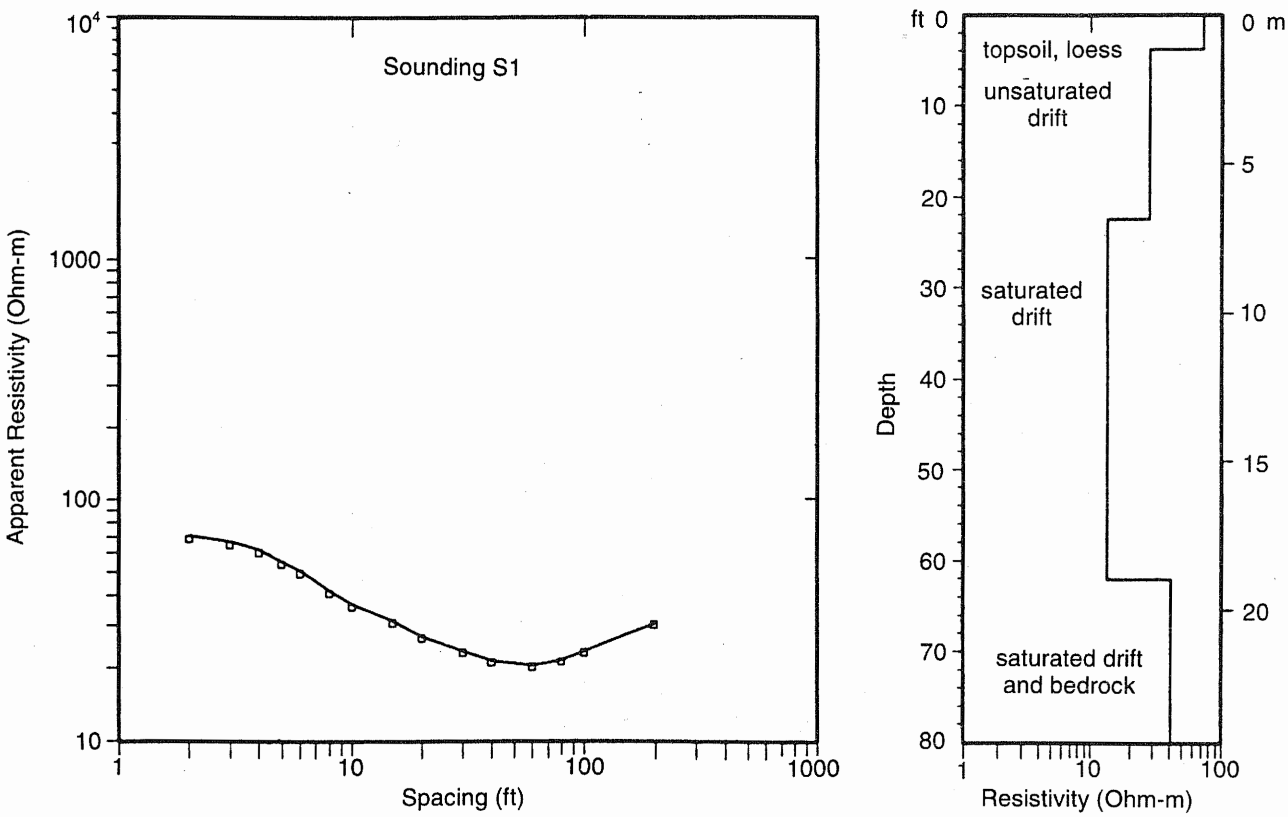

Figure 3 Vertical electrical sounding north of panel 1 and its layered model interpretation.

