State of Illinois
Rod. R. Blagojevich, Governor
Illinois Department of Natural Resources
Illinois State Geological Survey

Planned Coal Mine Subsidence in Illinois:

A Public Information Booklet

Robert A. Bauer

Circular 573 2008

Front Cover (clockwise from upper left): *Garage raised and kept level during subsidence; restored house after subsidence; unoccupied house on subsided land (white line shows level of the original ground surface); a road subsided over a longwall panel before mitigation repaired it.*

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Introduction

The trend toward coal mining methods that use planned subsidence continues in Illinois and elsewhere in the United States. Real concerns about possible effects of mining and geologic conditions on the state's water resources, farmland productivity, and structures were investigated during 9 years of research under the Illinois Mine Subsidence Research Program (IMSRP). This program was established by the Illinois Coal Association and the Illinois Farm Bureau in 1985 to investigate the impacts of planned subsidence mining methods in the state. In addition to the research findings, mining companies and regulatory agencies in Illinois have had 30 years of experience with over 240 modern mechanized longwall panels in 6 Illinois counties (Barkley 2007). This circular was produced to respond to community concerns about the possible effects of underground mining and surface subsidence (the sinking of land surface). The publication also provides background information on the coal industry and mining methods that will help increase understanding of planned subsidence.

The Illinois coal mining industry uses high-extraction mining methods, such as longwall, in areas where it has the right to subside the ground surface. Planned subsidence using the longwall mining method enables Illinois coal mine operators to maximize mining productivity and decrease the per ton cost of the delivered product, thus improving coal's marketability. Also, high-extraction mining methods conserve and extend coal resources for future use by wasting less coal than other methods that leave considerable amounts of coal behind.

Longwall mining in Illinois is not new. A longwall method that extracted coal mostly by hand was used from 1856 to 1954. Over 135 mines in 15 counties used this method. This longwall method started in Great Britain in the late 1600s (Hatcher 1993). Later, a fully mechanized method started in Europe and began to be used during the 1950s and 1960s in the United States. Longwall mining is currently used in 12 states with 52 operating longwalls (Fiscor 2007). Worldwide mechanized longwall mining is used in United Kingdom, Germany, Poland, Russia, China, India, South Africa, and Australia.

The main purchasers of Illinois coal are electric power-generating stations. Coal generates about 50% of the electricity in Illinois and the nation. As of 2007, several new conventional power generating stations in Illinois are being planned, and plants that will produce electricity with coal that is first turned into a gas (gasification) are being considered. Also, because of increasing petroleum prices and dwindling resources, there is renewed interest in the United States for plants that produce liquid fuel products (gasoline, jet fuels, and diesel) from coal as has been done in several other countries for over half a century.

Origin and Formation of Coal

Coal is called a fossil fuel because it is made up of materials that were once living plants. The stored energy from the ancient plant materials is released when the coal is burned (Illinois Coal Association 1992). One of the major coal-forming periods began about 320 million years ago during Pennsylvanian time when much of what is now the United States was repeatedly covered by swamps where giant ferns, reeds, and other plants grew. When the plants died, they fell into the swamp water and accumulated. The plant material, deprived of oxygen after it was buried, did not decay but formed peat. Over time, the peat was compacted, covered by layers of other materials, and eventually dried and hardened. The formation of individual minable coal beds took place over many tens of thousands of years. Under conditions of increasing burial, and thus increasing pressure and temperature, the peat was transformed into coal. From softest to hardest, the stages (rank) of coal formation after peat are lignite, subbituminous, bituminous, and anthracite coal. The harder the coal, the more energy it contains per unit volume. The coal mined in Illinois is bituminous.

Coal Mining and Coal Reserves in Illinois

Historians date the discovery of bituminous coal in America by Europeans to a sighting in 1673 in what is now the Ottawa-Utica area of Illinois. The discovery is attributed to explorers Jolliet and Marquette. Jolliet's map of 1674 shows the location of *charbon de terre* (coal) (Andros 1915).

Commercial mining in Illinois is thought to have started about 1810 in Jackson County. Coal mined there was barged down the Big Muddy River and Mississippi River to New Orleans. In the early 1820s, boats loaded with coal in Peoria also made their way to New Orleans. Early mines were located near rivers, where entrances were cut into seams exposed in the bluffs (called a drift entrance). Later, shaft mines (vertical entrance) were started in Belleville in the early 1840s. By 1900, coal was produced in at least 52 Illinois counties to supply commercial industries in towns such as St. Louis and Chicago and to fuel local residential furnaces and stoves (Illinois Coal Association 1992). Towns grew up around the mines and railroads, which were also major users of coal and suppliers of much of the transportation. As a result, many urban and residential areas are built over or near old abandoned mines in Illinois. A new study (Korose 2008, personal communications) found that about 333,100 housing units were over or adjacent to the 839,000 acres undermined for coal in Illinois. This study used the 2000 census and land cover data along with the 2007 mine outline information.

The expansion of the railroad system allowed mines to be located farther from their markets than they were during the early days of mining. Today most underground mines are located in southern Illinois, and a few are found in the central part of the state (Illinois Office of Mines and Minerals 2005). Underground mines in Illinois operate at 220 to 1,006 feet below the ground surface; average depth is 445 feet (Illinois Department of Commerce and Economic Opportunity 2006). In 2005, underground mines produced

83% of the annual tonnage mined in the state; the other 17% came from surface mining (Illinois Office of Mines and Minerals 2005).

