CHARACTERISTICS OF SUBSIDENCE FROM ABANDONED AND ACTIVE UNDERGROUND COAL MINES IN THE ILLINOIS COAL BASIN

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Abstract

In both active and abandoned coal mining in the Illinois Coal Basin, there have been and still are two fundamental mining types: ones that leave coal pillars behind to support the overburden and ones that remove the coal and support of the overburden at the time of mining. The later method has coal mine subsidence occurring at the time of mining and is considered planned coal mine subsidence.

Coal mining in the Illinois Basin has used four mining methods that left pillars behind to support the ground surface. The mining patterns have evolved from random directions and high percentage of extraction of coal (small amount of coal left to support the ground surface) to very systematic and a lower percentage of extraction to greatly insure supporting the ground surface. The higher the percent of coal removed, the greater the potential for subsidence, but review of case histories of subsidence associated with these mining methods shows no clear correlation with time. Individual subsidence events are not predictable, since there are too many variables of changes in thickness of weak floor materials, wet or dry mine conditions, exact size of pillars, amount of damage to pillars from blasting, etc. Therefore, it is felt that if an area is undermined by an old abandoned mine, there is always a possibility of subsidence.

The other coal mining type either extracted pillars or all of the coal and lowered the ground surface at the time of mining. Each of these three methods had predictable subsidence patterns on the ground surface. Subsidence characteristics for all the mining methods are reviewed along with the results of studies investigating subsidence impacts on groundwater.

Introduction

Underground mines were developed in the Midwest soon after the first settlers arrived. They mined coal, lead, zinc, fluorite, claystone, and limestone. During the early years, land over mining areas was sparsely populated. If the ground settled, little damage to structures occurred but at times settlement caused disruption of drainage on farmland. Many of the drainage problems were resolved through legal settlements and court cases. As towns and cities expanded over mined-out areas, subsidence impacted more structures and became a recognized problem.

Types of Subsidence

Researchers have learned much about the nature and causes of subsidence by studying the effects at the ground surface, drilling holes down to mines, lowering small television cameras down the holes to view mine conditions, and personally inspecting mines that are still accessible. In the Illinois Basin, subsidence of the land surface may take either of two typical forms: pit or sag (trough).

Pit Subsidence

Pits are usually 6 to 8 feet deep and range from 2 to 40 feet in diameter (Fig. 1), although most are less than 16 feet across. Newly formed pits have steep sides with straight or bell-shaped walls.

Pit subsidence usually occurs over mines less than 200 to 300 feet deep. The mine roof collapses and the void works up through the overlying bedrock and surficial layers of glacial deposits and loess to the surface, where a hole forms over one or two days. If the bedrock is only a few feet thick and the surficial deposits are loose, these materials may subside and wash into adjacent mine voids so that they produce a surface hole deeper than the height of the collapsed mine void.

When pits develop, the ground only moves in one direction-it drops vertically. Pits are most likely to form at the

surface after heavy rainfalls or snowmelts. Water does not usually accumulate in the pits but drains down into the mine. A common treatment is to fill the pit with sand or clay, cap the fill with a clayey soil, and compact the clay tightly so that its permeability is very low. Many pits have been permanently filled this way.

Structures can be damaged if pit subsidence develops under the comer of a building, the support posts of a foundation, or other critical spots. Otherwise, the probability of a structure being damaged by pit subsidence is low because most pits are relatively small, that is,only a few feet across. ff pit subsidence develops under foundation walls, it may not immediatelyaffect the house because the foundation temporarily bridges the pit. Eventually, the "bridge" may become damaged.

Subsidence pits that are not filled pose a special danger for both people and animals. They are often deep and steep-sided. Anyone who falls in may find it very difficult tcget out. Also farm equipment may partially fall into a pit if the equipment runs over it as it is in the final stages of reaching the ground surface.

Sag or Trough Subsidence

Sag subsidence forms a gentle depression over a broad area. Some sags may be as large as a whole mine panel--hundred feet long and a few hundred feet wide (fig. 2). Several acres of land may be affected. The maximum vertical settlement is usually 2 to 4 feet, as shown along the profile below the mine plan in Figure 2.

A major sag may develop suddenly (in a few hours or days) or gradually (over years). The profile in Figure 2 shows settlement that took place over 45 weeks.

Sags may originate over places in mines where the coal pillars have disintegrated and collapsed, or where the pillars have settled into the relatively soft underclay that forms the floor of most mines. Sags can develop over mines of any depth.

Tension cracks form as the ground is pulled apart by downward bending of the land near the outside edges of the sag. Generally the cracks parallel the boundaries of the depression and are a near surface feature going down 10 to 15 feet and decreasing in width with depth. Near the center of the sag, compression ridges form as the ground is squeezed by upward bending of the land. Ridges are observed less frequently than tension fractures because the area of compression is much smaller.

The ground moves in two directions during sag subsidence (Fig. 3). It drops vertically and moves horizontally toward the center of the sag. At the surface, the sag may be much broader than the collapsed part of the mine. For example, a failure in a mine 160 feet deep could cause minor surface subsidence more than 75 feet beyond the edge of the undermined area. The deeper the mine, the larger the area affected.

Sag subsidence has an orderly pattern showing tensile features surrounding possible compression features. Mapping of all the tensile features shows orderly movements toward the center of the sag.

Type and extent of damage to surface structures relate to their orientation and position within a sag. In the tension zone, any large cracks that develop in the ground may damage buildings and roads as well as driveways, sidewalks, pipes, sewers, and utilities. Houses in the tension zone may need to be supported until subsidence has ceased. Then repairs may be made.

In the comparatively smaller compression zone roads may buckle and foundation walls be pressed inward. The foundations of any houses in the center of the sag would be under horizontal compression. Although the area affected by compression is substantially smaller than the tension zone, buildings damaged by compression may need their foundations rebuilt. They may also need to be releveled.

Room-and-Pillar Mining-Unplanned Subsidence

The early coal mining efforts left enough coal m pillars to support the underground working area and therefore, the ground surface. The mining methods changed through time from unsystematic to systematic mine designs. These methods, frequently used before the early 1900s, were characterized by rooms that varied considerably in length, width, and sometimes direction (Fig. 4), forming irregular mining patterns. After about 1910, mining was conducted in a room-and-pillarpattern. In the production areas or panels, workers created rooms and crosscuts at right angles to form a grid pattern. These production areas (panels) were separated from main entries providing more support to the main en for their long-term use and improved Ventilation. This was the modified room-and-pillar or panel system (Fig 5). This system provided more regular configuration of production areas (panels) which had well-defined boundaries as a result of the broad barrier pillars or unmined areas left between panels. Two fairly modem room-and-pillar methods are the blind room and the checkerboard (figs. 6 & 7). Using the first method, miners bypass every sixth or seventh room of a production area. The unmined area (blind room) functions as a large pillar to support the roof and provide barriers to reduce the spread of any floor squeezes and fires. This method is still used today. The checkerboard system has evenly spaced square pillars in a checkerboard pattern of panels thousands of feet long and wide. In comparison to earlier mining, modem room-and-pillar mines have many main and secondary entries to provide for required ventilation.

No one can predict when or if the land above a room-and-pillar mine will sink. If any coal has been removed from an area, subsidence of the overlying geologic materials is always a possibility.

High Extraction-Planned Subsidence

High-extraction coal mining methods mine almost all the coal in a I area. They always result in the surface subsiding above a mine within several days or weeks after the coal has been removed. The sinking or subsiding of geologic materials lying over the mined-out area will continue for years, although movements will diminish rapidly after a few months. Once subsidence has decreased to levels that no longer cause damage to structures, the land can usually be developed or damaged structures can be repaired. In early longwall mines (Fig. 8), workers maintained the haulageways (entrances) by leaving areas of stacked rock, wooden props, and rock-filled wooden cribs to replace the support lost by the removal of coal. The mine roof, then the overlying bedrock and earth, settled onto the stacks of rock. When this occurred, a few feet of subsidence resulted at the ground surface.

Modem high-extraction systems are designed to achieve a high rate of production (figs. 9 & 10). Using the high-extraction retreat method, miners remove as much coal as possible in a small area until the roof starts to collapse; then they retreat to the next area. Using this method 80% to 90% of coal in the panel is removed. The size and number of pillars that must be left to maintain worker safety varies with underground geologic conditions (Hunt, 1980). The roof collapses in a manner that is controlled by temporary supports, and planned subsidence is initiated immediately. Using the modem longwall method, workers mine 100% of the coal along a straight working face beneath Artificial roof supports. The mine roof collapses immediately behind the working face, causing 4 to 6 feet of subsidence. This amounts to 60% to 70% of the mined height of the coal seam plus any roof or floor materials that have been removed.

Modern Longwall Mining

In the United States, mining companies began using the mechanized longwall method in the 1960s, although it was developed and used much earlier in England and Europe. Like high-extraction retreat, longwall mining begins at the outer edges and works toward entries that are used to haul the coal, mine personnel, and machinery. In the longwall system, all the coal is removed from a panel, but a few rows of pillars (called chain pillars) are left between panels. In Illinois, longwall panels may be 600 to 900 feet wide, up to several miles long, and 350 to 800 feet below the ground surface.

The effects of subsidence from longwall mining are uniform and anticipated. The surface over the center of the panel drops approximately 4 to 6 feet. The decline tapers off toward the edges of the panel and forms a gentle trough.

Subsidence of about 1 to 1.5 feet occurs over the entryways and chain pillars between mined out panels. The areas of surface subsidence go beyond the edges of the panel to a point of zero subsidence which is found at a distance of about 0.35 to 0.45 times the depth to the mine.

At one site, researchers in Illinois showed that subsidence movements continued for years after an area had been undermined by longwalls; this is called residual subsidence (Mehnert et al. 1992). These movements were measured six months to dm years after mining and amounted to 5% (about 0.3 ft) of mined-out height. Residual subsidence seemed to be fairly uniform over the panel and the pillars between panels. Residual subsidence caused no differential subsidence and no over the sides of the panel, two effects that would damage structures. This occurrence is similar throughout many areas of the world where residual subsidence may last six months to seven years, depending on the strength of the strata above the coal seam (Whittaker and Reddish 1989, Orchard and Allen 1975, and Fejes 1985).

Longwall Subsidence and Groundwater

A program in Illinois monitored the hydrology in the bedrock and near surface glacial materials and the amount and location of fracturing in the bedrock over several active mining areas. A high-extraction retreat panel and several longwall panels were studied. Water levels in deep and shallow test wells was monitored before, during, and after subsidence. Water levels were checked continuously by electronic recorders. Water chemistry and quality were evaluated. Results from several deep longwall panels show that rural wells in glacial materials (sand, clay, and silt) were unaffected by subsidence. Water levels in test wells in bedrock, where the water producing zone was very continuous across the area, were temporarily lower and recovered several months after mining (Booth 1992). In water bearing zones that were not continuous (limited in areal extent), water levels were lowered since fracturing of the zone produced a larger amount of void space for the quantity of water in the zone. Also there is speculation that the water yield of bedrock aquifers may be enhanced by longwall subsidence; however, this enhancement also depends on site-specific geologic factors that control the occurrence of groundwater. At the study sites, subsidence-induced fracturing improved the way water flowed through bedrock. The storage capacity of the bedrock aquifer was also enhanced.

Conclusion

The various forms of coal mine subsidence in the Illinois Basin have been cited in reports and publications for about one hundred years. During the past 20 years, systematic studies of the characteristics of each of the different gills of subsidence has led to an Understanding of their movements and impacts on groundwater.

Acknowledgments

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SUBSIDENCE: A REGULATORY PERSPECTIVE

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Abstract

Underground coal mining in Illinois has shown an increasing percentage of total coal mined relative to surface mining. In the past 20 years, the percentage of underground to surface mine production has steadily increased. Underground mining is expected to continue to dominate coal production into the 21st century. Once the dust has settled from the clean air act, the drive for higher production and lower operating costs should increase the number of longwall and high extraction retreat mines. This will involve either conversion of existing room and pillar mines or the initiation of new underground mining operations,

As the industry continues to evolve, so do the environmental regulations that govern the mitigation of impacts. Federal regulations promulgated in 1992 under the Energy Policy Act (EPACT) mandated additional restrictions and regulatory requirements beyond those adopted in 1977 under the Surface Mining Control and Reclamation Act (SMCRA).

The regulation of subsidence mitigation in Illinois has developed through the years. Initial growing pains were experienced by both the coal operators and the Illinois state regulatory authority (RA) with lessons learned through experience. Today, subsidence permitting and mitigation are more standardized with clearer communications between the operators and the RA to achieve the goal of maintaining surface capabilities and making surface owners whole while m g the utilization of our coal resources. This paper describes the existing Illinois regulations, their impact on the coal industry and on the landowners above underground mining and how they have been implemented, and outlines currently proposed changes.

Introduction

Illinois underground production has captured an increasing percentage of total coal mined. In the past 20 years, the percentage of underground to surface mine production has increased from approximately 53% to 85% (Fig. 1). The production from longwall mining has also grown since its introduction in Illinois in the early seventies (Fig. 2). It is anticipated that underground mining will continue to dominate Illinois coal production into the 2lst century. The industry will continue to strive for higher production and lower operating costs and, therefore, the number of longwall and high extraction retreat mines should increase through conversion of existing room and pillar mines or initiation of new underground mining operations. The growth of underground mining in Illinois has been accompanied by the evolution of regulations governing underground mining effects over the past two decades.

On August 3, 1977, the Surface Mining Control and Reclamation Act (SMCRA) became law. The Act created the U.S. Department of Interior's Office of Surface Mining Reclamation and Enforcement (OSM). As suggested by both the name of the act and the regulatory body created to administer the act impacts of underground mining were not the primary focus or centerpiece of the legislation. In the infancy of SMCRA and at the beginning of state primacy, OSM left the choice of enforcement of subsidence repair and compensation of land and structures affected by mine subsidence to state law.

At one point m time, the surface property owner also controlled the mineral, oil, gas, and coal rights for a given land track. As far back as the early 1900s, companies began securing control of large blocks of coal reserves from surface owners not only for existing operations but also for speculation on future extraction. The contract severing the surface property from the mineral rights often incorporated language granting the entity obtaining the mineral property the right to extract all of the resource without liability for surface damage. This right is often referred to as the "right to subside." As the surface property changed hands through time, the knowledge of who controls the subsurface rights or even whether the property is already undermined could get lost.

The first specific protection afforded landowners occurred when the Illinois General Assembly created the Illinois Mine Subsidence Insurance Fund in 1979. The insurance fund was created to address the problems of old abandoned mines

causing damage, but only provided insurance protection to homes and structures. Subsidence damage to surface lands such as farmland was not covered. From its inception, the Illinois regulatory program created as a result of SMCRA recognized the importance of Illinois farmland and the need to protect property owners from loss due to mine subsidence. Specific subsidence permitting and performance regulatory requirements were enacted at the state level to achieve the goal of balancing the lights of surface owners impacted by subsidence and the legal rights of the coal operators to extract their resource.