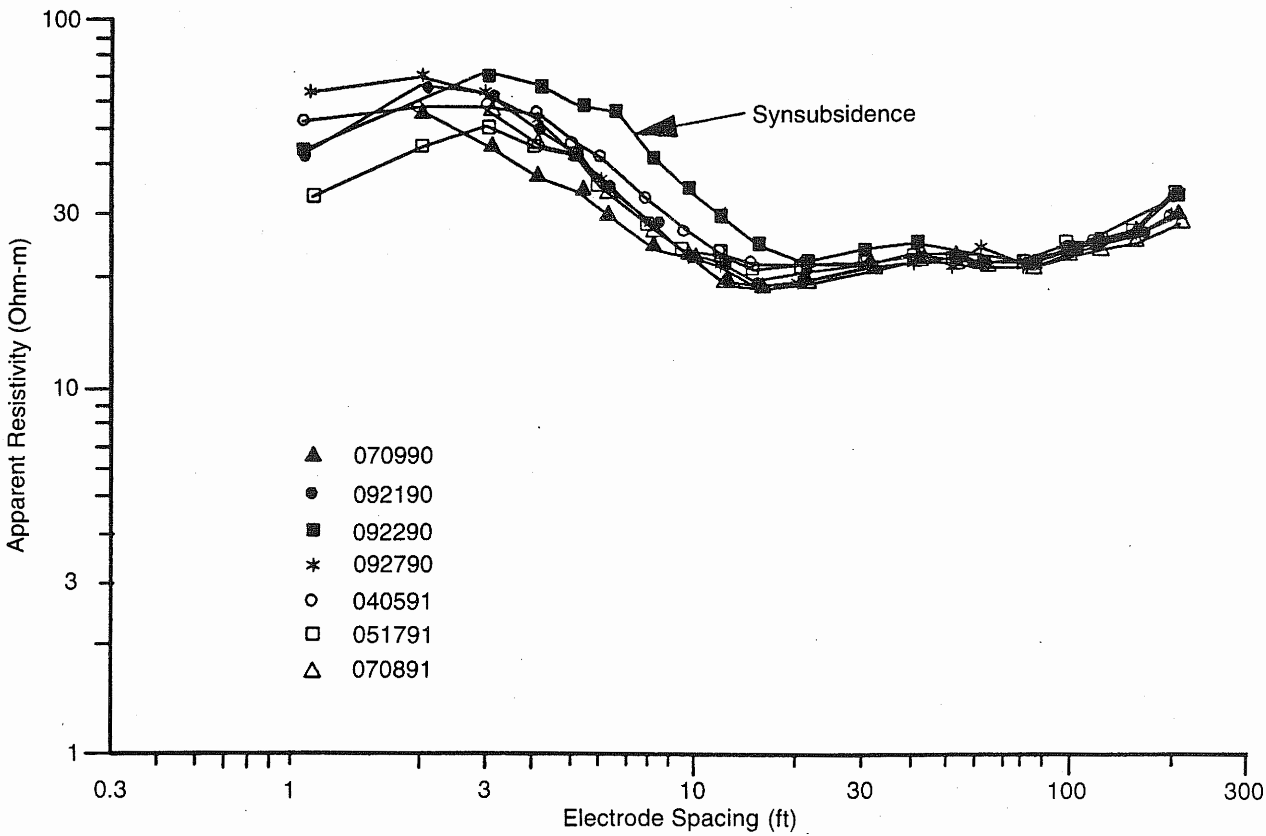

Figure 4 At monument 98, repeated soundings illustrating changes in apparent resistivity before, during, and after subsidence of panel 2.

pillar showed no significant resistivity changes, however, despite the development of major fractures along the tension zone.

■ ***Resistivity pseudosections*** Lateral changes in apparent resistivity were mapped along profile lines by moving Wenner arrays along the earth's surface at a constant spacing. Two profile lines crossed panel 2, one along the monument line and one 490 feet east of the monument line. Profiles were made at different spacings, and pseudosections were generated by plotting apparent resistivity values as a function of spacing. Pre-, syn- and postsubsidence Wenner array profiles at electrode spacings of 5, 10, 20, 40, 60 and 80 feet were used to generate the pseudosections.

Pseudosections of resistivity differences along the profile east of the monument line were computed by subtracting postsubsidence apparent resistivities from presubsidence apparent resistivities. Positive values indicated a resistivity decrease during or after subsidence. Such decreases occurred along both the north and south margins of panel 2. It should be noted that pseudosections provide only a general qualitative indication of two-dimensional resistivity changes. Pseudosections are not equivalent to geologic cross sections because electrode spacing does not convert to a linear depth scale; "deeper" apparent resistivity anomalies may reflect shallow resistivity variations. Offline anomalies may be projected onto the pseudosections and resolution decreases with increasing spacing.