Reserves and Location

Illinois has abundant coal resources. All or parts of 86 of the 102 counties in the state have coal-bearing rocks below them. Figure 1 shows where coal is present in Illinois and the location of mined-out areas. As of 2007, about 1,050,400 acres (about 2.8% of the state) have been mined out for coal: 836,655 acres by underground mining and 213,725 acres by surface mining. In 2005, Illinois ranked ninth nationwide in coal production, and the state's annual total coal production was about 32 million tons (www.eia.doe.gov). Illinois is first in the nation for reserves of bituminous coal, the country's most widely used coal rank (Illinois Department of Mines and Minerals 1990, Illinois Coal Association 1992).

Underground Coal Mining Methods

Underground mining methods have evolved as technology has changed and as laws have been enacted to regulate the industry. Room-and-pillar, high-extraction retreat, and longwall are three modern methods used to mine coal. Current methods reflect the coal companies' compliance with federal and state regulations requiring approved mine plans, improved ventilation, roof support plans, and liability for surface effects of subsidence. Coal companies in Illinois continue to use high-extraction mining methods to decrease costs and improve productivity, but room-and-pillar (low-extraction) methods are still used in most of the mines. Longwall mining requires a high initial capital investment for equipment, an expense many smaller coal companies cannot afford, and the method requires legal rights to subside the ground surface. Figure 2 depicts the surface and underground facilities of a modern mine.

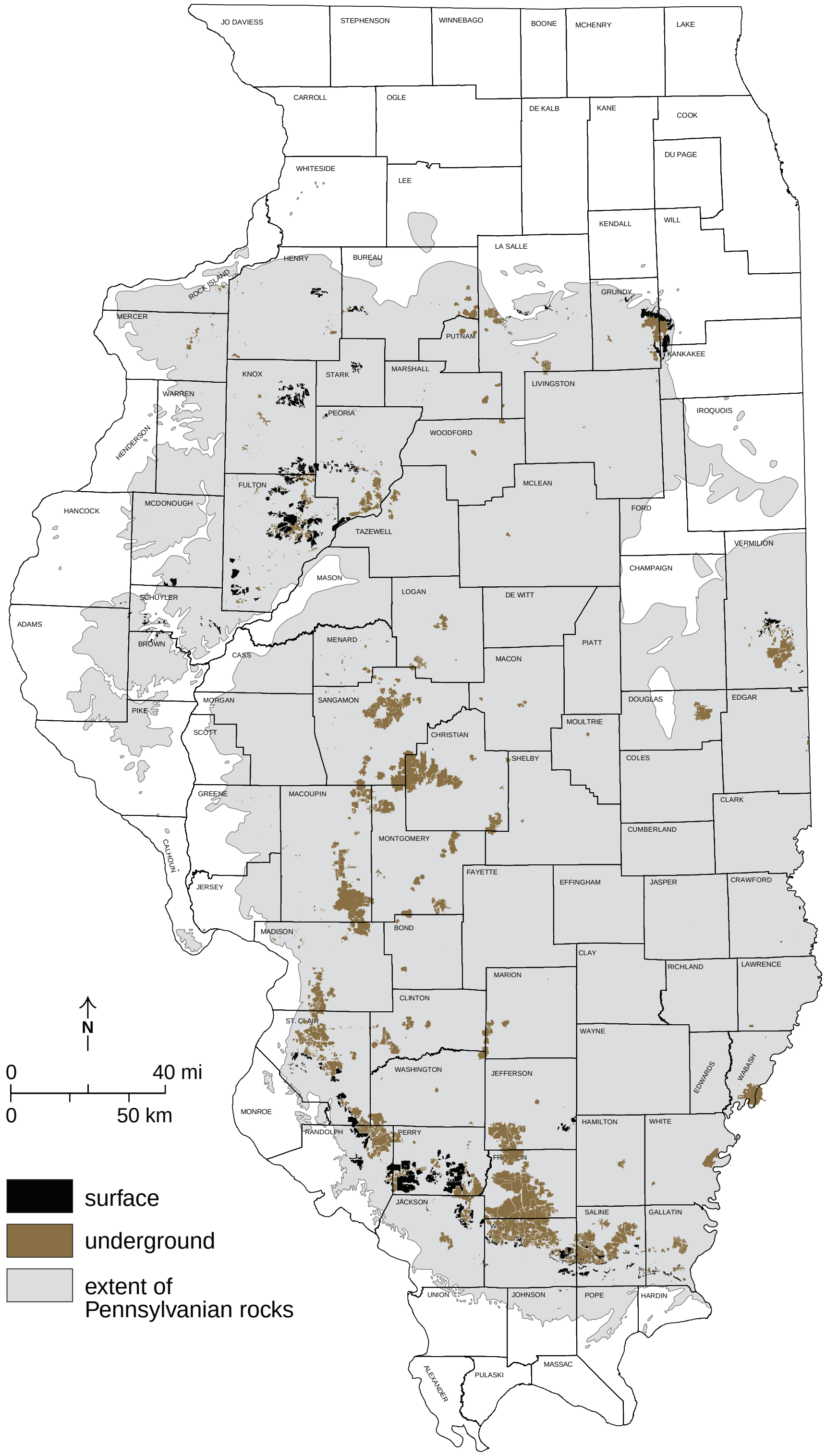

Figure 1 This statewide map of Illinois shows the extent of coal and the location of mined-out areas from surface and underground coal mining (Bauer 2006).