SMCRA and the Illinois Regulations of 1983

Although some form of Illinois mining reclamation law governing surface coal extraction had been in place prior to SMCRA dating back to 1962, no requirements for correction of subsidence impacts existed. Based on the expected trends of underground mining and planned subsidence operations, the Illinois state regulatory authority (RA) believed it necessary to protect both land and surface structures and therefore crafted the state regulatory program rules accordingly. The state of Illinois' Permanent Program Rules and Regulations were enforceable on February 3, 1983 and thus established coal operators' legal liability for subsidence. Underground coal extraction performed by any method after this date would be subject to subsidence control. To assist in determining jurisdiction to enforce the newly created requirements, operators were required to provide maps that define the specific location of underground operations on and after February 3, 1983.

Several legal challenges were launched by the industry contesting the mandate to mitigate, repair, or compensate for damages caused by subsidence. Certain companies contended that the transaction severing the surface and mineral rights also granted the right to extract all of the resource without liability for surface damage. The challenge contended that the right to subside without liability was acquired as part of a legal transaction. Therefore, the coal companies reasoned that it should be construed as taking of property rights if mine operators were mandated to provide compensation or execute repairs.

Illinois' ability to enforce subsidence repair and compensation was continually upheld by the courts. Coal operators must repair subsidence damage to land and structures regardless of any waiver. Mining maintains stringent subsidence requirements based on the potential for subsidence affecting not only structures but also land capabilities. Structures damaged by subsidence must be repaired, replaced, or compensated for, while surface lands must be mitigated to maintain the value and capability that existed prior to subsidence.

Subsidence Control Plans

Any underground mine active on or after February 1, 1983 must receive a permit to mine regardless of the method of extraction. Areas undermined after February 1, 1983 and projected areas to be undermined in the future are termed the "shadow area." The regulatory framework is divided into *permitting* requirements and *performance* requirements. Permitting requirements set the threshold of information required in an application to receive an permit. Performance requirements measure the effectiveness of the operation to achieve the regulatory goals. A key permitting element of an underground mining application is the mine subsidence control plan. The subsidence control plan must demonstrate that either maximum mine stability is being provided to prevent subsidence, termed "unplanned subsidence," or that mining will be carried out to produce "planned subsidence." Planned subsidence involves nearly total seam extraction and results in immediate surface subsidence in a predictable and controlled manner. Longwall mining and high extraction retreat room and pillar mining are examples of planned subsidence operations.

As part of the subsidence control plan, operators must provide information on the technique of coal removal, percentage of coal to be extracted, pillar sizes, extraction dimensions, and nature of the geologic strata above and below the mine. The subsidence control plan must include a survey of all structures and surface features. This is largely a general description of the land and surface features above the shadow area.

If planned subsidence is proposed, operators are required to define the extent and location of subsidence, damage expected to occur, and measures to be taken to mitigate any material damage to land and structures. Site specific monitoring of subsidence movements to verify the accuracy of subsidence predictions is required initially for a given area. Pre-subsidence surveys of all structures potentially impacted is also required. The surveys help document the pre-subsidence condition of the structures to distinguish damages attributable to subsidence clearly from preexisting conditions.

Subsidence Mitigation

The measure of the effectiveness of subsidence mitigation is found within the performance requirements of the regulations. Crops and coal are two very important components of the Illinois economy. Over the past 15 years, the effects of subsidence on cropland have been closely monitored for mitigation. Unlike the permit area, which is the bonded surface facilities of a mine, the shadow area is not bonded. Instead, the Department relies on the ability to impose violations when mitigation is not being accomplished. A pattern of violations could easily develop if a company became lax in their mitigation efforts. If a pattern of violations develops, a cessation order can be imposed with a show cause order for the operator to defend why the state should not revoke the permit. As a result the lack of a structured bonding mechanism has not hindered achieving land mitigation.

Subsidence from longwall or high extraction retreat mining creates a "sag" type subsidence on the surface. A low lying, bathtub shaped depression results that can be 1,200 feet m width and a mile or two long. The width and length of the surface area affected is controlled by the depth of overburden and longwall equipment specifications. This bathtub effect is experienced side by side as a series of longwall panels are mined over several years creating a washer board effect. The surface subsidence can create closed depressions and pond water. To successfully drain closed depressions, the surface can be or surface waterways can be installed to carry away water collected in the depressions. Cut and fill operations are also performed to help restore surface drainage. When suitable soils are present subsurface drainage tiles can be placed to aid drainage. Often, a combination of the above may be incorporated over several mine panels to successfully mitigate a watershed affected by subsidence.

A second impact that occurs to surface lands is a series of tension ground cracks. The ground movements that take place can create uniform and parallel cracking asthe wall progresses. The cracking varies in width from an inch or less under most circumstances but can occasionally reach as much as a foot m width. Transverse cracks occur in a radial pattern in advance of the mining direction. The transverse cracks tend to close as the dynamic subsidence wave passes. Longitudinal cracks occur at the panel's edge in thetensional zone. The longitudinal cracks along the edge can remain open and require some form ofmitigation (Van Roosendaal et al. 1992) (Fig. 3). In farm fields, narrow cracking is easily eliminated by plowing. Wider tension cracks can necessitate filling with appropriate soil, sand, or lime, then mulched to control erosion Sand and lime are used because they are inexpensive flowable fills that can efficientlyseal ground cracks. It can also be beneficial to excavate larger cracks down to a depth where the separation has tightened before beginning to backfill and compact to ground level. Top soil should be removed and replaced upon completion of repairs.

The timing of mitigation repairs can often be complicated by several extenuating factors. Repairs to structures and land are not required until the subsidence movements have stabilized. Mitigation carried out before the am is stable would only have to be repeated later. Structures are more sensitive than farmland to the residual movements that can occur six months to a year or more after mutation of subsidence. Residual subsidence under farmland is only an issue in areas with very little relief. Adverse ground conditions due to precipitation can prevent drainage repairs and push the necessary construction work into the next growing season. Most farmers prefer that such work take place m the fall when the fields are dry and thecrops have been harvested. Another delaying factor in farmland mitigation can be the need to allow a second or third panel to be mined and subsided to implement proper drainage repair to a larger watershed. Because of these unavoidable delaying factors, the Department has required a mechanism for crop loss compensation in planned subsidence permits. If acreage is inundated because mitigation has yet to be accomplished, the operator must compensate the landowner for the acreage that is unfarmable. This compensation is a temporary measure until mitigation is successfully completed.

Often, to meet the regulatory performance requirements associated with subsidence, operators must work with local road authorities and local drainage districts. It is sometimes necessary to deepen existing main branch drainage ways or road ditches to allow tiling or waterways to outlet properly. Culverts must sometimes be placed under a roadway where they did not exist before the subsidence altered topography. Communication and cooperation with the various local road and drainage jurisdictional bodies is essential to achieving drainage mitigation.

Energy Policy Act of 1992

The passage of the 1992 Energy Policy Act (EPACT) introduced federal legislation on subsidence repair and compensation to land and structures similar to the Illinois regulations. It also requires operators to replace drinking,

domestic, and residential water supplies lost or contaminated by mine subsidence. OSM was required to promulgate rules under SMCRA within one year of the passage of EPACT. Controversy over the content of the regulatory language proposed by OSM delayed final promulgation until the publication of the March 31, 1995 Federal Register.

Most of the performance requirements now in place at the federal level through EPACT are being enforced in Illinois through existing regulations. One specific area of EPACT that was not previously a regulatory performance requirement in Illinois is the mandate to replace water lost or contaminated by subsidence. The requirement to replace water was apparently one of the driving forces behind the incorporation of subsidence language into the EPACT. Water loss due to subsidence tends to be a more prominent issue in the Appalachian coalfields than in the Illinois Coal Basin. Groundwater in much of the area of underground coal mining of the state of Illinois is not of sufficient quantity and/or qual4 to make it potable, and therefore much of the drinking water is derived from natural or man-made surface water bodies. When subsidence does affect groundwater, the geology of Illinois tends to be forgiving and allows most impacts to be short term (Van Roosendaal et al. 1992).

To bring water replacement requirements into the Illinois program, the Department took the initiative to promulgate water replacement language mining EPACT before the March 31, 1995 Federal Register. This regulation, 62 Ill. Adm. Code 1817.12 1 (c)(3), was eventually approved on May 29, 1996.

The March 31, 1995 Federal Register detailed permitting requirements envisioned by OSM to achieve the regulatory goal of subsidence mitigation of water, and es. Requirements such as bonding, timing, and content of pre-subsidence surveys, public participation, and level of detail in the permit application were described and contained in the rules. Currently, the nuts and bolts of carrying out the regulations are still being worked out on the state level. Many states are presently working through their own regulatory procedures to arrive at a counterpart rule.

Conclusion

Illinoishas always regarded subsidence control and mitigation as a top priority. We believe Illinois's approved program under SMCRA has been highly successful in the regulation of mine subsidence. The regulations work to strike a balance between the coal company's legal rights and therights of the surface owners. Illinois will continue to strive to protect the public and the environment while working with the industry to maximize the use of our coal resources.

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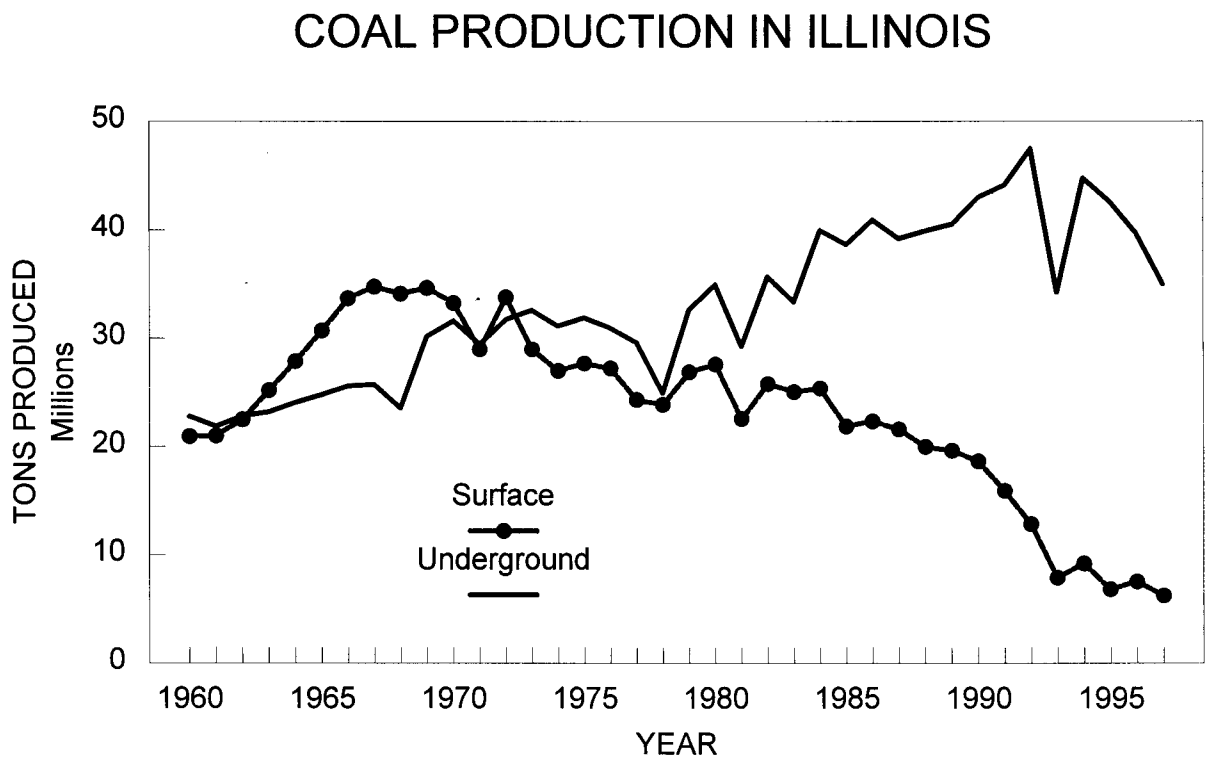
COAL PRODUCTION IN ILLINOIS
TONS PRODUCED
Millions
50
40
30
20
10
0
Surface
Underground
1960
1965
1970
1975
1980
1985
1990
1995
YEAR

Figure 1.

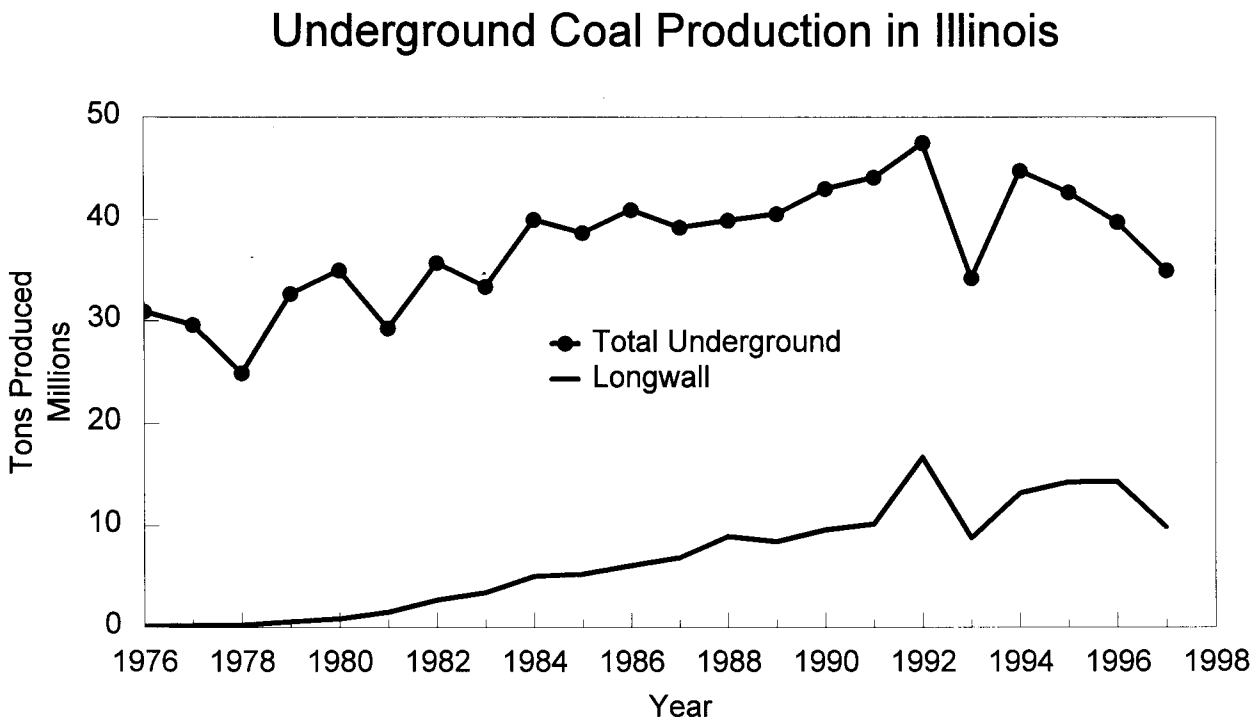
Underground Coal Production in Illinois
Tons Produced
Millions
50
40
30
20
10
0
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
Year
Total Underground
Longwall

Figure 2.