Azimuthal Resistivity Surveys Azimuthal resistivity surveys have proven effective in identifying fracture trends and predicting hydraulic conductivity, both in anisotropic consolidated and unconsolidated materials (Taylor and Fleming 1988, Ritzi and Andolsek 1992, Carpenter et al. 1994). In this study, azimuthal resistivity surveys were made near the centerline and over the north barrier pillar of panel 2. Wenner arrays with electrode separations of 5 and 15 feet were rotated 360° around their center points, and measurements were taken every 10°. Apparent resistivities were then plotted on a polar diagram as a function of azimuth.

Permanent concentric electrode arrays consisting of seventy-two 10-inch steel carriage bolts were used to ensure that electrodes occupied exactly the same position during measurements. Four of these carriage bolts were hooked up at the same time in a Wenner configura tion along each azimuth (fig. 5) Electrodes are hooked up in a Wenner configuration at various azimuths such as the one shown oriented N30E. Current electrodes are labeled "I" and potential electrodes are labeled "V." The degree of repeatability (or precision) in azimuthal resistivity measurements was about 1 ohm-m; azimuthal resistivity variations less than this are not significant. No azimuthal measurements were made before subsidence because of the dense, 6-foot-tall weeds that covered the site.

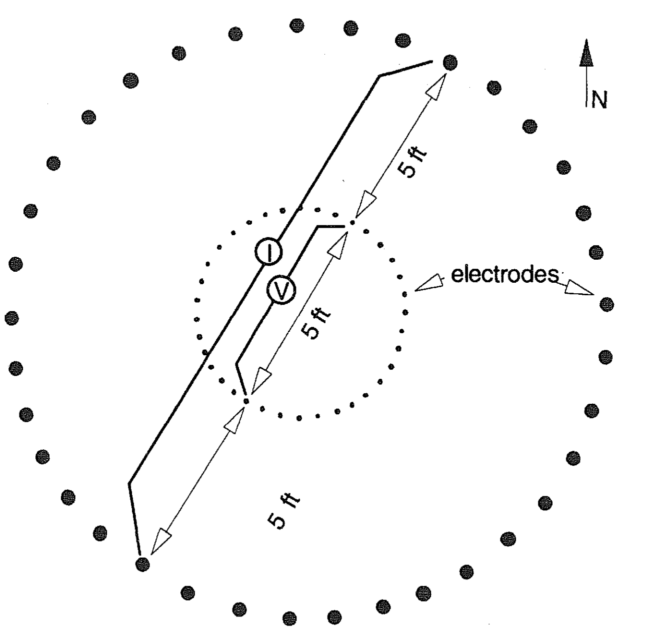

Figure 5 Azimuthal resistivity array consisting of filled permanent electrodes.

Two azimuthal arrays were placed in the dynamic compression zone of panel 2 to monitor fracture development during and after subsidence. In this area, a nearly isotropic resistivity distribution became strongly anisotropic during subsidence at 5- and 15-foot electrode spacings (fig. 6). The maximum apparent resistivity was recorded at a 5-foot spacing on September 25, 1990, when electrodes were oriented N10E. Apparent resistivities measured with