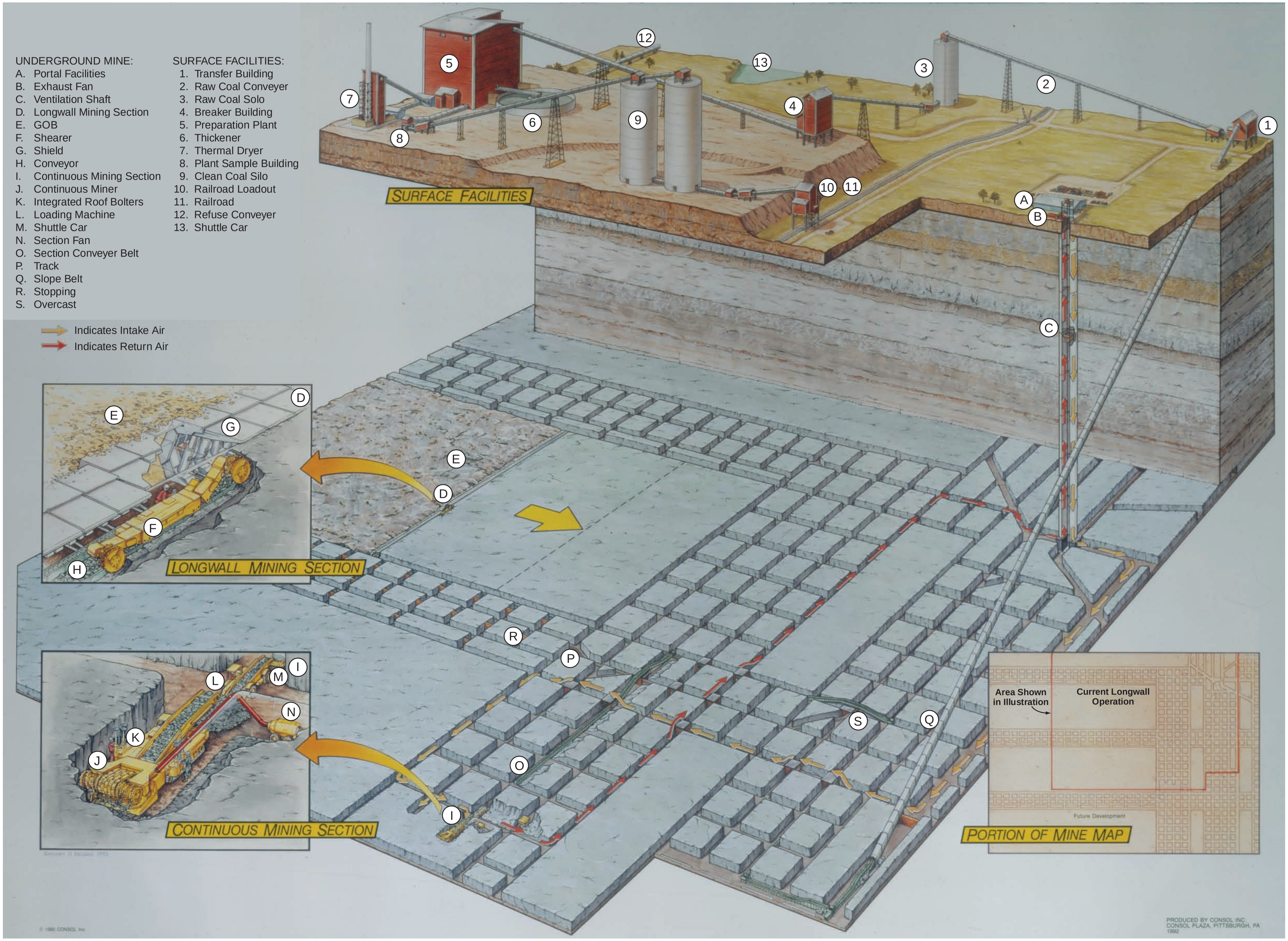

Figure 2 The conceptual diagram illustrates the parts of a modern coal mine. (Diagram used by permission of Consol, Inc.)

Room-and-Pillar Mining

Mines in the Early 1900s Many mines at the turn of the last century had entries varying in length, width, and direction, forming irregular mining patterns. After about 1910, mining was conducted with a more systematic pattern of rooms and pillars. In the production areas, or panels, workers created rooms and crosscuts at right angles to form a grid pattern. The widths of these rooms ranged from about 20 to 40 feet (Hunt 1980). Blocks of coal called pillars were left unmined to support the roof of the mine and the surface. In the older mines (1930s and before), 40% to 80% of the coal was extracted (Hunt 1979). Most of the subsidence problems associated with the room-and-pillar method occurs over higher extraction areas of these older mines. Subsidence from these old room-and-pillar mining operations can occur at any time after mining, from a few years to decades to centuries afterward. More information about the design of older mines can be found in *Mine Subsidence in Illinois: Facts for Homeowners* (Bauer 2006).

A distinction should be made between these older mines and modern (post-1983) room-and-pillar mines, which are designed on the basis of the strength of the local geology to prevent subsidence as required by the 1983 federal and state regulations.

Modern Mines In modern room-and-pillar mines, production areas are still called panels. Figure 2 shows the checkerboard pattern of a room-and-pillar area. The modern room-and-pillar mine is designed to leave enough coal unmined in pillars to support the overburden and prevent subsidence. Modern mines have a regular configuration of production areas and entryways. The widths of rooms and entries in modern mines range from 18 to 24 feet, which is considerably narrower than those in older mines (Hunt 1980).

The machine used to make passageways or entries through the coal is called a continuous miner. In the continous mining process, workers install roof bolts (steel anchors) in the mine roof to support it as the continuous miner advances. The unmined areas between the panels and between the entries and the panels are called barrier pillars. Modern room-and-pillar mining generally recovers less than 50% to 60% of the coal. Regulations for securing permits for this mining method require analysis to show that the size of pillars and amount of coal removed will result in a stable underground mine opening and will be expected to not fail and subside the ground surface.

Subsidence and Room-and-Pillar Mines Subsidence is possible wherever coal has been removed in a room-and-pillar mine. The roof, pillars, and floor are the components that surround the openings in a room-and-pillar mine, and the capacity of these components to keep an entry open and maintain a stable working area (and thus prevent subsidence) is based on their geologic characteristics and properties.