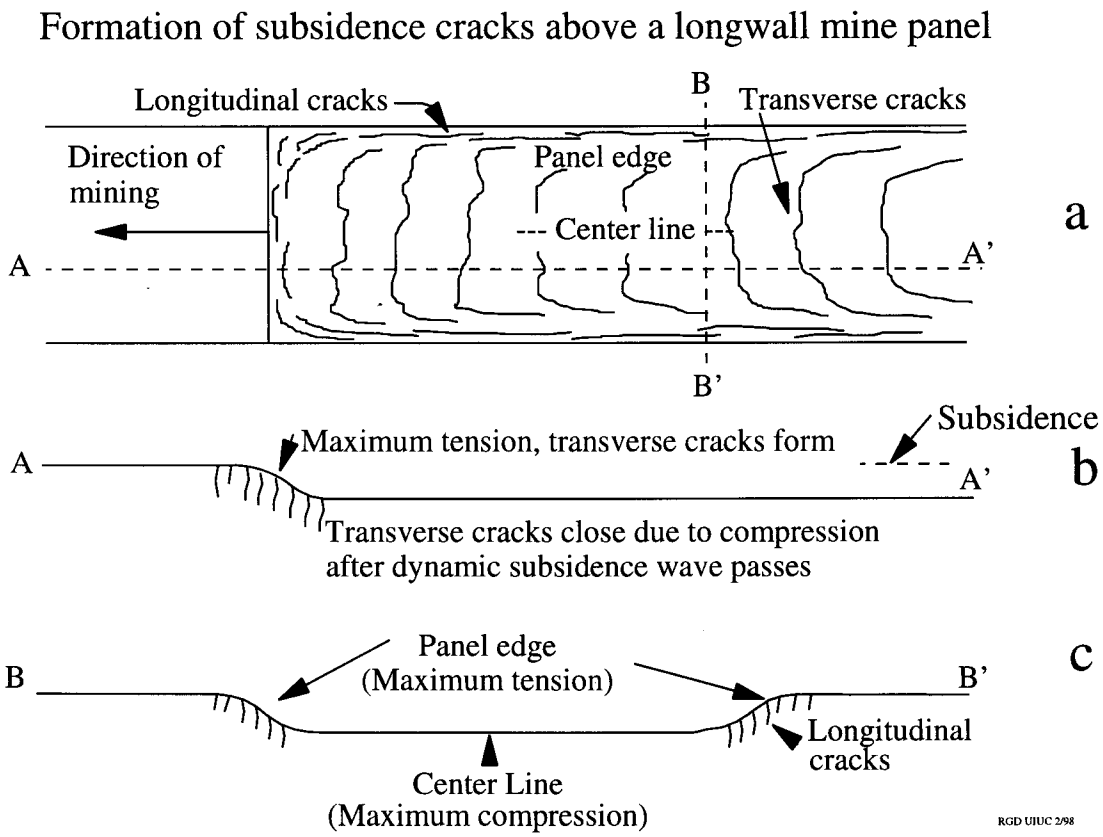
Formation of subsidence cracks above a longwall mine panel
Longitudinal cracks
B
Transverse cracks
Direction of mining
Panel edge
Center line
A
A'
B'
a
Subsidence
Maximum tension, transverse cracks form
A
A'
b
Transverse cracks close due to compression after dynamic subsidence wave passes
Panel edge (Maximum tension)
B
B'
c
Longitudinal cracks
Center Line (Maximum compression)
RGD UIUC 2/98

Figure 3.

IMPACTS OF MINE SUBSIDENCE ON GROUNDWATER

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Abstract

By changing the hydraulic properties of overlying aquifers through fracturing, mine subsidence affects ground-water levels, well yields, and water chemistry,independently of drainage to the mine. In the low-relief Illinois coalfield, the impacts of subsidence above two longwall mines differed according to the aquifer type. The shallow glacial-drift aquifer was not significantly affected, but water levels in bedrock sandstone aquifers fell considerably. At one site, the levels recovered and well yieldimproved because the aquifer was transmissive and well connected to recharge sources; however, the water quality deteriorated. At the other site, the sandstone was thin and poorly permeable; water levels did not recover from the subsidence effects except locally where the sandstone was in contact with an overlying drift aquifer.

Introduction

Underground coal mining affects aquifers in two ways. First, water may drain into the mine workings, depleting groundwater resources and lowering water levels. Second, mine subsidence fractures the overlying strata, changing the permeability and porosity and thus changing groundwater levels, well yields, and, through new flow patterns, groundwater chemistry. Although subsidence can affect aquifers over abandoned room-and-pillar mines, it is more significantover longwall mining, in which large rectangular areas (panels) of coal are completely extracted without the use of permanent roof support. This causes rapid subsidence of the overburden, accompanied by fracturing and bed separation and producing a subsidence trough at the ground surface.

Studies in the Appalachian Coalfield

Numerous case studies of the effects of longwall mining have been made in the Appalachian coalfield (e.g., I-fill and Price, 1983; Schulz, 1988; Dixon and Rauch, 1988; Walker, 1988; Matetic and Trevits, 1992). The region has considerabletopographic relief, abundant minor sandstone aquifers, well-fractured strata, and outcropping bedrock, all of which favor relatively active groundwater flow systems.

Unlikeroom-and-pillar, longwall mining affects most overlying wells (Stoner, 1983 Tieman and Rauch 1987)-, water levels in bedrock aquifers decline considerably during subsidence. This impact is not generally caused by drainage of groundwater into the mine, which normally remains hydraulically separated from shallow aquifers by low-permeability confining units (Singh and Kendorski, 198 1)þut by the sudden increase in fracture porosity within the strata. The water-level response is most severe over the panel and diminishes rapidly off-panel (e.g., Moebs and Barton, 1985). Water levels commonly recover within a period of months to years; Tieman and Rauch (I 987) observed recovery within one to three years in half the wells over their study panel and in all off-panel wells. However, changes in the fracture permeability can also produce permanent changes in groundwater levels, leakage between aquifers, and spring discharges as a result of altered hydraulic gradients.

The well response is strongly influenced by topography. Johnson (1992) found that hilltop wells were more affected and less liable to recover than valley wells, probably because they have smaller recharge areas and are more influencedby loss of water through fractures in underlying low-permeability layers. Similarly conclusions were made by Leavitt and Gibbens (I 992) from data on 174 wells (I 20 over panels and 62 deepened or replaced after mining).

Illinois

The Illinois Basin coalfield has low relief a cover of glacial sediments on top of the bedrock and a shale-dominated bedrock sequence of low overall permeability. These features produce a sluggish groundwater flow system and generally poor groundwater resources. Room-and-pillar mines in Illinois have usually been dry and had little effect on groundwater resources (Cartwright and Hunt 1981). The hydrologic effects of subsidence above abandoned room-and-pillar mines are not well documented, but seem to be minor, localized and permanent. For example, Booth and

Saric (1987) observed local water-level anomalies above two long-abandoned mines in southeastern Illinois.

In the first hydrogeological study over a longwall mine in Illinois, Pauvlik and Esling (1987) observed temporary water-level fluctuations and minor permeability changes in a glacial till aquitard due to subsidence. Over a 250-ft-deep high extraction retreat mine (comparable to longwall), Bauer et al. (1987) observed that water levels declined rapidly in the bedrock and gradually in the glacial drift.

This paper summarizes information from hydrogeological studies above longwall mines at sites in Jefferson and Saline counties in Illinois by the author and colleagues from Northern Illinois University and the Illinois State Geological Survey, presented in various reports including Booth and Spande (1992), Mehnert et al. (1994), Van Roosendaal et al. (1994), and Booth et al. (1997). Both sites have rolling landscapes with less than 50 ft local relief, mines into the Pennsylvanian Herrin Coal; overlying bedrock strata comprising mainly shale and siltstone with minor sandstone, limestone, and coal; and a cover of glacial drift comprising mainly till with minor sand and gravel. However, local geological differences produced markedly different impacts of mine subsidence.

Studies at the Jefferson County Site

Site Description

At the Jefferson County site, the mined Herrin Coal is about 10 ft thick and 725 ft deep. The overlying bedrock strata are mostly poorly permeable, but about 570 ft above the mine is the 80-ft-thick Mt. Carmel Sandstone aquifer. Above this is a shale, up to about 60 ft thick, overlain by 9 to 30 ft of glacial drift (till, minor sand, and gravel) and loess. Residential and farm wells tap the upper shale and the drift. The sandstone is used nearby, but not over the study site, although piezometers and a test well were installed for this study.

Four longwall panels, each about 600 ft wide and a mile long, were mined between 1987 and 1989. Our study (I 988-1995) focused on panel 4, which undermined the instrumentation in February 1989 and produced ground subsidence of 6 ft within six weeks and 0.67 ft more within three years. The strata were heavily fractured, especially by shear in the marginal tensional zone and bedding-plane separations in the central subsidence trough (Mehnert et al., 1994).

Response of the Drift Aquifer

Water sampled from large--(diameter wells in the shallow drift was fresh (total dissolved solids less than 600 mg/1) and mainly sodium-calcium-sulfate type, with relatively high nitrate levels that often exceeded the 10 mg/l US EPA potability limit The chemistry did not change noticeably due to mining; nor, except for temporary adjustments to changing ground levels, did the drift water levels. However, the water table in wells on topographic highs overlying barrier pillars had slight long-term declines, probably because the ground level and water table in the adjacent topographic lows had subsided.

Response of the Upper Shale

Water levels in shale wells over and next to the longwall panels were substantially lowered by mining, and took from several months to three years to recover. Shale wells 600 ft off the panel were unaffected. The shale water was brackish (1000 to 4000 mg/1) and of mixed cation, sulfate type, with some nitrate. Post-mining analyses showed a slight reduction in salinity that may reflect increased recharge from the drift.

Physical Response of the Mt. Carmel Sandstone

The sandstone at the site is 75 ft deep and 80 ft thick, but divided into hydraulically separate upper and lower benches by a shaly siltstone unit up to about 20 ft thick. Pumping tests showed that the upper sandstone receives some leakage from the overlying shale, but the lower bench behaves as a separate confined aquifer.
Sandstone piezometers over panel 4 were monitored from 1988 until damaged by subsidence in Spring 1989. Monitoring continued from 1991 to 1995 in two new piezometers, drilled into the lower sandstone bench in the central area and tension zone of the subsidence trough, and in centerline test well P350, open through the whole aquifer. Pre- and post-mining permeabilities were determined from slug and pump tests, and from packer tests in two centerline boreholes cored through the bedrock before and after mining. The permeabilities (i.e., hydraulic

conductivities) of the sandstone were between $10^{-6}$and 10^{-4}cm/s before subsidence, depending on test method and location, and increased approximately one order of magnitude in the central subsidence trough and two in the tension zone. Storage coefficients increased about one order of magnitude. These changes resulted in a200% increase in specific capacity (indicating yield) of the test well.

The sandstone water levels responded systematically to subsidence (Booth and Spande, 1992; Mehnert et al. 1994; Booth et al., 1997). They declined gradually as the mine face approached, then fell rapidly to a minimum during the tensional early phase of subsidence. After a decline of about 30 ft due to the mining of adjacent panel 3, the water levels over panel 4 recovered briefly, declined as the panel 4 face approached, then dropped rapidly to about 135 ft (70 ft below initial values) during undermining (Fig. 1). The rapid head drop in the subsiding zone is due to the sudden increase in porosity caused by opening of fractures, joints, and bedding planes. The earlier gradual decline is a secondary drawdown effect transmitted through the aquifer from the approaching potentiometic low.

After a rapid partial rise during the compressional phase, the water levels recovered gradually over two years after mining to the initial levels about 65 ft below ground, and by 1995 to about 40 ft (Fig. 2). The long-term recovery reflects inflow of water from surrounding areas of the aquifer into the potentiometric depression over the panel.

Changes in Groundwater Chemistry in the Mt. Carmel Sandstone

The pre-mining chemistry of the sandstone water was indicated by early samples from well P350 and by later smwles from well W18 in the unmined area 3.3miles to the east. The water was sodium bicarbonate dominant and fresh to slightly brackish (total dissolved solids (TDS) 900-1200 mg/1); sulfates were low in W18 but around 200 mg/l in P350. After mining, the water in P350 became more brackish (TDS 1990-2620 mg/1) with increased sulfates (over 800 mg/1), a significant deterioration in quality. The geochemical changes are evidently due to water flowing back into the aquifer from two possible sources: leakage of high-sulfate water from the overlying shale, and lateral flow, through the aquifer, of more oxidizing water that could liberate sulfate from sulfide minerals present in the sandstone.

Studies at the Saline County Site

Site Description

At the Saline County site, the mined Herrin Coal is about 6 ft thick. Several farms and homes around the site have large diameter wells tapping the shallow drift water-table aquifer, and a few have wells drilled into thin sandstone aquifers such as the Trivoli, typically 0-25 ftthick. None of the aquifers provides good yields and most homes are now connected to the water supplies of the nearby small towns.

Six longwall panels were mined between 1989 and 1994. Hydr6geological studies were conducted over panels I and 5. Because of the northward dip, the coal seam and bedrock units were about100 ft higher in elevation at panel 5 than at panel 1; also, the depth to bedrock (thickness of drift) decreased from about 90 ft at panel 1 to less than 65 ft at panel 5.

Panel 1 (669 ft wide, 400 ft deep) undermined the instrumentation in December 1989. Although the strata were fractured, the overburden generally subsided as a coherentmass (Van Roosendaal et al., 1994); maximum ground subsidencewas about 4.7 ft. Panel 5 (943 ft wide, 318 ft deep) undermined its instrumentation in early January 1993, producing a centerline subsidence of 4.5 ft.

Shallow Drift ReMonse

The nearest shallow drift wells, several hundred feet from the panels, did not respond to mining. At panel 5, two study piezometers were screened in sandy gravels within 20 ft of the land surface. Except for fluctuations during subsidence, the water levels were not significantly affected by mining and have subsequently maintained normal seasonal variations in the range of 3 to 12 ft below ground.

Deep Drift Response

Piezometers at panel 1 were screened at depths of 63 to 73 ft in sand and gravel in the lower drift. Water levels fluctuated during subsidence then declined 8 to 11 ft. At panel 5, four piezometers were screened in the lower drift, which varied across the panel from a low-permeability clay till (permeabilities 10^{-7} to 10^{-6} cm/s) in the central panel area, to a permeable sand (10^{-5} to 10^{-4} cm/s) over the southern barrier. The permeabilities were not affected by subsidence. The water levels were initially 5 to 12 ft below ground and their responses varied with setting (Fig. 3). In the southern sand unit, which is in continuity with the underlying sandstone, they started to decline in December 1992 as the panel approached and dropped to 40 ft in the tension zone and 30 ft on the barrier during subsidence in early January. In the till over the central area, water levels fluctuated erratically during subsidence, then declined gradually a total of 10 to 15 R.

Response of the Bedrock Sandstones

Pre-mining hydraulic tests above both panels indicated very tight bedrock. Initial permeabilities in the Trivoli Sandstone were in the range 10^{-6} to 10^{-5} cm/s, and post-subsidence testing showed only minor localized increases probably related to discrete fractures. At panel 1, piezometers were screened into the sandstone at depths in the range 138 to 196 ft. The water levels were initially about 40 ft deep, and fell rapidly to 160 to 180 ft just before and during undermining (Fig. 4). Except for a slight rise during the compressional phase, the water levels did not recover during two subsequent years of monitoring.