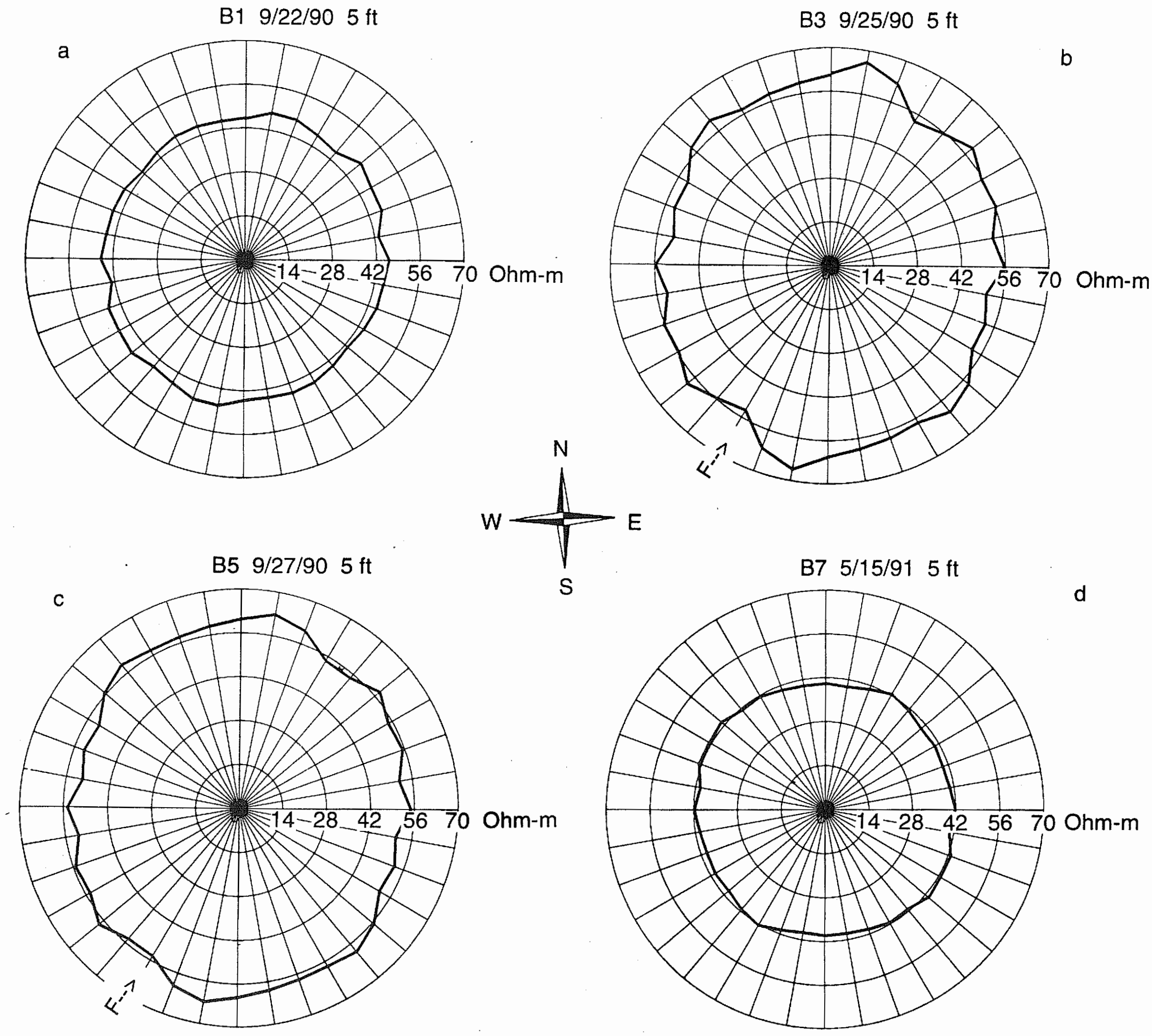

Figure 6 Azimuthal resistivity plots at array B for electrode spacing of 5 feet: (a), (b), and (c) represent syn-subsidence measurements; (d) represents postsubsidence measurements. "F" denotes surface fracture trends.

the 15-foot array were generally higher when the array was north to south (33 ohm-m), the predicted orientation of fractures at the centerline. Increased resistivity, also observed along N60W and N40E trends with the 15-foot array, possibly reflected arcuate (fig. 1) or conjugate fractures. During subsidence, a fissure with a N30E trend opened, then closed beneath array B. (Its trend is marked by an "F" on figure 6.) Minimum resistivity values were recorded at this azimuth by the 5-foot array, but not by the 15-foot array. Azimuthal surveys made in May 1991 produced a roughly isotropic resistivity plot at a 5-foot spacing (fig. 6d), suggesting that most shallow fractures had closed or been filled within 8 months after subsidence.

Syn- and postsubsidence azimuthal resistivity variations were also monitored at an array over the north barrier pillar of panel 2. A complex pattern of apparent resistivity increases trending northeast and northwest were recorded at a 5-foot electrode spacing. Little resistivity variation was recorded at a 15-foot spacing, however, aside from a slight overall resistivity increase during the postsubsidence period.