Floor failure is the most common cause of subsidence in Illinois in modern room-and-pillar mines. The claystone that is usually found underneath Illinois coal seams is weaker than the coal or the roof rock, a condition that makes the floor the most unstable component in the mine (Hunt 1980). When the floor of the mine fails, the weak claystone beneath a pillar is squeezed out from underneath, like toothpaste, into the mine opening, which allows the pillar to sink into the floor (fig. 3). Another failure in shallow mines can lead to subsidence. The immediate rock above the mine entry can weaken and fall into the mine void. These roof falls are minimized but not always prevented by placing bolts into the roof in a set pattern. Roof falls are still a threat to miner's safety even in modern mines. In most cases, roof falls are not considered to be a cause of subsidence; however, when the mine is located at a very shallow depth (less than 200 to 300 feet), and the bedrock between the mine level and the ground surface is thin (tens of feet) and contains no competent layer such as limestone, holes or pits may form on the ground surface. Pillar failures are rare in modern mines.

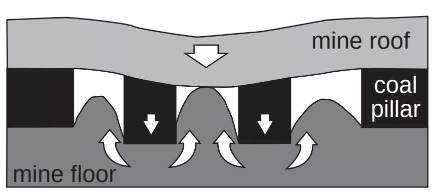

Figure 3 Failure of a coal mine floor is shown.

High-Extraction Retreat Mining

No Illinois mines currently use high-extraction retreat mining, but from the 1940s to 2002, this method was used in mines of several companies in the state. High-extraction retreat mining operations first develop a room-and-pillar panel. The miners then systematically begin taking additional coal from the pillars that were left behind. This secondary extraction occurs in a retreating fashion, working from the outer edges of the panel back to the main entries. Most coal pillars, which support the roof, are removed shortly after a few rows of rooms and pillars have been formed, leaving only small pillars called stumps or fenders. The high-extraction retreat process recovered more coal (up to 80 to 90% in a panel) than did room-and-pillar mining. In high-extraction retreat mining, the size and number of pillars that had to be left to maintain worker safety varied with underground geologic conditions (Hunt 1980). The roof collapsed in a manner that was controlled by temporary supports, and planned subsidence of the surface was initiated immediately. Sometimes pillars were left unmined in a certain area to control surface subsidence and protect a structure. Figure 4 shows a high-extraction retreat panel. This method, in older operations, was also called pillar extraction, punching pillars, pulling pillars, or pillar robbing.

Longwall Mining

In the United States, mining companies began using the fully mechanized longwall method in the 1950s and 1960s, although the method was developed and used much earlier in England and Europe. A completely different type of equipment is used in longwall

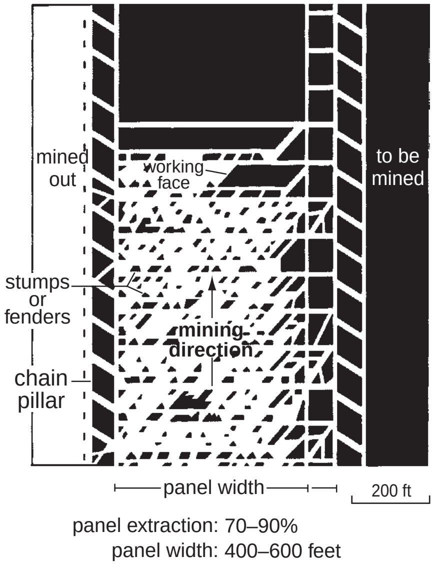

Figure 4 This diagram of a high-extraction retreat panel shows the small stumps of coal pillars left for safety during mining and the chain pillars that may be mined to increase coal extraction (Hunt 1980).

Figure 5 The longwall mining equipment photograph shows hydraulic shield supports (left) and cutting drum (right).

mining than is used in room-and-pillar or high-extraction retreat mining. In longwall mining, coal is removed by a rotating cutting drum or shearer that works back and forth across the coal face, cutting off coal as thick as the coal seam (5 to 9 feet) and as wide as 30 to 32 inches with each pass. The coal falls onto a conveyor below the cutting machine and is transported out of the mine (fig. 5). All of this is performed under a canopy of steel supports that sustains the weight of the roof along the mining face (fig. 2). Each support is about the size of a car and can move forward with each pass of the cutting machine.

Room-and-pillar mining methods must be used in conjunction with longwall mining. Entryways are driven around the perimeter of a block of coal to form a longwall panel to allow access for workers, mining equipment, and air flow (ventilation) for miner safety. Like high-extraction retreat, longwall mining begins at the outer edges and works toward (retreats toward) the main entries. In the longwall system, all of the coal is removed from a panel, but a few rows of pillars (called chain pillars) are left between panels. In Illinois, in 2007, longwall panels are 900 to 1,250 feet wide, up to 2.6 miles long (Fiscor 2007 and Barkley, personal communications), and 330 to 970 feet below the ground surface. In 2005, 53% of the coal produced in Illinois was mined using the longwall method (Illinois Office of Mines and Minerals 2005), which is similar to the percentage mined in the entire United States by longwalls (Weisdack and Kvitkovich, 2005).

As the coal is mined, a series of steel shields supports the mine roof and protects the shearer, conveyor—and most importantly—workers (fig. 2). The shields advance as the shearer cuts coal from the longwall face. The mine roof material then collapses behind the shields, and the shearer and shields move toward (retreat toward) the main entries. Planned subsidence occurs as the mining is taking place. A safer work environment for the miners is maintained at the cutting face because they are always working under the steel supports (Illinois Coal Association 1992).

Subsidence

History of Subsidence Research

Subsidence research related to coal mining has been conducted for many years in Europe, the United Kingdom, China, South Africa, Australia, and the United States. In the 1820s, Belgian engineers started a systematic study of mine subsidence because of surface damage to structures (New South Wales Coal Association 1989). Until the early 1900s, most studies were conducted in Europe and the United Kingdom, where subsidence research continues to the present. The *Subsidence Engineer's Handbook,* a landmark publication produced in the United Kingdom by the National Coal Board (1965), became the basis for studies associated with longwall subsidence in the United States (Yarbrough 1983).