At panel 5, the bedrock surface was about 65 ft deep, and the Trivoli Sandstone was locally in contact with the glacial drift. The pre-mining potentiometric surface in the sandstone was essentially flat, with water levels between 7 and 20 ft deep depending on topography. The levels started to decline when the mine face was 1,000 ft away, falling about 55 ft over the panel and 40 ft on the barrier by undermining (Fig. 5). The three bedrock piezometers over the panel were almost dewatered during subsidence, and subsequently maintained low water levels except for slight (10 ft) rises in winter 1994-1995. However, the water level in the piezometer on the southern barrier recovered quickly by about 13 ft in early 1993 and remained high, probably due to recharge from the overlying lower drift sand aquifer (which experienced corresponding head losses).

Groundwater Chemistry at the Saline County Site

The water in the off-panel private shallow drift wells was fresh to slightly brackish, mixed cation, bicarbonate-sulfate type, with nitrate widely present. The shallow drift piezometers over panel 5 contained similar but slightly more mineralized water. There was no apparent change in chemistry due to mining. Water in the deep drift piezorneters was similar but more brackish (TDS 1200-2000 mg/1) and had only minor changes due to subsidence, probably due to mixing of waters through local fracturing.

The Trivoli Sandstone over panel 5 contained slightly brackish sodium-bicarbonate water (TDS 1100-1400 mg/1) with relatively high sulfate. Changes from before to after subsidence were slight but there were consistent decreases in sodium and chloride, increases in calcium sulfate, and TDS; and the appearance of low levels of nitrates. These changes suggest the introduction of water from the overlying dnft into the sandstone.

Summary

At both study sites, subsidence had negligible impact on the water levels and chemistry of shallow drift aquifers. The water table fluctuated briefly during active ground movements, but long-term water-level changes were minor and probably due to readjustment to the local changes in topographic relief.

The response of confined sand-and-gravel aquifers in the deeper drift depended on the hydraulic connection to the underlying bedrock. In isolated aquifer zones, slight changes of water level were probably due to elevation changes and leakage through local fracturing. Significant water-level loss was observed only in a drift aquifer in good contact with underlying sandstone.

The impacts on bedrock aquifers are considerable. The primary mechanism is the increase in fracture porosity and permeability caused by fracturing and bedding-plane dilation. Bedrock water levels over longwall panels drop substantially to a low during undermining and active subsidence. The effects are more sudden, severe, and localized in fewer transmissive units. Recovery depends on the "rechargeability" of the aquifer-its transmissive characteristics

plus continuity with sources of recharge water. At Jefferson County, the water levels in the Mt. Carmel Sandstone recovered within two years because the aquifer was moderately permeable, transmissive, and in good continuity with adjacent areas of the aquifer. The combination of increased permeabilities and water-level recovery increased the well yield. At Saline County (Fig. 6), the Trivoli Sandstone was thin, poorly permeable, and largely isolated from potential recharge sources by overlying confining units and by continued mining up-dip of the study sites. Water-level declines were severe, and recovery was negligible except for a localized area of recharge from an overlying drift aquifer.

Two processes apparently affect the groundwater chemistry. First, subsidence-related fracturing increases leakage from overlying to underlying units. At Jefferson, fresher drift water leaked into the shale, and brackish high-sulfate shale water leaked into the less-brackish bicarbonate water in the sandstone. Nitrate (or other) contaminants from shallow aquifers may leak to deeper aquifers. Second, oxidizing recharge water moving through the aquifer may mobilize sulfates from sulfide minerals present in the sandstone. At Jefferson, the deterioration in quality detracted from the physical enhancement of the aquifer. Nevertheless, it is neither inevitable (it depends on the local geochemistry) nor (given current point-of-use treatment systems) necessarily a bar to using the water.

Acknowledgments

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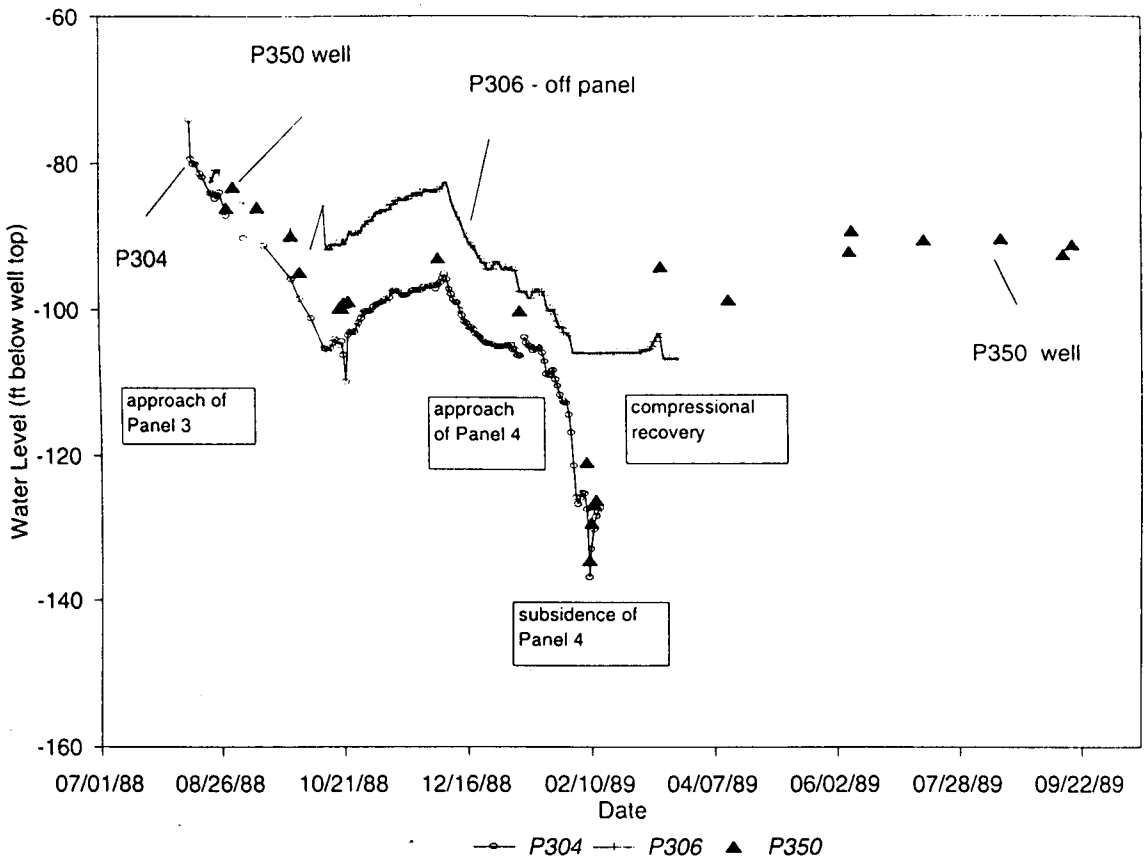

Fig. 1 Water Levels in Sandstone Aquifer During Mining, Jefferson Panel 4, 1988-1989.

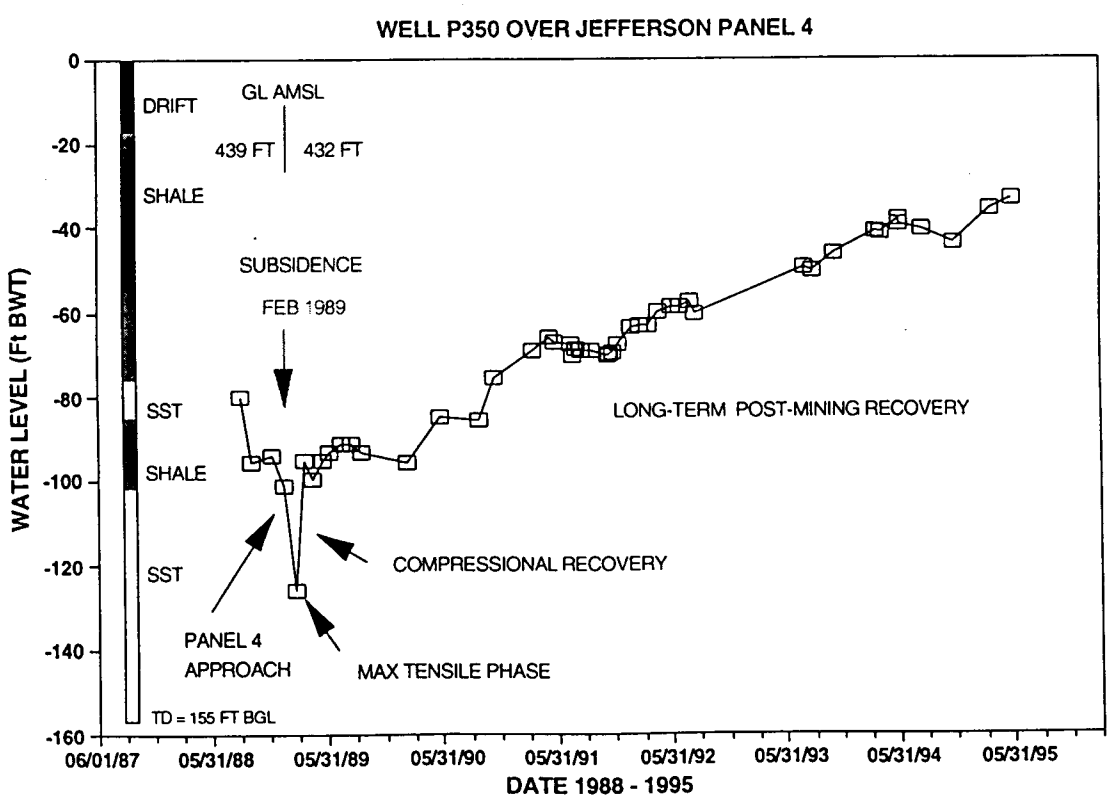

Fig. 2 Long-Term Recovery of Sandstone Water Levels Over Panel 4, 1991-1995.

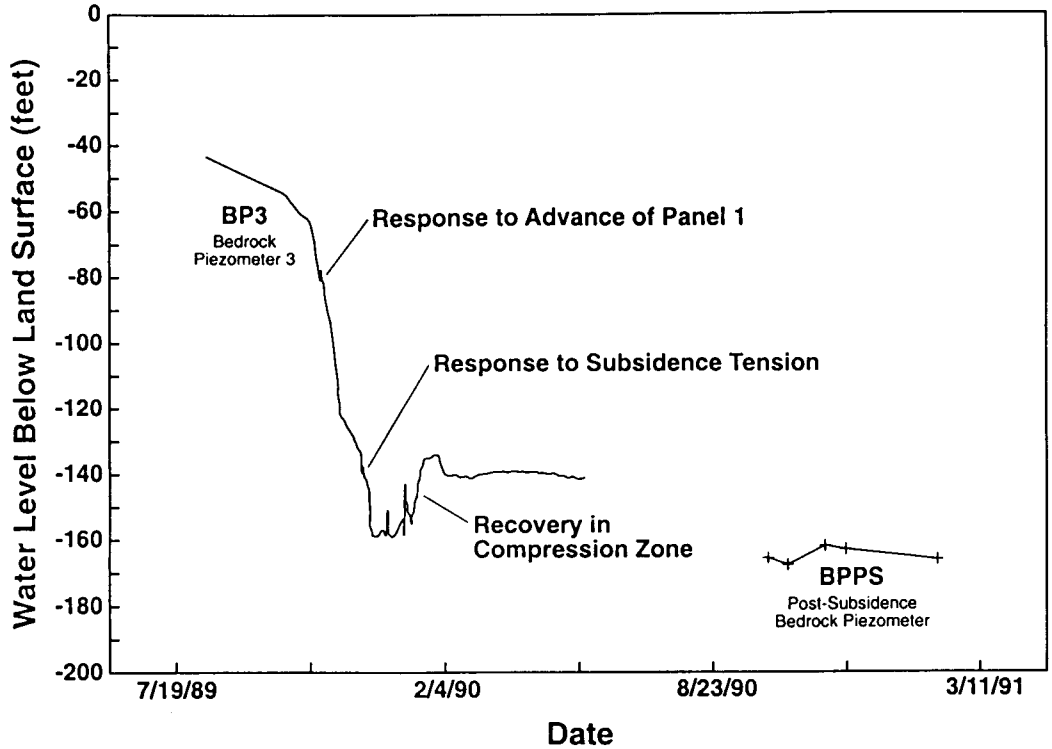

Fig. 3 Water Levels in Trivoli Sandstone Over Saline Panel 1, 1989-1991.

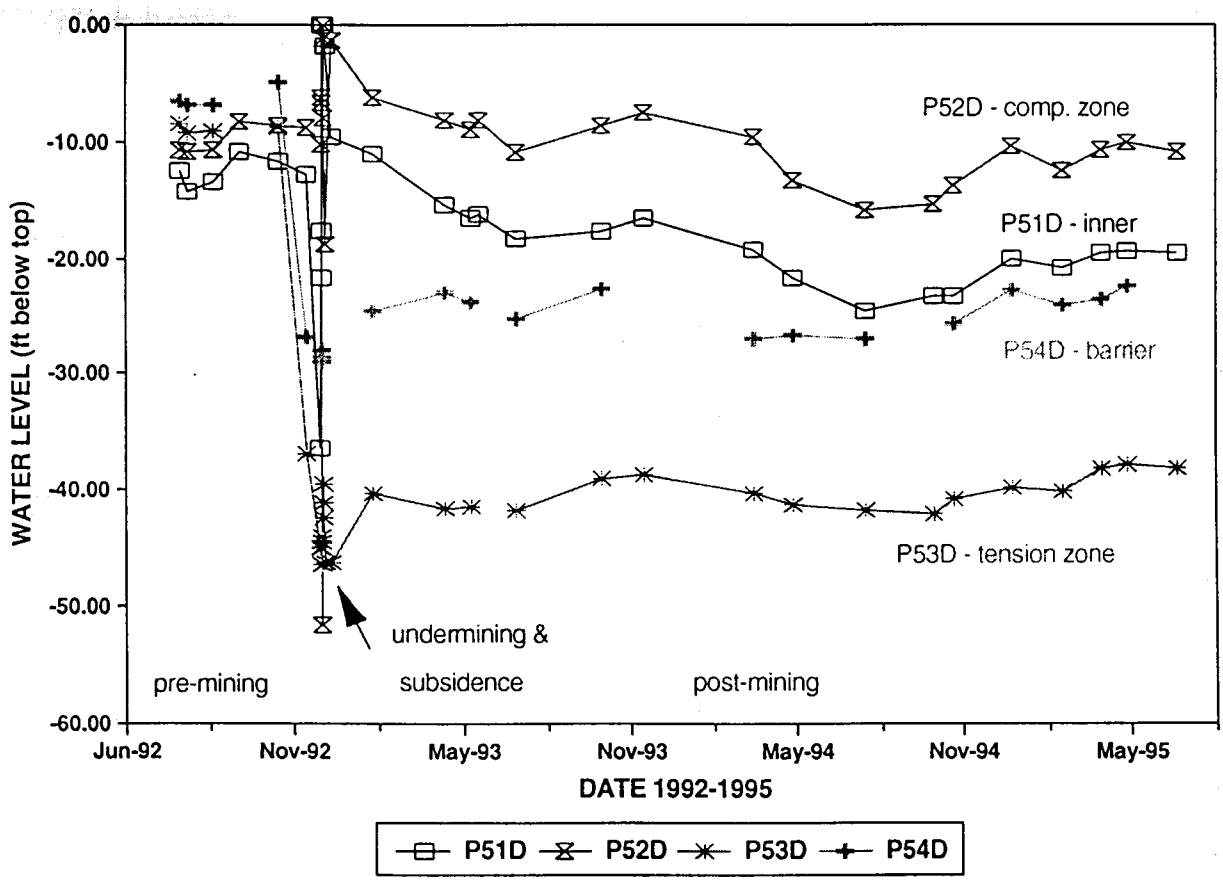

Fig. 4 Water levels in the Deep Drift Over Saline Panel 5, 1992-1995.