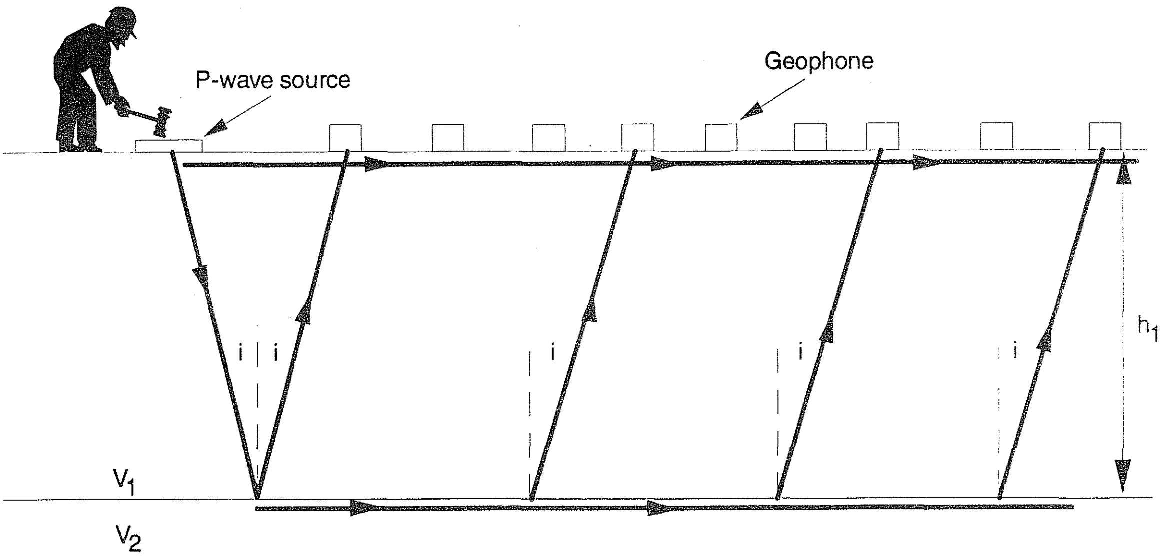

Figure 7 Schematic representation of the seismic refraction method.

Seismic Refraction Method Seismic refraction surveys (fig. 7) over panels 1 and 2 in Saline County were made to map fractures (areas with reduced P-wave velocity) and monitor water table changes during subsidence. An overview of the seismic refraction method may be found in Dobrin (1976). The energy source for the refraction surveys was an 8-pound sledgehammer striking a metal plate. Twelve geophones were placed along the survey lines with spacings of 5, 10, or 20 feet. For the 10-foot spacing, which was used most often, the source was offset 10 feet from the nearest geophone. Lines were reversed to identify dipping layers. Geophone outputs were recorded by a seismograph, and the data were later transferred to a personal computer and analyzed using the program SEISVIEW (EG&G 1987). This routine uses the intercept-time method to compute dipping multilayer models from first arrival times.

A total of 50 seismic refraction lines (including repeated lines) were completed throughout the panel 2 subsidence event. Most lines were concentrated along the centerline and over the northern tension zone of panel 2, where fracturing and water table changes were expected to occur. Most refraction data were modeled with three layers. Borings and water levels from shallow drift piezometers (R.G. Darmody, personal communication, 1992) were used to interpret the refraction models. The top layer in the models is usually 3 to 4 feet thick and represents loess and topsoil. The second layer consists of a more consolidated clay and extends to the water table at a depth of 13 to 20 feet. Layer 3 represents saturated clayey and sandy drift. Some of the saturated, low-rigidity, clay-rich materials exhibited velocities less than that of sound in water.

Uncertainty in estimating velocities can arise from errors in reading arrival times and from the use of a layered model, which is an oversimplification of actual field conditions. In this study, uncertainties were quantified by comparing multiple interpretations of the same line and by examining velocity variations between adjacent lines. No major hidden low velocity layers were encountered when refraction models were compared with borings and inverted resistivity soundings.

Effects of Subsidence on P-Wave Velocity and Water Level ▪ *Panel 2 centerline* Two-layer models of combined pre-, syn-, and postsubsidence refraction surveys were used where three layers could not be resolved on graphs of refraction time versus distance. No significant changes in velocity were recorded during the subsidence event over panel 2, either above or below the water table. An 8-foot drop in the water table was recorded next to the monument line. This could not be confirmed, however, by other syn-subsidence refraction profiles along the monument line. Otherwise, water levels remained remarkably uniform throughout subsidence, although some local changes in the water table appeared after subsidence.