Early researchers in the United States first studied mine subsidence and its effects on the ground surface and structures in Illinois and Pennsylvania. The Illinois State Geological Survey (ISGS) has documented coal mine subsidence since 1908. The first studies began after an investigation of the state's coal resources and mining practices was authorized by the 47th Illinois General Assembly. This authorization resulted in cooperative research by the ISGS, the University of Illinois, and the U.S. Bureau of Mines. Subsequently, publications on coal mine subsidence were produced from 1916 to 1938. Several modern ISGS studies were performed in the mid-1970s because of renewed interest in environmental issues. Hunt (1980) presented a comprehensive review of subsidence in Illinois and documented many case histories.

Mechanics of Subsidence

The amount, effects, and timing of subsidence differ depending on the mining technique. For a coal seam approximately 7.5 feet thick, the average maximum subsidence over the center of a mined-out high-extraction retreat panel is about 4 feet, or about 50% to 60% of the mined-out height underground at the mine level. Over a longwall panel, maximum subsidence averages about 4 to 6 feet, or about 60% to 70% of the mined-out height underground (fig. 6). The amount of subsidence is never as much as the mining height, and most subsidence occurs within days to several weeks after an area is undermined by longwall or high-extraction retreat methods, depending on the actual rate of mining.

On the surface, cracks in the ground are usually caused by tension (pulling apart) near the edges of the mining area undergoing subsidence at the location of maximum tension (fig. 6). The tension cracks are also associated with a moving longwall face (and moving subsidence wave on the ground surface), usually close naturally, whereas some along the sides of the panel may need to be filled. Areas inward from the tensile cracks (closer to the center of the panel) are compressed (pushed together) at the location of maximum compression (fig. 6), causing the soil to sometimes buckle upward a few inches. The surface effects of subsidence depend on the original slope of the land before mining. Subsidence may or may not be visible if the land is hilly, because slope

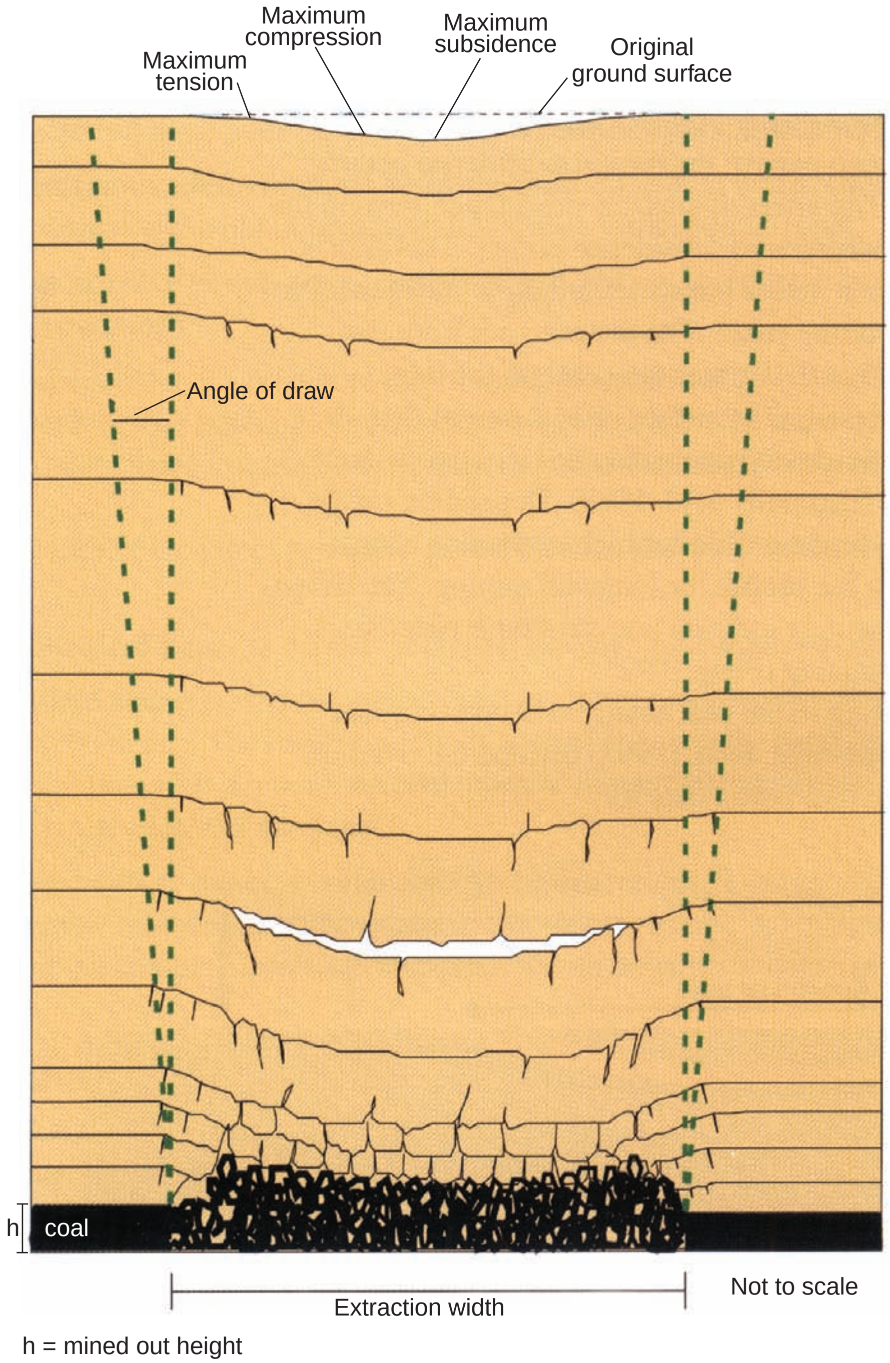

Figure 6 This schematic diagram shows the general behavior of overburden above longwall panels and the location of surface subsidence features (Peng and Chiang 1984, New South Wales Coal Association 1989).

changes caused by subsidence are harder to see. In flatter terrain, drainage interruption may be more evident.