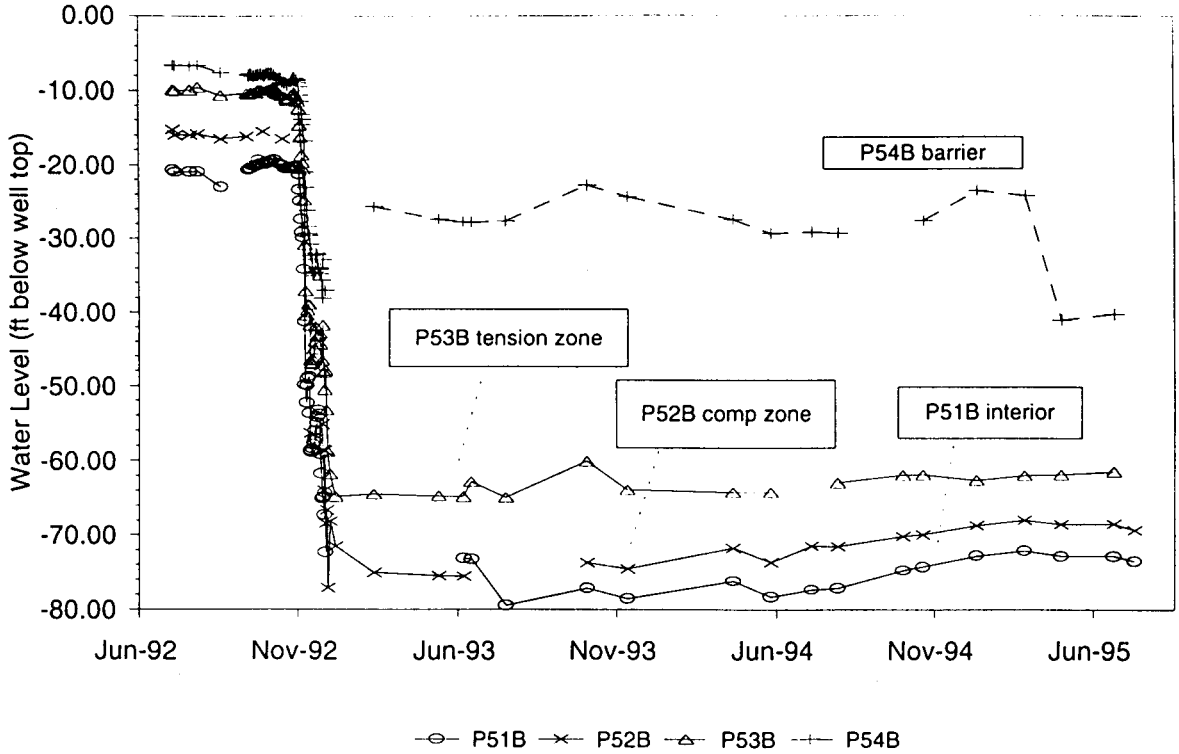

Fig. 5 Water Levels in the Trivoli Sandstone Over Saline Panel 5, 1992-1995.

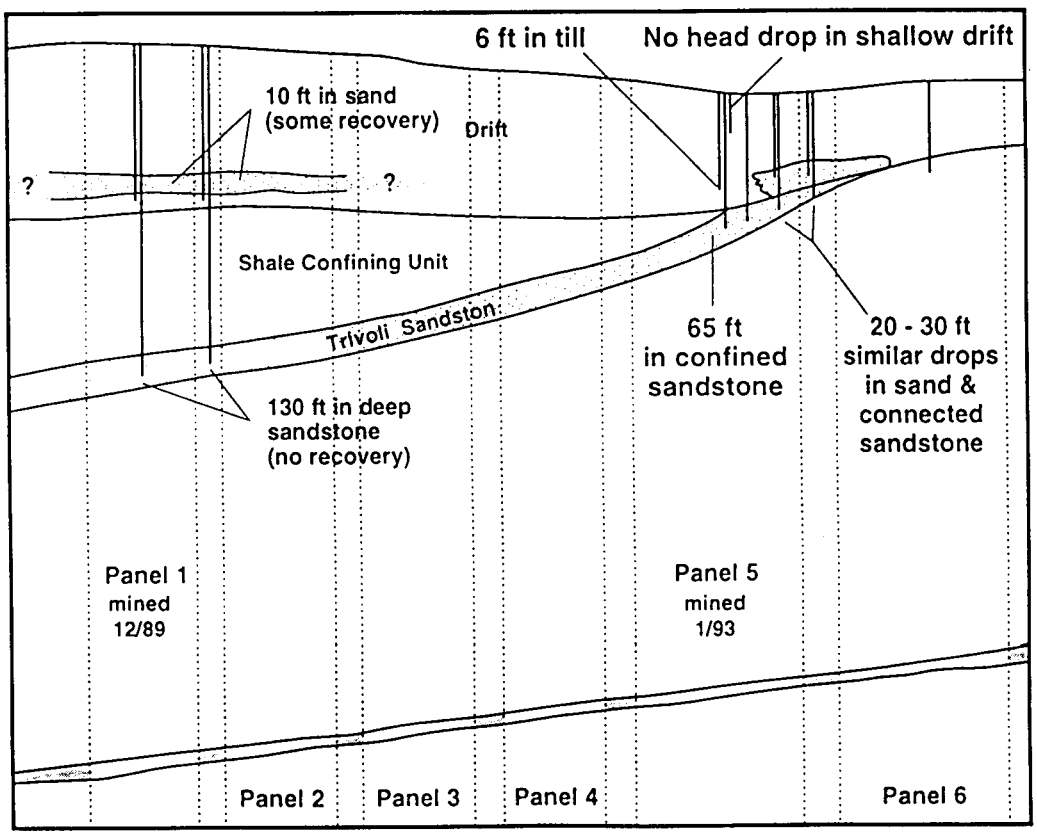

Fig. 6 Summary of Geologic Setting and Water-Level Response to Mining, Saline County Site.

RECLAMATION OF AGRICULTURAL LAND AFTER PLANNED COAL MINE SUBSIDENCE

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Abstract

Underground coal mining, although not as as surface mining, can alter the surface and impact agriculture. Surface alterations include subsidence that disturbs and creates depressions. Subsidence has always been a potential long-term problem with conventional room and pillar mining, but newer forms of mining create certain and immediate subsidence. This difference isdue to the amount of coal left behind to support the overlying soil. In conventional mines, about half the coalremains unmined as pillars, and subsidence is not expected to occur. In high extraction mining, all of the coal is removed and the surface subsides immediately. The advantage of high extraction mining is that less of the coal is left in the ground and subsidence can be planned for and mitigated shortly after subsidence. Subsidenceis a problem particularly where water tables are near the surface and the landscape is of low relief. Under these conditions, ponds can form in the subsided areas. Research has shown that subsidence mi|igation, properly applied, can restore agricultural productivity to undermined areas in most cases.

Introduction

Coal mining and agriculture are large industries that require extensive land areas to be efficient and often compete for the same land. This is a problem wherever coal and agriculture coexist (Hu and Gu, 1995; Holla and Bailey, 1990). In the midwestern U.S.A., and in Illinois in particular, coal underlies areas of prime agricultural soils (Fig. 1). Both mining and agriculture contribute to the economic health of a region, but coal extraction must not be done at the cost of long-term agricultural productivity. Long after the economic benefit of coal has been realized, the soil will continue to be needed for food and fiber production. It is the goalof coal mining regulations and reclamation to provide the potential for both industries to contribute economically.

The trend in Illinois is toward underground coal mining. Over the last 30 years, underground mining has gone from 48 to 8 1 % of the total production, and it will dominate Illinois coal production into the 2 1st century (IDMM 1994). In addition, the underground coal mining industry of the Eastern Interior Coal Basin is moving away from conventionalpartial extraction mining methods, such as room and pillar, toward higher extraction mining methods. In room and pillar mining, coal is removed from the rooms, butabout half the coal is left undisturbed as pillars to support the roof (Bauer et al., 1995). Room and pillar mining wastes much of the coal and is not absolutely guaranteed to prevent subsidence in the future. Subsidence can occur due to pillar, roof, or floor failure, particularly in older mines (Bauer et al., 1995). This type of subsidence can be gradual and long-term as the floor slowly heaves creating a subtle sagging on the surface; or it can happen quickly in relatively well defined areas long after the mine is abandoned. Subsidence of this nature is not predictable and is difficult to manage.

Higher extraction mining methods include retreat mining and longwall mining. High extraction retreat mining involvesremoving portions of the pillars from a room and pillar mine. Extraction ratios are about 80 to 90% within a mine panel (Hunt 1980). Maximum subsidence at the surface from this method is about 50 to 60% of the mined-out height underground (Bauer et al., 1995), but it can be unpredictable because local conditions in the mine influence the actual amount of extraction. In addition, pillars left standing as in conventional room and pillar mining may eventually fail. Subsidence effects at the surface above high extraction retreat mines are similar to, but less clearly demarcated than, effects caused by longwall mining (Darmody et al., 1989). Longwall mining is more efficient than either room and pillar or high extraction retreat mining. It involves removal of all of the coal within the mine panel with a continuous longwall mining machine. Consequently, with no pillars left in the panel to support the roof, subsidenceoccurs almost immediately at the surface (Bauer and Hunt 1992) (Fig. 2). Total subsidence in the center of the mine panel is typically 60 to 70% of the extraction thickness (Bauer and Hunt, 1992; Kahair and Begley, 1992). In nearly level terrain, a subsided longwall mine area appears as a series of troughs between low ridges. The

troughs vary in size, but in Illinois they are typically about 1 to 2m deep in the center with dimensions of 0.2 by 3 km (600 by 10,000 ft), and cover about 60 ha (150 ac) (Bauer et al., 1995).

The subsidence pattern at the surface is a reflection of the coal extraction pattern underground in the coal mine. Subsidence troughs are the result of fall extraction in the mine panels. The ridges between them are the partially extracted barrier pillars left standing between the panels. While the panel centers experience the most subsidence, some subsidence may also occur over the chain pillars (Mehnert et al., 1992). As a panel is mined, the surface begins to subside above the active mine face after the mining advances beyond a critical distance. Tension cracks at the surface open as the dynamic subsidence passes a given spot. Cracks at the advancing edge close due to compression after the area fully subsides. Cracks along the panel edges stay open because they are in a tensile-strained area between the unsubsided ground beyond the panel and the subsided panel center (Fig. 3). While most of the subsidence associated with longwall mining occurs rapidly, slight residual subsidence may continue as long as three years (Mehnert et al., 1992).

Subsidence from longwall mining is predictable, and damage to buildings and other civil structures can be prevented or moderated. Because of its efficiency, safety, and predictability, longwall mining is the method of choice for high extraction coal mining. Its use is increasing, but high start-up equipment costs, as compared with traditional room and pillar mining, and fears of planned subsidence hinder acceptance of this method (DuMontelle et al., 198 1).

Coal companies anticipating subsidence as a consequence of mining need to control the legal right to subside the surface. Subsidence rights were sometimes purchased by coal companies when the mineral rights were originally sold by the landowner. In other instances, if the coal company does not own the surface, subsidence rights are included in negotiations with landowners before the actual mining. Prior to the passage of SMCRA there were no federal regulations to control surface impacts of subsidence. SMCRA addressed subsidence mitigation, but deferred enforcement of that portion of the act to the states. Regulations were developed in Illinois by 1983 requiring coal companies to mitigate damage caused by subsidence (D. Barkley, IDNR, 1996, personal communication). Coal companies were required to compensate landowners or repair damage to structures and to restore land use capability to pre-mining conditions. This is different from regulations for surface mining of agricultural land that require restoration of agricultural productivity.

This presentation deals primarily with subsidence problems associated with longwall mining. Most research on agricultural impacts of subsidence has dealt with longwall mining. Subsidence from high extraction retreat mining is similar to longwall but generally not as severe because of the lesser amount of subsidence associated with that form of mining. Unplanned subsidence from room and pillar mining is unpredictable and site-specific which makes generalizations difficult. However, the general principles discussed here apply to all types of mine subsidence.

Subsidence Effects

Subsidence impacts on structures

Subsidence has deleterious effects on man-made structures. Nevertheless, because the subsidence from longwall mining is predictable and short-term, damage to structures can be reduced. Damage is most severe to structures that span the edge of subsided troughs (Boscardin, 1992). Structures toward the center of the subsidence trough are generally less prone to damage because they are let down more uniformly after the dynamic subsidence wave passes (Fig. 3). Repairs can begin soon after mining because most of the subsidence occurs within a few days after undermining, and the surface typically within three to six months (Mehnert et al., 1992).

To prevent subsidence damage, small buildings can be isolated from their foundations, or "floated," during the subsidence event and later placed upon new foundations. Railroads can be continuously regraded and leveled during subsidence so that traffic is not interrupted. Buried pipe lines can be exhumed to relieve soil pressure and allow flexing during subsidence. This reduces the chance of breakage and may allow uninterrupted use of the pipeline. Power lines can be subsided with no damage or interruption of service given sufficient slack in the lines and sturdy towers (van der Merwe, 1992). Roads also can remain open during subsidence; however, they need to be closely monitored during subsidence to prevent development of hazardous conditions. After subsidence, roads may need regrading and resurfacing; this is typically done a year after mining (Bauer et al., 1995). Subsidence can also lead

to changes in springs, wells, and regional groundwater quantity and quality (Booth and Spande, 1992; Matetic and Trevits, 1992). These effects are site-specific and may be unpredictable.