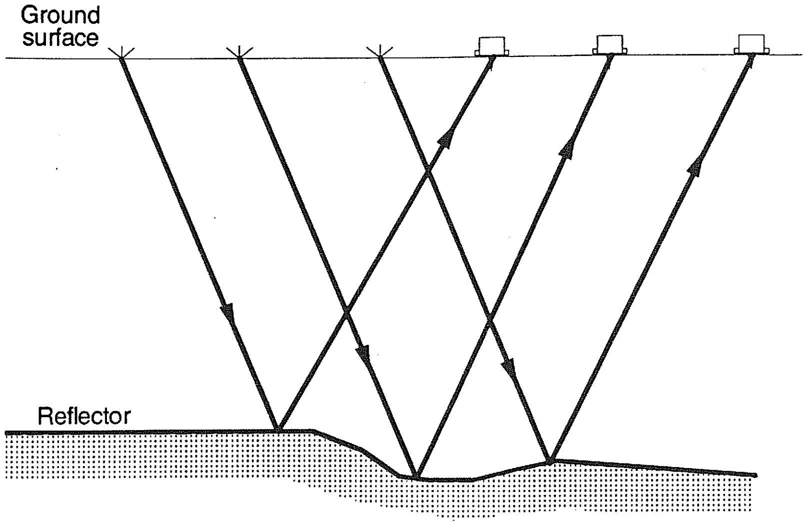

Figure 8 Schematic representation of the common-offset seismic reflection method.

■ *Tension zone* The pre- and postsubsidence velocity models computed from refraction lines made across the north tension zone of panel 2 were essentially identical, except for a slightly thicker, low-velocity upper layer in the postsubsidence model. The substantial lateral velocity variations exhibited by the top layer during subsidence made interpretation of underlying thicknesses and velocities difficult. The lowermost saturated drift exhibited a slightly (although not significantly) lower syn-subsidence velocity. The syn-subsidence water table was not significantly different from the presubsidence water table; however, the water table dropped several feet during the postsubsidence period.

Seismic Reflection Surveys The common offset (CO), or optimum offset, seismic reflection method (Pullan and Hunter 1985) was used to investigate the extent of fracturing at, and immediately below, the bedrock surface at the Saline County site. The CO method consists of a source (a sledgehammer striking a metal plate several times) and a geophone, both moved along the profile line at a fixed separation or offset (fig. 8). Reflections recorded by the geophone are combined from several hammer blows and plotted on a time section at the midpoint between the source and geophone.

One CO seismic reflection line was made across the south edge of panel 1 before panel 2 was mined. Reflection points were separated by 10 feet and the shot-receiver offset was 180 feet. This offset allowed the bedrock surface and shallow bedrock reflectors to be imaged, while amplitudes of earlier refracted, direct and surface waves were kept to a minimum. The CO reflection survey was made approximately 8 months after subsidence of panel 1 and shortly before subsidence of panel 2.

A strong reflection that represented the bedrock surface was recorded at a 2-way travel time of 70 to 80 ms. A strong pair of reflections with travel times of 100 to 130 ms lost their coherency across the margin of subsided panel 1. Geophysical logs over the center of panel 1 suggested that the uppermost (100 ms) of these deeper reflections represented a thin (1–2 ft) limestone at a depth of about 125 feet. Fracturing of this limestone may have disrupted these reflections. Because reflections from the bedrock surface above the limestone were not strongly disrupted, the limestone, which is more competent than the surrounding shales, may have fractured more extensively than the shales in response to subsidence. Fracturing of limestone or competent units embedded in shale has been observed in subsidence over other abandoned mines (Bauer 1984). Packer tests conducted on this limestone interval at the center of panel 1 showed an increase in hydraulic conductivity from less than 10^{-8} cm/s before subsidence to approximately 10^{-7} cm/s after subsidence (Booth and Spande 1991).

JEFFERSON COUNTY SITE

Data Collection and Results

Geophysical Surveys Geophysical surveys were also performed over two previously subsided longwall panels in Jefferson County, Illinois, to test the results of geophysical surveys made at the Saline County site, and to identify major changes that might occur within 2 years of subsidence at the Jefferson County site. Four longwall panels had removed about 9 feet of the Herrin Coal from the Carbondale Formation, approximately 725 feet beneath the surface. A detailed analysis of the hydrogeological impact of subsidence of panels 3 and 4 may be found in Spande (1990) and in Booth and Spande (1992). Five resistivity soundings and three seismic refraction surveys were made over panels 3 and 4 at least 2 years after subsidence.