The effects of subsidence from longwall mining are uniform and anticipated (fig. 6). The surface over the center of the panel drops approximately 4 to 6 feet. Maximum subsidence occurs over the center of the mined-out panel and tapers off toward the edges of the panel, forming a gentle trough. Less subsidence occurs over the entryways and chain pillars between panels. The areas of surface subsidence beyond the edges of the panel are defined by a point where zero vertical subsidence occurs. This area is defined by an angle called the angle of draw (fig. 6), which varies according to differences in local geology, seam depth, and panel width. The distance from the panel edge to zero subsidence may be 0.35 to 0.45 times the depth to the mine. This point or location is not necessarily related to damage since the amount of tension large enough to affect various structures is located just within the edge of the panel to nearly over the edge of the underground panel.

High-extraction retreat mining produces similar surface effects except that, depending on the topography, high-extraction retreat panels may be less clearly demarcated on the surface than longwall panels are (Darmody et al. 1988). Depending on the amount of pillar extraction, the final subsidence profile for high-extraction retreat mining is less regular and predictable than the profile for longwall mining. The irregular effects of high-extraction retreat mining indicate the uneven stump pillar sizes, which, even when crushed, produce different amounts of support for the subsided roof of the mine (Peng 1992).

As the longwall mining process creates a large opening underground, it changes the equilibrium of nearby rock materials. The void at the mine level does not work its way slowly upward through progressive collapse up through the overburden. Monitoring of the overburden above longwalls show that, overall, the entire overburden from the mine level to the ground surface moves downward nearly as one mass with some bending and flexing as bedding planes slide past each other. This dynamic is similar to the bending of a phone book. If every page were to be glued together, the book could not be bent. A phone book bends because the pages slide past each other. The bedrock layers that slide past each other form thin beams that partially crack from the bending taking place. These tension cracks do not typically progress through the entire rock beam but terminate at about the center of each beam (fig. 6). Because these cracks are discontinuous, they do not form a path for groundwater to flow from the ground surface down to the mine level.

The extraction width of the panel in relation to the depth of mining generally determines the shape of the final subsided area at the ground surface (fig. 7):

- The subcritical panel extraction width is narrow. It causes less than maximum possible subsidence at the ground surface.
- The critical panel extraction width is slightly wider. Only its center point reaches the maximum possible subsidence.The critical width of a panel is generally considered to be at least 1.5 times the depth to the coal seam, if maximum subsidence is to occur at a point at the center of the panel.
- The supercritical panel extraction width is wider than the critical width. It causes a flat area of maximum subsidence in the center of the surface trough. Although the lateral area of maximum subsidence increases, the angle of draw does not increase.

Subsidence Movements

Longwall and high-extraction retreat mining cause vertical and horizontal surface movements. The ground drops vertically and moves horizontally toward the center of the trough (Bauer 2006), which may affect surface structures or other features.

Vertical Subsidence Structures such as railroads, canals, and sewers, which must retain a certain elevation, are most affected by vertical subsidence (Peng 1992). Water may pond in flat areas that have subsided vertically; hilly areas are less affected.

Tilt The difference in the amount of vertical movement between two points is called tilt. Tilt may also affect surface structures that depend on gravity, including gutters, drains, and water treatment plants.

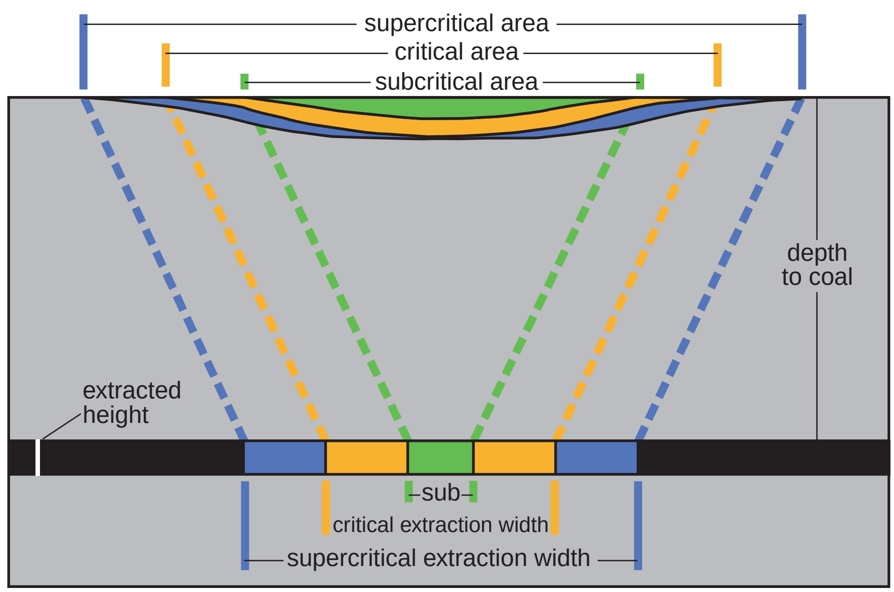

Figure 7 The development of surface subsidence is affected by the width of the extracted area (panel) in relation to depth of mining (after New South Wales Coal Association 1989).