Subsidence affects on soils

Research on the reclamation of lands subsided by longwall mining is limited. Subsidence effects on agriculture land have been documented in Illinois (Darmody et al., 1989; Guither, 1986; Guither et al., 1985; Guither and Neff, 1983), the United Kingdom (Selman, 1986), India (Kundu and Ghose, 1994), China (Hu and Gu, 1995), South Africa (van der Merwe, 1992), and Australia (Holla and Bailey, 1990; Ham, 1987). These effects include soil erosion, disruption of surface and subsurface drainage, wet or ponded areas, and reduction of crop yields. Much of the impact of subsidence on soils and landscapes is related to the pre-mining surface topography. Landscapes with erosive soils on long slopes may be subject to increased erosion potential because of slope increase or displacement of erosion control structures (Ham, 1987). In low areas with high water tables, ponding is a particular problem. This can be due to disruption of surface drainage patterns as runoff collects in the low portions of the subsidence troughs. In addition, the surface could subside below the elevation of the water table (Fig. 4). As subsidence progresses, and the surface lowers, it may appear that the water table is rising (Fig. 4a). What actually happened in this case was the water table maintained a constant elevation as the surface dropped (Fig. 4b). Soil drainage or seasonal groundwater fluctuations may mask this effect (Fig. 5). In some situations ponding might be viewed in a positive way because it creates wetlands beneficial to wildlife, but negatively when it reduces net returns to a food or fiber producer.

In areas of rolling topography or high relief, there may be little or no obvious subsidence effect. The noticeable exception to this, however, can be found in areas of very steeply sloping ground or cliffs. These areas may experience slope instability or rock falls (Shea-Albin, 1992). In addition, there may be a change in the local hydrology that may cause alterations in wells, springs, and ephemeral water supplies (Werner and Hempel, 1992).

Large cracks that develop at the soil surface after subsidence can pose a hazard and may alter soil hydrology. Most subsidence cracks are small and are quickly obscured by normal cultivation. Larger cracks are generally backfilled or graded to prevent them from posing a hazard to foot or wheel traffic. Along the panel edge, cracks remain open after the dynamic subsidence wave passes (Fig. 3). This may allow surface water to infiltrate more easily and may increase the hydraulic conductivity of some soil horizons (Fig. 6). These changes are in a very small portion of the mined area and may revert to the original conditions with time (Seils et al., 1992).

Subsidence affects on crops

Underground coal mining is generally not restricted by relief; however, agriculture is generally confined to areas of relatively low relief. Consequently, subsidence impacts on agriculture generally are more severe in areas with low relief and high water tables. Southern Illinois, for example, has abundant coal reserves and highly productive agriculture. It 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). In this landscape, subsidence from underground longwall coal mining creates wet or ponded areas that delay and disrupt farming practices, causes low seed germination, and reduces crop growth and grain yields. Darmody et al. (1989) found a 4.7% average reduction in overall corn yields on subsidence-affected land in southern Illinois. In the same study, areas classified as moderately and severely affected by subsidence represented 2.3% and 5.3% of the mined land area and registered 42% and 95% corn yield reductions, respectively. These severe yield reductions were in unmitigated portions of the subsided landscape.

Subsidence Mitigation

Introduction to mitigation

Coal companies repair or mitigate areas adversely affected by subsidence by cutting drainage ditches or grass waterways, adding fill, recontouring the landscape, or a combination of these methods. Drainage ditches are typically

constructed using small tractor-pulled scraper pans. Fill material either is excavated from existing ditches, borrowed in the construction of a pond, or moved from high spots in the field. Topsoil is usually pushed aside using low

ground pressure bulldozers or stockpiled using scrapers in both the borrow area and the area to be mitigated. Subsoil from the borrow area is used as fill. Topsoil is then returned to both areas. Fill depths typically range from one-half to one meter.

Mitigation techniques can be classified into three Mm: (1) ditch, (2) fill, and (3) ditch plus fill. Site conditions dictate the amount and type of mitigation done. The success of mitigation in restoring grain yields is dependent on several factors including the amount of subsidence, the type of mitigation work necessary, the resources and materials available for the job, and the skill of the operators doing the work. Consequently, the impact of subsidence and the success of mitigation is site-specific.

There are many publications on reclamation of cropland after surface mining for coal. However, cropland reclamation after coal mine subsidence has not received much attention. Soil compaction caused by large earthmoving equipment used m subsoil and topsoil replacement has been identified as a major factor limiting crop productivity of reclaimed surface mined soils (Fehrenbacher et al., 1982). While the equipment used in subsidence mitigation tends to be smaller, the potential for soil compaction from scrapers excavating and placing fill and from bulldozers used for cutting ditches still exists. Soil compaction causes an increase in soil density and a simultaneous reduction in fractional air volume (Gupta, et al., 1989). Consequently, plant growth is altered due to poor soil aeration, low nutrient and water availability, slow permeability, and mechanical impedance to root growth (Indorante et al., 1981). Fehrenbacher et al. (I 982) found significant differences in corn yields and root densities related to different soil replacement techniques. Dunker et al. (1995) documented the success of mitigation of compacted reclaimed mine soils. Their research demonstrates the importance of sound soil replacement techniques.

Subsidence mitigation effectiveness

Effectiveness of mitigation to restore soils to their former productivity after longwall mining was studied in southern Illinois (Darmody et al., 1992). The research sites were located in farmers' fields and received varying amounts of subsidence and mitigation. Dominant soil series were Okaw (Fine, montmorillonitic, mesic Typic Albaqualf, Bluford (Fine, montmorillonitic, mesic Aeric Ochraqualf), and Cisne (Fine, montmorillonitic, mesic Mollic Albaqualf). The soils were classified as highly, moderately, and somewhat sensitive to subsidence damage due to their natural drainage and landscape position (Darmody, et al., 1989). A site consisted of the mitigation area, usually no larger than one-half hectare (1.2 acres), paired with an undisturbed reference area within the same field. The fields were planted to corn or soybean and managed by individual farmers. There was variability among sites in planting dates and other management practices; however, these variables were constant within each paired mitigated and reference site.

Selected physical and chemical measurements were made at the research sites to confirm consistency of soils and management within each research site pair and to help explain yield variability. These measurements included macro and micro-soil fertility levels, organic matter content, bulk density, saturated hydraulic conductivity, and particle-size distribution of the 0 to 23 cm depth. Penetrometer resistance of the upper 1 10 cm was also measured at selected sites to detect soil compaction (Hooks and Jansen, 1986).

Soil fertility could be adversely 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. To avoid soil fertility problems, topsoil is typically removed before adding fill and then replaced upon completion of the work. In the southern Illinois study (Darmody et al., 1992), organic matter and soil fertility estimates did not differ significantly within each paired site.

Subsidence mitigation may also influence soil physical properties. Mitigated sites tend to have massive or platy soil structure in added fill material (Hetzler and Darmody, 1992). Table 1 shows mean values for bulk density, penetrometer resistance, and saturated hydraulic conductivity at mitigated and reference sites. Soil compaction as measured by bulk density was not greatly influenced by mitigation. The lack of soil in fill material did not significantly change the bulk density from reference soils. This is due in part to similar textures between mitigated and reference areas sampled and perhaps the number of samples collected was not enough to detect statistically significant differences in bulk density. In addition, although the structure was massive in filled areas, it was not necessarily highly compacted throughout Compaction was mainly in traffic interfaces that may not have been

sampled. Lower bulk densities were observed at sites reclaimed during dry conditions.

Penetrometer resistance measurements were taken in late spring when soil water content was approximately at field capacity throughout the sod profile. The penetrometer resistance of most mitigated and reference depth segment means were not different (a = 0.05). However, compaction from reclamation was detected at several sites (Fig. 7). Prominent points in the penetrometer profile identify traffic or scraper lift faces. These interfaces of high compaction disrupt internal drainage and may result in prolonged soil saturation. 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 between 2 and 2.5 MPa have been identified as potential root restricting values (Taylor and Burnett, 1964). These values are exceeded at some sites and may be causing root restriction. However, most often the mitigated values are statistically indistinguishable from reference areas (Table 1).

Soil hydraulic conductivity in filled mitigated areas tends to be lowered somewhat by mitigation because of the destruction of soil structure and compaction (Table 1). Also, inclusion of foreign material in the fill can impede conductivity; however, the changes are not of great significance if the undisturbed soil has slow to moderately slow permeability. In general, hydraulic conductivity did not vary by mitigation method. In the soils studied, which tend to be poorly drained, fine softly-textured, and slowly permeable, soil physical properties were not significantly influenced by mitigation.

Despite the similarities in chemical and physical soil properties, average crop yields were lower at mitigated sites (Table 2) (Darmody et al., 1992). Corn yield differences were significant, averaging 19% lower on mitigated sites. Soybean yields, however, were not statistically different averaged over the four years. Yields from individual years were influenced by weather. During the drier growing season of 1988, crops in the mitigated areas appeared to have benefitted 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 same areas. The apparent better response of soybean to mitigation is attributed in part to a later planting date under typically better soil temperature and moisture conditions.

Crop yields at individual sites varied widely within a given year. Consequently, "best case" extremes or sites where mitigated yield was higher compared with reference yields were usually not statistically different (Table 3). In contrast, most "worst case" extremes are significantly different. This indicates productivity has been returned to pre-mined levels at some sites while at other sites significant yield reduction can still occur after mitigation. Table 4 shows crop yields for different mitigation methods. Crop yields at ditch type mitigation sites were statistically similar to yields at reference sites. In contrast, corn yields with the other two mitigation types, fill and ditch plus fill, were significantly lower than yields at reference sites. Soybean yields were restored in areas mitigated by the ditch method or by the fill method, but were not fully restored where the ditch plus fill method was used. These differences in success rates of the various mitigation methods is related to the extent of mitigation applied at each site. Ditch plus fill is used where subsidence impact is greatest and where probability of success is lowest. In contrast the ditch method is used where subsidence impact is slight and the probability of success is great.

Subsidence mitigation

Research demonstrates that all types of mitigation (ditch, fill, and ditch plus fill) can be successful in restoring land use and crop yields (Darmody et al., 1992). Rainfall and other factors may compound yield response at any site to cause significant yield reductions despite mitigation. 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 measured mitigation success rate. For example, ditching may be done when subsidence creates a gentle and continuous trough, as opposed to a localized depression or "pit" which would require fill. The disadvantage of ditch mitigation is that waterways in fields take land out of production and require maintenance.

Results from this study indicate that soil physical properties were similar in mitigated and reference soils. Bulk density and saturated hydraulic conductivity tend to be somewhat lower and penetrometer resistance slightly higher at some mitigated areas. However, these small differences in soil properties are independently unlikely to affect crop yields. Field inspections revealed that yield differences were due to inadequate water drainage at poorly producing

mitigated sites.

Because mitigated areas are relatively small (Fig. 8), a decrease in yield on one hectare will not significantly reduce overall field yields. However, it is important that mitigation is attempted on all mine subsidence damaged agricultural land not only from a productivity standpoint, but also to prevent associated agricultural problems such as weed and pest control and to maintain normal field patterns for planting and harvest.

The research indicates that the following practices may improve mitigation: 1) reduce soil compaction by working soil and adding fill when the soil is dry, 2) minimize traffic and use low ground pressure equipment, 3) apply deep tillage during and after mitigation work to alleviate compaction interfaces, 4) provide better water drainage by excavating existing drainage ways, and 5) add sufficient depths of fill to low areas. In addition, adding drainage tiles to mitigated areas may improve mitigation success. Drainage tiles are not commonly used in southern Illinois due to low soil permeability and siltation problems in high sodium soils. A single subsurface drain with surface inlets may be more economical than surface ditches for depressions in these soils (Drablos and Moe, 1984). In non-compacted fill material, a subsurface tile may provide adequate drainage for crop growth provided an outlet is available (Fig. 9).

Summary

Longwall mining causes immediate subsidence of the surface. Because essentially all of the subsidence occurs quickly, within a few weeks to months after undermining, most surface damage can be predicted and mitigated. This makes planned subsidence much more manageable than unplanned subsidence resulting from room and pillar mining. The most serious subsidence impact on agricultural soils is due to excess wetness. This is usually caused by disruption of surface drainage but can also be due to lowering of the land surface below the elevation of the seasonally high water table. Because of high water tables or inadequate surface drainage, wet soils are more difficult to manage for conventional agricultural crops, must be drained to increase productivity, and are more sensitive to subsidence. Subsidence mitigation as practiced in the Midwestern U.S.A. is largely in restoring land use and agricultural productivity. In some situations, however, subsidence may permanently alter land use and create wetlands. This is most probable in areas of poorly drained soils that may be marginally too wet for agriculture. In this instance, subsidence may be viewed as beneficial because it creates wetland wildlife habitat.

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Table 1. Selected soil properties (45-100 cm) at subsidence mitigated and reference sites in Illinois

Mitigation Method	Bulk Density ($g\ cm^{-3}$)		Penetrometer Resistance (Mpa)		Hydraulic Conductivity ($cm\ d^{-1}$)		
	Ref.‡	Mit.	Ref.	Mit.	Ref.	Mit.	n§
Ditch	-†	-	1.6	2.3	3	7	1
Fill	1.48	1.41	2.0	2.3	21	18	4
Ditch+Fill	1.49	1.36	1.7 ¶	1.9 ¶	19		

‡Ref. for Reference, Mit. for Mitigated.
†No sample. ¶Means of 4 sites. Source: Hetzler and Darmody, 1992.

Table 2. Crop yields at subsidence mitigation research sites in Illinois.

Treatment	1988	1989	1990	1991	Mean
Corn	----------Yield ($Mg\ ha^{-1}$)----------				
Reference	5.96	7.84	7.02	6.65	6.87
Mitigated	6.02	7.27	4.95	4.64	5.72
Difference	0.06	-0.57	-2.07*	-2.01*	-1.15*
LSD	0.44	1.07	0.94	1.51	0.75
n†	6	7	11	4	28
Soybean					
Reference	1.75	1.95	1.88	2.08	1.92
Mitigated	1.68	2.42	1.61	1.68	1.85
Difference	-0.07	0.47*	-0.27	-0.40*	-0.07
n†	7	3	3	10	23

*Significantly different (α=0.05). †Means of n sites. Source: Darmody et al., 1992.

Table 3. Crop yield extremes at individual subsidence mitigation research sites.

	Year	Reference	Mitigated	Difference
Corn		----------Yield (Mg ha^{-1})----------		
Worst Case				
	1988	6.58	5.27	-1.31*
	1989	9.91	6.71	-3.20*
	1990	7.65	1.44	-6.21*
	1991	6.96	3.89	-3.07
Best case				
	1998	5.27	7.27	2.00*
	1989	4.64	5.71	1.07
	1990	4.95	4.70	-0.25
	1991	6.96	6.84	-0.12
Soybean				
Worst case				
	1988	2.26	1.76	-0.50*
	1989	1.88	2.20	0.32
	1990	2.01	0.94	-1.07*
	1991	2.32	1.25	-1.07*
Best case				
	1988	2.01	2.01	0.00
	1989	2.07	2.63	0.56
	1990	2.07	2.26	0.19
	1991	2.45	2.76	0.31*

* Significantly different at the 5 percent level.
Source: Darmody, 1994.

Table 4. Crop yields for different mitigation methods.

Mitigation Method	Crop Yield (Mg ha^{-1})	
	Corn	Soybean
Reference	6.90 a†	1.95 a
Ditch	6.08 ab	1.88 a
Fill	4.76 b	1.95 a
Ditch+Fill	5.58 b	1.54 b

†Means within columns followed by the same letter are not significantly different (α=0.05). Source: Darmody et al., 1992.