Resistivity Soundings The primary objective of the resistivity soundings between the edge and center of panel 3 was to identify resistivity changes that might reflect earth resistivity changes associated with drift and bedrock fracturing. Additional soundings were made over panel 4 and in a then-unmined area to the north to establish the degree of natural resistivity variation. All soundings were inverted for layered resistivity models (fig. 9). Interpretation of resistivity soundings was based on data from nearby boring and piezometer logs.

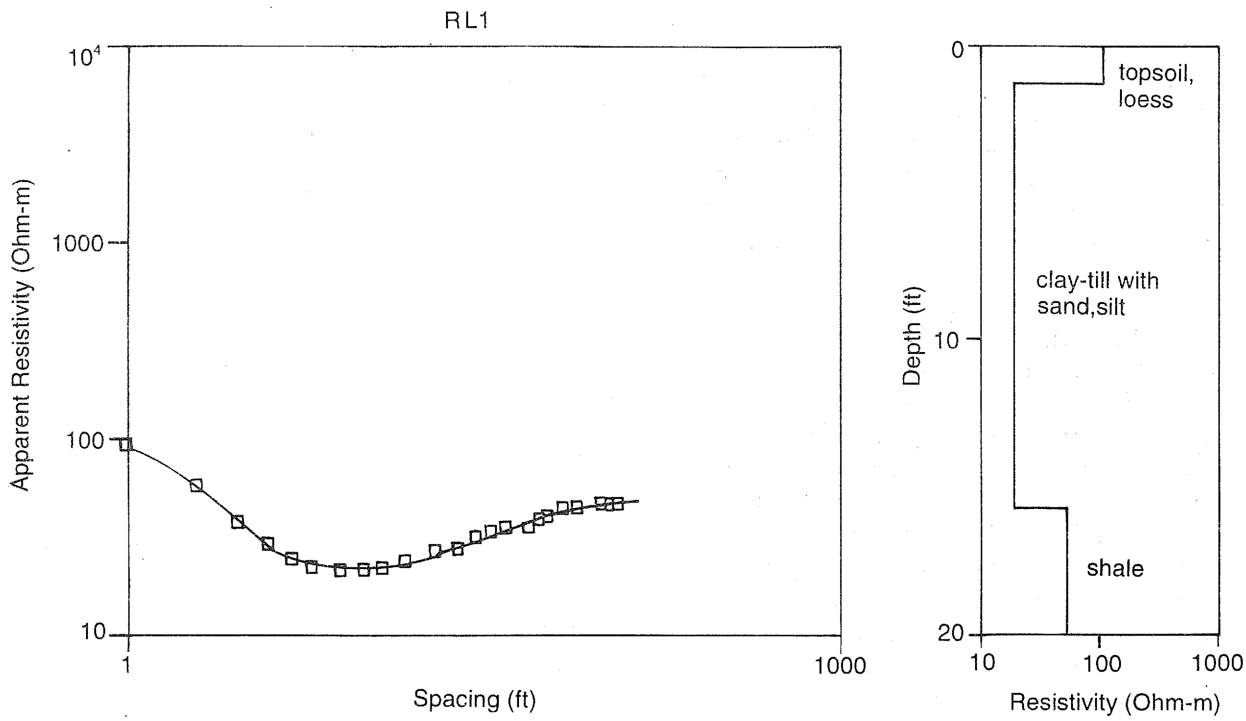

Figure 9 Typical vertical electrical sounding from the Jefferson County site; layered model interpretation is based on well logs and borings.

- *Effect of fracturing on resistivity* East-to-west-oriented soundings made over the center and north static tension zone of panel 3 showed a thicker low resistivity zone over the tension zone at a depth of 14 to 20 feet. Seismic surveys indicated that the decrease in resistivity occurs in the lowermost till. Equivalence analysis suggested that this low resistivity zone is real, although it is not known whether it represents some long-term fracture effect (such as water moving along tension zone fractures) or a preexisting lithologic variation.