Strain Horizontal strain is a change in the length between two surface points. If the length between the points increases, a tensile strain is produced. If the length decreases, a compressive strain develops. Horizontal strain is a major factor in surface structural damage, especially tensile strain (Peng 1992). Some building materials are more susceptible than others to horizontal strain. Steel is tolerant of tensile strain; masonry is not. Rocks and masonry are more tolerant of compressive strain than wood. Buildings and foundations can be designed, however, to withstand some level of strain.

Subsidence Related to Time and Coal Face Advance

Surface subsidence at a fixed point on the ground surface occurs more quickly when the longwall equipment passes rapidly than when it advances more slowly. For any surface point, extremely small subsidence movements begin before the longwall face is directly under the surface point (fig. 8). The depth from the surface to the coal seam controls when these movements begin. Peng (1992) found, in the eastern United States, that subsidence started to affect a surface point when the approaching longwall face was at a horizontal distance that equaled the depth from the ground surface to the level of the coal mine. In Illinois, this horizontal distance is about 50 to 60% of the depth to the mine. The largest amount of surface movement and tensile strains occurs after the longwall face has undermined and passed under a surface point.

At one site, researchers in Illinois showed that subsidence movements continued for years after an area had been undermined by longwalls; this type of subsidence is called residual subsidence (Mehnert et al. 1992). These movements were measured 6 months to 3 years after mining and amounted to 5% (about 0.3 feet) of the mined-out height. Residual subsidence seemed to be fairly uniform over the panel and over the pillars between panels. Residual subsidence caused no differential subsidence and no additional strains over the sides of the panel, two effects that would damage structures. This

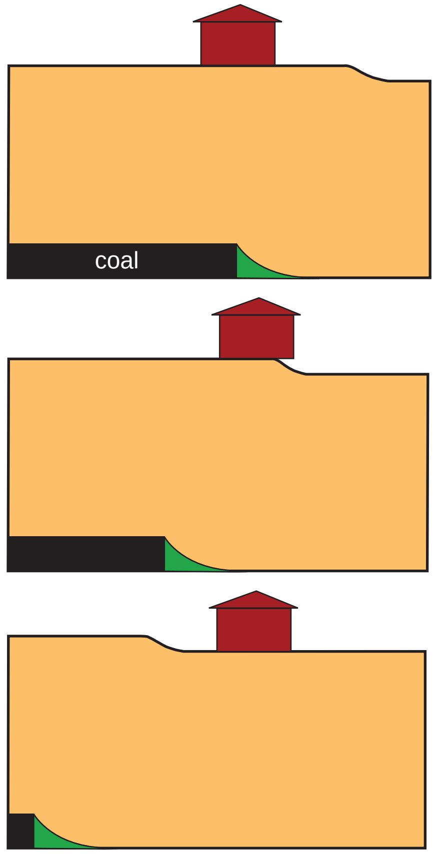

Figure 8 The position of an advancing longwall face is shown in relation to the location of major surface movements occurring behind the mining operation (New South Wales Coal Association 1989).

occurrence is similar throughout many areas of the world where residual subsidence may last 6 months to 7 years, depending on the strength of the strata above the coal seam (Whittaker and Reddish 1989, Orchard and Allen 1975, Fejes 1985).

Subsidence Monitoring

Planned subsidence over active mines is monitored by researchers and mining companies. Various methods and equipment are used to document vertical and horizontal movements associated with subsidence. Surveying is used to measure surface movements. Several types of instrumentation placed in the ground can measure vertical and horizontal movements beneath the surface and monitor fracturing and other changes (or their absence), such as groundwater levels and chemistry, during subsidence. As with any type of monitoring for changes, baseline data are collected well before subsidence begins. Measurements are taken most frequently during the event, and follow-up monitoring continues in order to detect residual movements. Monitoring may be required as part of a company's legal permit to mine. More importantly, data collected during monitoring help the mining company design mitigation for the land and plan better for effects on surface structures.

Figure 9 depicts the measured percentage of subsidence versus the ratio of panel width to mining depth for several Illinois mines. (The percentage of subsidence is the ratio of the maximum amount of surface subsidence to the height of the mined-out void.) Panel width, mining depth, and extraction method influence the amount of subsidence. Regional geology also plays a small part because the strength properties of the overburden can influence the amount of surface subsidence; in general, the weaker the overburden, the higher is the percent subsidence.

Scientists can compare subsidence monitoring data to known geologic conditions to predict (or model) the amount and extent of subsidence that might result from various mining methods. Models may be based on data collected in the laboratory, field, or both. Models may be derived from mathematical formulas based on collected data (Triplett and Yurchak 1990)

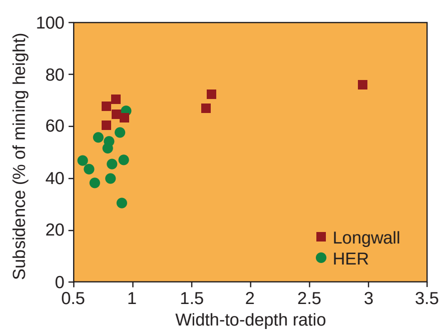

Figure 9 The percentage of subsidence is shown in relation to the width-to-depth ratio for longwall and high-extraction (HER) mines in Illinois (ISGS data).

or from physical replicas of geologic and mining features. Projected subsidence profiles based on modeling or actual surface monitoring data are used to generate postsubsidence contours and expected changes in drainage patterns.

Federal and State Regulations

Many laws govern the mining industry, but coal mine subsidence was not regulated until 1977 with the passage of the federal act, Public Law 95-87, the Surface Mining Control and Reclamation Act (SMCRA). State law is in place to enforce the federal act and regulate subsidence from underground coal mining operations. These laws and their associated rules and regulations have become increasingly stringent.