Figure 1. Distributions of coal reserves and prime agricultural soils in Illinois (source: IDNR and USDA

NRCS).

Figure 2. Schematic diagram of longwall mining, overhead view (a) and cross section (b).

Figure 3. Formation of surface cracks above a longwall mine panel in a level topographic area.

Figure 4. Piezometric response to subsidence above the panel centerline in a nearly level, somewhat poorly drained
soil, as measured with reference; a) (upper) ground surface, b) (lower) elevation (Darmody, 1994).

Figure 5. Piezometric elevations in a somewhat poorly drained soil at an undisturbed site and above the center line and edge of a nearby longwall mine panel (Darmody, 1994).

Figure 6. Effect of subsidence on soil saturated hydraulic conductivity (Darmody, 1994).

Figure 7. Penetrometer resistance profiles at five subsidence mitigated sites and at nearby reference sites (Hetzler and Darmody, 1992).

Figure 8. Schematic of the distribution of surface effects of longwall mine subsidence.

Figure 9. Schematic of proposed improved subsidence mitigation plan.

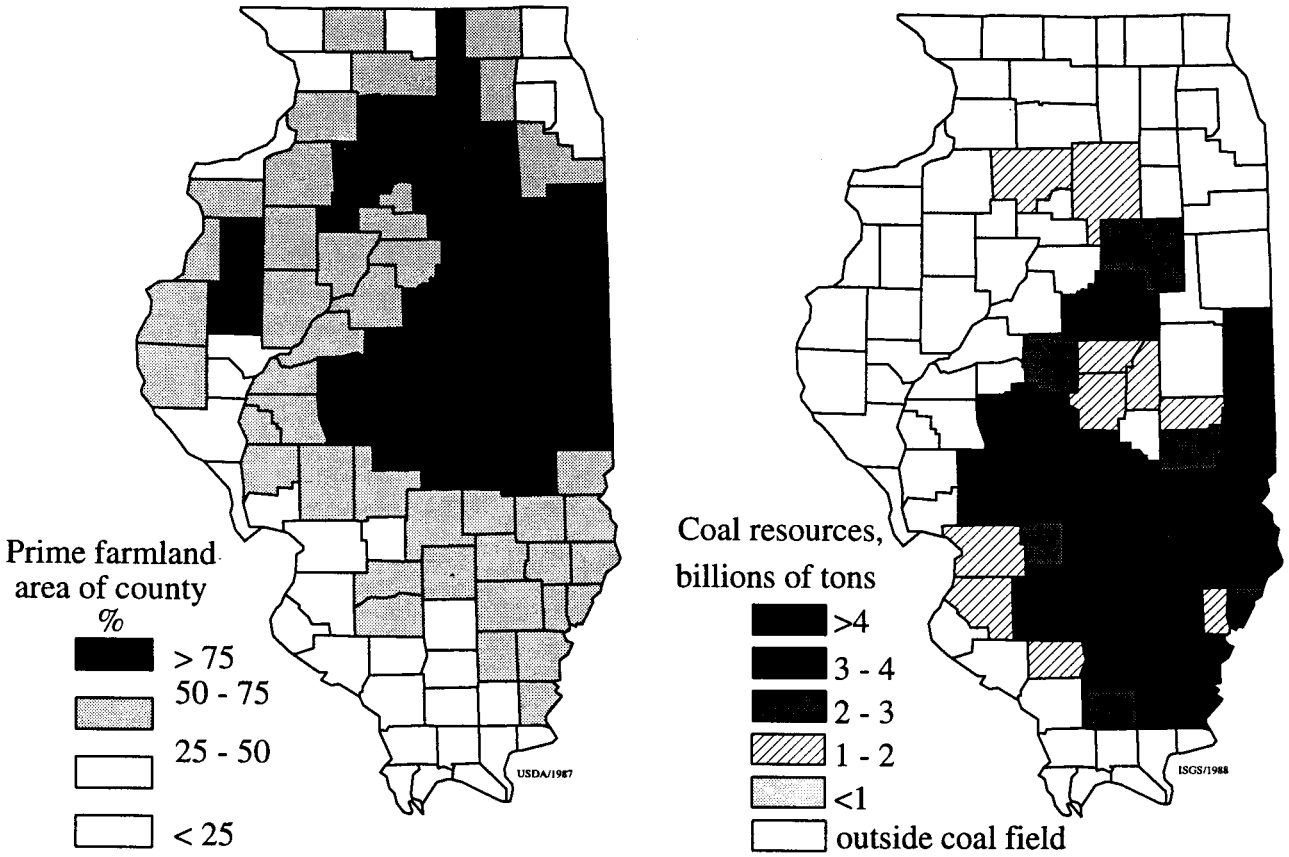


Figure 1. Distribution of coal reserves and prime agricultural soils in Illinois (source: IDNR and USDA NRCS).

LONGWALL COAL MINING SCHEMATIC

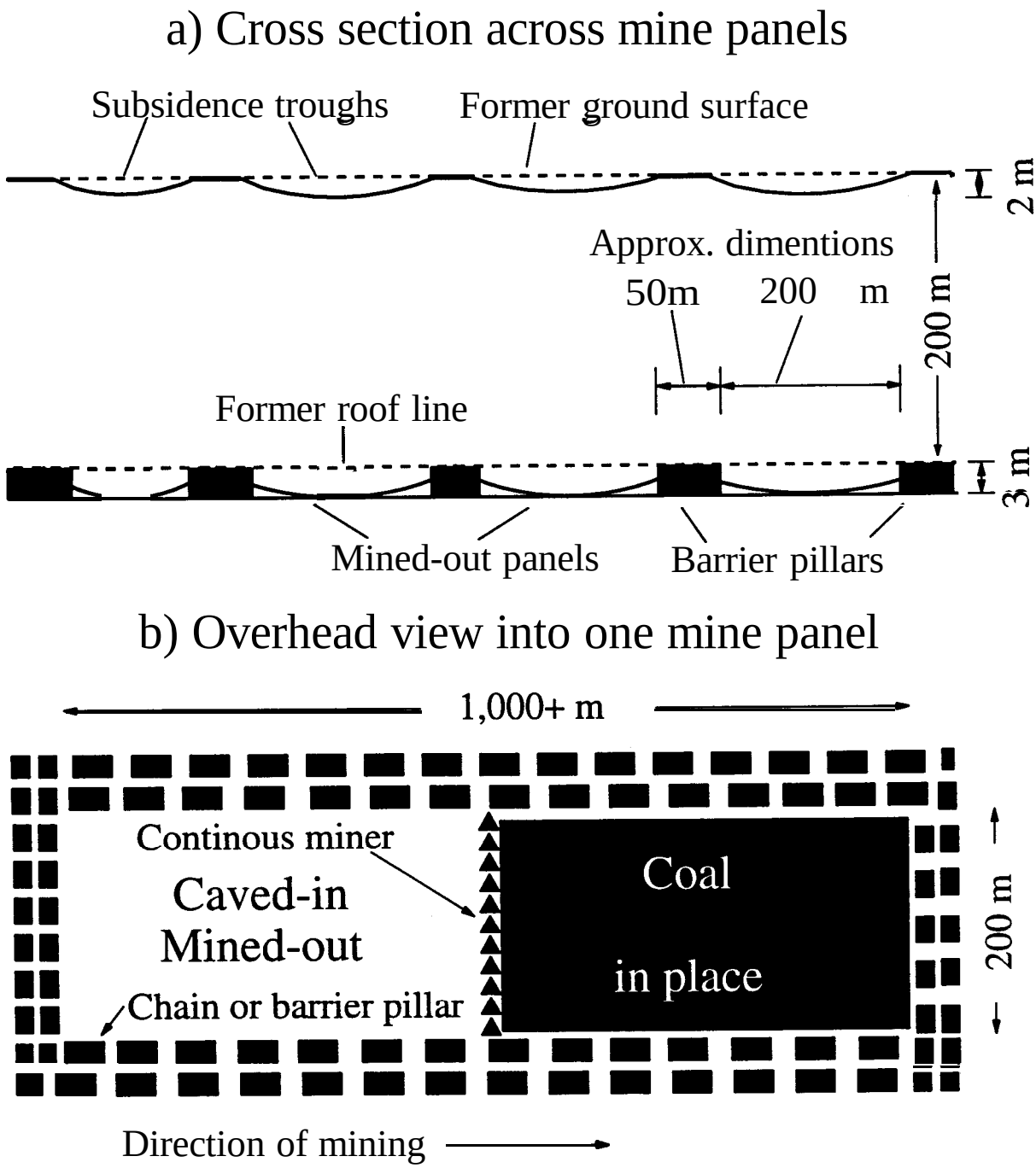


Figure 2. Schematic diagram of longwall mining, overhead view (a) and cross section (b).

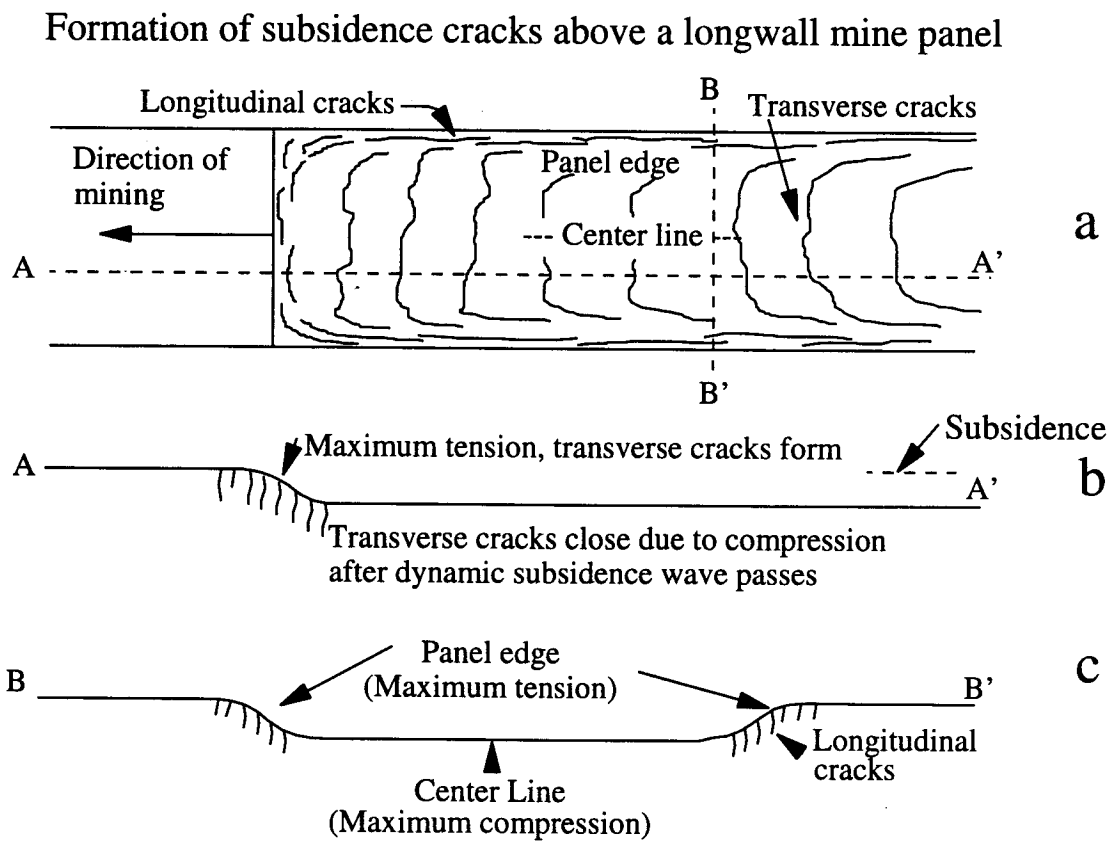


Figure 3. Formation of surface cracks above a longwall mine panel in a level topographic area.

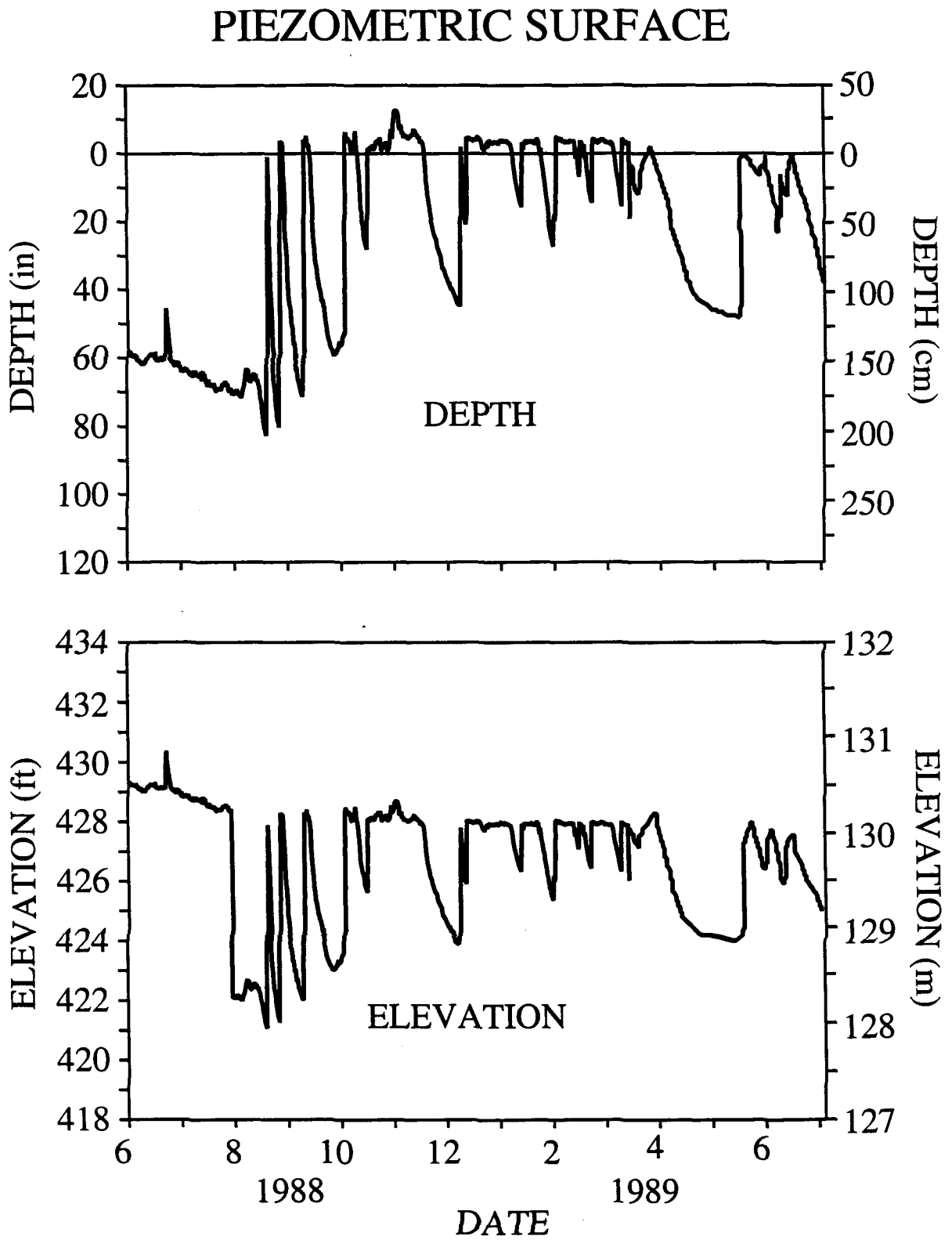


Figure 4. Piezometric response to subsidence above the panel centerline in a nearly level, somewhat poorly drained soil, as measured with reference;a)(upper) ground surface, b)(lower) elevation (Darmody, 1994).