Seismic Refraction Surveys Three seismic refraction surveys were made to test the hypothesis that velocity reductions (as seen in the syn-subsidence profile over panel 2 in Saline

County) persist over the static tension zones. One line was located along the centerline of panel 3, and two lines were located over the static tension zones of panels 4 and 3, respectively. An 8-pound sledgehammer was used as the seismic source with 12 vertical-component 8-¾ Hz geophones and an EG&G ES-1225 recorder. Source offset from the nearest geophone and geophone spacing was 10 feet on all lines.

A two-layer model provided the best fit to travel times measured along the centerline of panel 3; three-layer models were used to interpret refraction data from the tension zone lines. The uppermost layer in all models corresponded to unsaturated topsoil, loess, and clayey drift. The velocity of this layer at the center of panel 3 was significantly lower than it was along the north margin of panel 3, and may reflect lithologic variations in the upper layer because it was the opposite of what would be expected from tension zone fracturing. The velocity of saturated drift below 6 to 7 feet did not vary significantly between the panel center and margin. Shale bedrock was indicated along the tension zone lines at 15 feet deep over panel 4 and 24 feet deep over panel 3. No bedrock refracted waves were observed over the panel 3 centerline.

DISCUSSION OF RESULTS

Electrical resistivity soundings, profiles, azimuthal surveys, and seismic refraction and reflection surveys were evaluated as tools for characterizing fracturing and water table changes in both bedrock and glacial drift above longwall coal mines in Saline and Jefferson Counties, Illinois. The results may be summarized as follows:

- Resistivity soundings suggested that fractures in the dynamic tension zone along the centerline of panel 2 in Saline County extended to a depth of at least 5 feet. The resistivity sounding method could not resolve fractures deeper than this nor could it provide constraints on the lateral extent of drift fracturing. Resistivity soundings could not delineate bedrock fracturing.
- Areas of reduced apparent resistivity along the margins of panel 2 in Saline County were identified on resistivity pseudosections; however, these resistivity reductions could not be confirmed through soundings. An area of reduced resistivity was also identified between a depth of 14 and 20 feet along the north tension zone of panel 3 in Jefferson County. These resistivity reductions, if real, may indicate water moving along tension zone fractures penetrating much of the drift.
- Azimuthal resistivity variations were consistent with predicted fracture directions in the drift along the centerline and the dynamic compression zone of panel 2 in Saline County. Repeated azimuthal surveys suggested that shallow fractures closed within 8 months of subsidence. Superficial fissures, small-scale heterogeneity, and seasonal resistivity changes added complexity that impeded interpretation of azimuthal resistivity plots.
- Pre-, syn- and postsubsidence seismic refraction surveys along the centerline of panel 2 in Saline County revealed no major changes in P-wave velocity or widespread changes in the configuration of the water table. Syn-subsidence fracturing, however, introduced severe lateral velocity heterogeneity that hampered interpretation. Syn-subsidence P-wave velocity reductions were observed along the northern tension zone of panel 2, possibly in response to fracturing above a depth of 16 feet. In Jefferson County, seismic refraction surveys between panel centerlines and margins showed no velocity differences that could be attributed to fracturing.
- Areas of probable bedrock fracturing over the southern margin of panel 1 in Saline County were identified using common offset reflection surveys 8 months after subsidence. Packer tests confirmed increased permeability in a thin limestone layer exhibiting disrupted reflections at a depth of 125 feet over the panel margin. Seismic reflection surveys identified no fractures in the subcropping bedrock surface.
- The most useful information provided by the geophysical surveys was the minimum estimates of fracture depth from the repeated resistivity soundings and the identification of a fractured bedrock unit through the common offset seismic reflection surveys. Depth and

lateral resolution were generally poorer with the resistivity methods than with the seismic methods; however, the resistivity methods were less affected by lateral heterogeneity introduced by fractures. Resistivity profiles (pseudosections) and azimuthal resistivity surveys both showed interesting changes with subsidence, but they were labor intensive to perform in the field and difficult to interpret quantitatively.

Subsidence-induced changes in the bedrock were monitored through a single common offset reflection survey made after the subsidence of Saline panel 1. Results of this survey are encouraging, and this technique may be more widely applied in ongoing investigations of panels 4 and 5 in Saline County. Refraction surveys could also be used to obtain information from the bedrock surface; they were not used in this investigation because of the long line lengths required.

Ongoing hydrological investigations are funded under an Office of Surface Mining contract and are being performed by researchers at Northern Illinois University and the Illinois State Geological Survey.

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