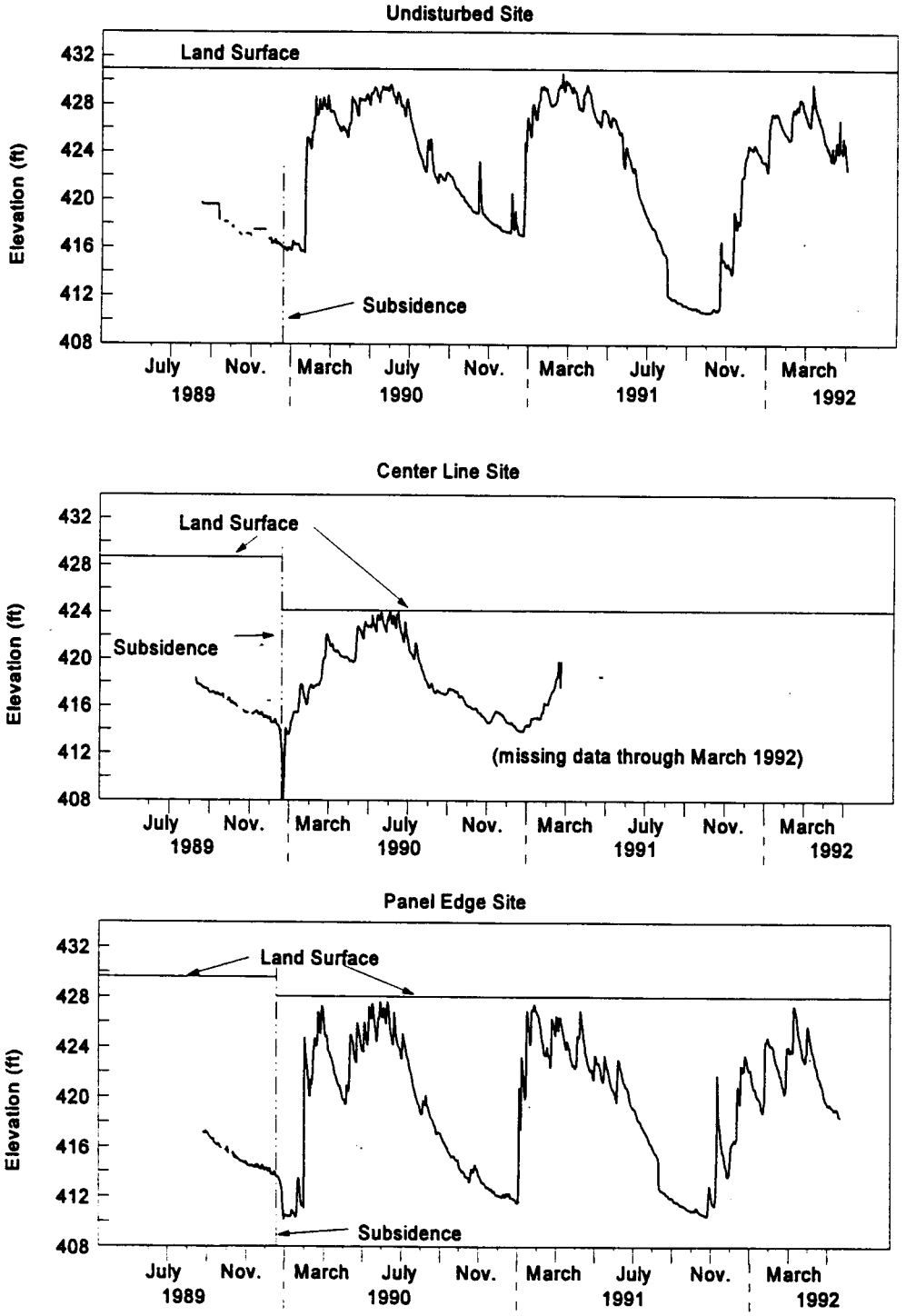


Figure 5. Piezometric elevations in a somewhat poorly drained soil at an undisturbed site and above the center line and edge of a nearby longwall mine panel (Darmody,1994).

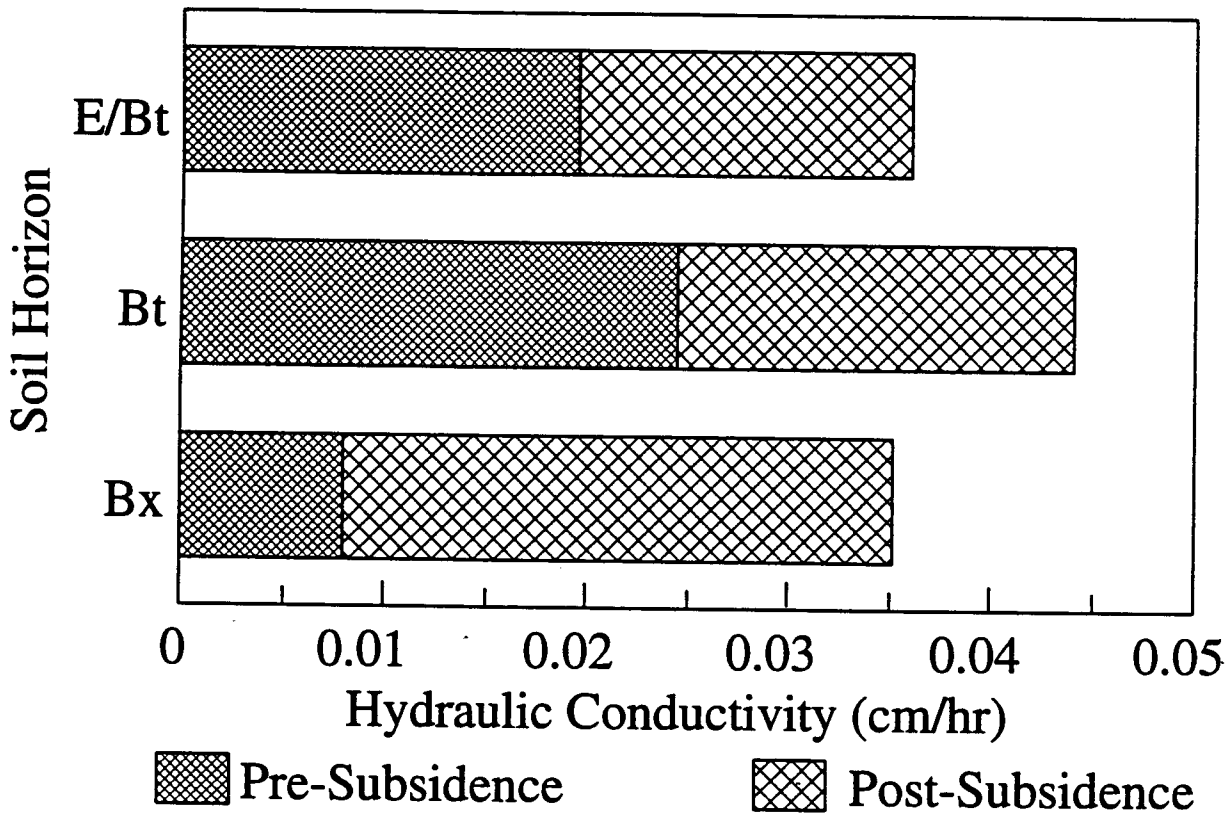


Figure 6. Effect of subsidence on soil saturated hydraulic conductivity (Darmody,1994).

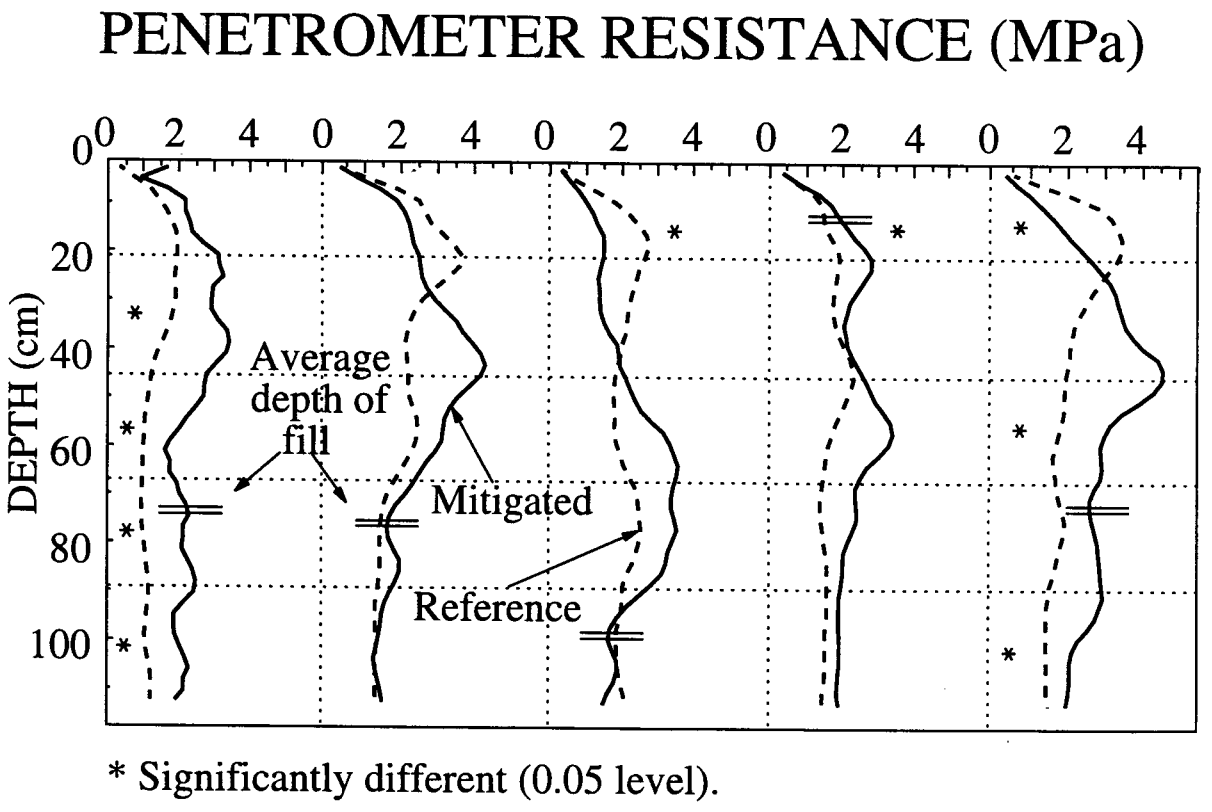


Figure 7. Penetrometer resistance profiles at five subsidence mitigated sites and at nearby reference sites (Hetzler and Darmody, 1992).

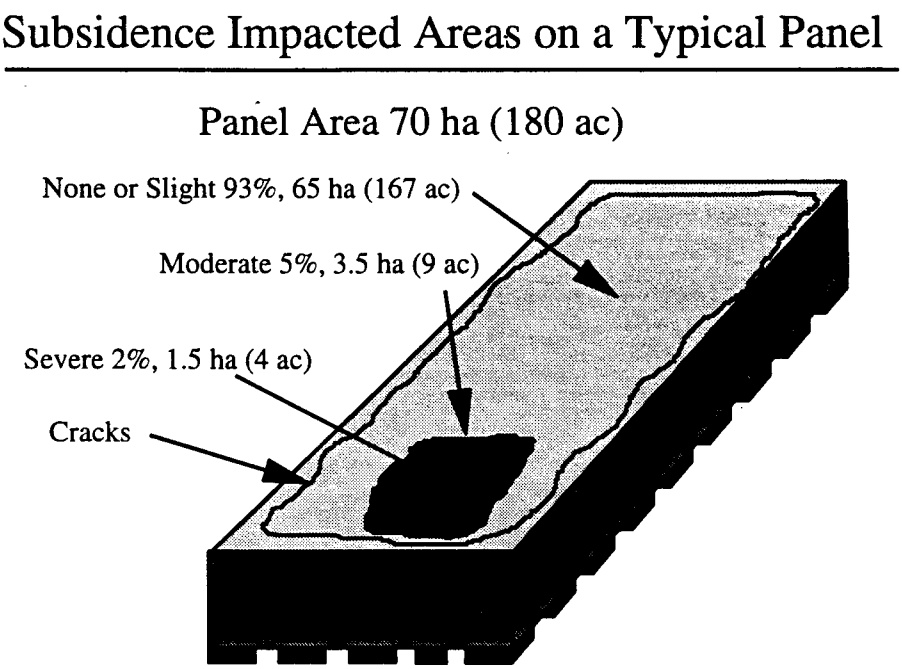
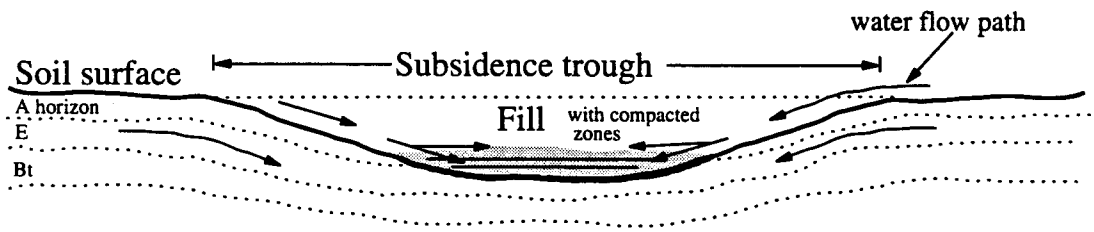


Figure 8. Schematic of the distribution of surface effects of longwall mine subsidence.

a. Subsidence troughs are run-on sites for both surface and subsurface water. This creates excessively wet or ponded areas. Compaction may be a problem within the fill and at the burried interface 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 mitigate success.

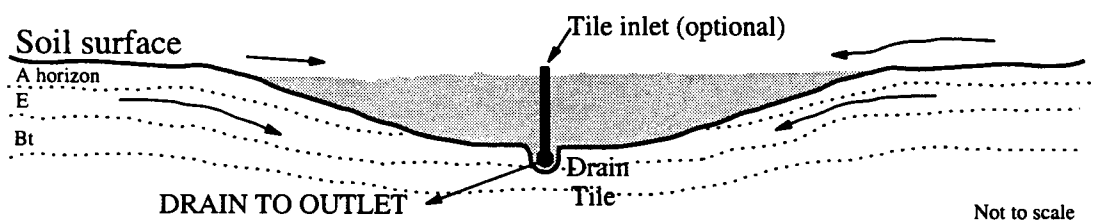


Figure 9. Schematic of proposed improved subsidence mitigation plan.