Federal Law The SMCRA, which governs surface and underground mines, established national standards for land reclamation. Under SMCRA, each state was required to develop its own rules that were as effective as the federal act. The federal Office of Surface Mining oversees each state's mine permitting and reclamation program. The law requires mine operators to adopt measures consistent with known technology (1) to prevent subsidence from causing material damage to the extent technologically and economically feasible, (2) to maximize mine stability, and (3) to maintain the value and reasonably foreseeable use of such surface lands, except in those instances where the mining technology used requires planned subsidence in a predictable and controlled manner (Illinois State Geological Survey 1980). Planned and controlled subsidence methods are available to operators under SMCRA and state law with specific requirements concerning control and repair of surface effects.

State Law Illinois' initial regulation concerning subsidence from underground mines went into effect February 1, 1983, with implementation of the state's permanent rules to fulfill the federal SMCRA (Ehret 1986). Changes to the rules have occurred since 1983. Active mines in Illinois must submit a mine subsidence control plan. This plan is part of the mine operator's application for a permit, which must be reviewed and approved by the Illinois Department of Natural Resources, Office of Mines and Minerals, before mining can begin. The plan includes mine maps; geologic information; details on planned subsidence; a survey of surface structures and features, wells, and springs; and plans for monitoring subsidence. A subsidence control plan is required regardless of whether the mine operators intend to use planned subsidence methods (longwall or high-extraction retreat) or mining methods designed to prevent subsidence (room-and-pillar).

All surface property owners and occupants of dwellings above the underground works must be notified by the mine operator at least six months prior to being undermined. All subsidence impacts that occur, whether planned (e.g., longwall mining) or unintentional (room-and-pillar mining), must be corrected.

Land damaged by subsidence must be returned to a condition capable of maintaining the uses the land was capable of supporting before subsidence damage. Repair methods may include cut-and-fill grading, tiling, and/or the installation of waterways and ditches. The mine operator is required to pay the landowner for crop loss until repairs are completed. All structures damaged by subsidence must be repaired or replaced or the owner compensated for their value.

Domestic water supplies from wells or springs must be replaced on a temporary or permanent basis if the water quality or quantity is affected. Replacement can take the form of drilling a new well, hauling in water on a temporary basis, or connecting the impacted party to a public water supply. If the landowner's water supply is replaced by being connected to a public water supply, the mine operator must pay for installation costs and any operation and maintenance costs in excess of what would be considered customary and reasonable.

If longwall mining and planned subsidence are proposed, landowners will be contacted by the mine operator to schedule a pre-subsidence survey of their structures and water supply. The purpose is to record the structural conditions before subsidence so that these can be returned after subsidence. For wells and springs, both the quality and quantity of the water normally available from the well or spring are recorded for comparison after subsidence.

Because longwall mining creates planned subsidence, the mine operator must take steps before undermining to minimize damage to structures, unless the owner of the structure provides a written waiver. Damage minimization techniques can include installation of flexible utility connections, supporting the above-ground portion of the structure on beams to keep it level while subsidence takes place, and trenching around the foundation to minimize foundation damage. Methods are selected based on the type and extent of subsidence expected.

In addition to complying with subsidence and reclamation regulations, mine operators must comply with local, state, and federal laws concerning worker safety, clean air and water, historic preservation, and many other laws. Mining regulations can be expected to continue to change as more information becomes available through research on mine design and subsidence monitoring.

Planned Subsidence Regulation

Protection from the negative effects of planned subsidence is mandated by law. Mining companies operate under regulations and must have previously obtained permission or have negotiated the rights to subside any property. In most cases, the mine operator owns or leases the coal seam but does not own or control the surface above the coal. Based on the deed or lease language, the operator would have the right to extract the coal by underground mining, but may or may not have the right to remove enough coal to intentionally subside the surface.

If a company wants to conduct longwall mining but does not have a coal deed or coal lease agreement granting it the right to subside the surface, the company must reach a separate subsidence agreement with the surface owner or obtain ownership of the surface.

Some deeds or lease agreements are very old, and the language found in them may not be clear on the issue of subsidence. Landowners are strongly advised to seek legal counsel if they have questions about mineral rights or subsidence rights for their property. If a landowner is approached by a coal company wanting to purchase either their mineral rights or the subsidence right, the landowner should seek the counsel of an attorney experienced in mineral rights issues.

Planned subsidence regulations require minimizing damage to structures unless waived by the owner. Most coal companies negotiate an agreement with the homeowner to protect surface structures during undermining. Figure 10 shows two photos of a house and garage raised from their foundations and kept level while it was being undermined and two photos of the house and garage replaced on new foundations after mining was completed. People lived in the house during this time. Figure 11 shows an unoccupied wood frame house, located on the centerline of a longwall panel, that subsided 4.5 feet. The white line painted on the house represents the level of the original ground surface. This very flexible wood frame house with asphalt shingle siding showed very little damage from these movements.

Mine Subsidence Insurance

In 1979, the Mine Subsidence Insurance Act created subsidence insurance for Illinois as part of a homeowner's policy. Homeowners in any of the Illinois counties undermined by approximately 1% or more automatically

Figure 10 The coal company took measures to protect this home in advance of subsidence. Structures were raised from the foundations and kept level during subsidence. Foundations were restored and structures lowered onto them after damaging ground movements ceased.

Figure 11 This unoccupied structure located above the centerline of a longwall panel was subsided 4.5 feet. The white line represents the level of the original ground surface.

have mine subsidence insurance as a part of their policy, unless coverage is waived in writing by the homeowner. This insurance is a built-in safeguard for the property owner. Mine subsidence insurance is especially important for homes located near or over mines that operated before the 1977 Surface Mine Control and Reclamation Act. The companies that operated these mines may no longer be in business. Homeowners should contact their local insurance agent or the Illinois Mine Subsidence Insurance Fund (IMSIF) for more specific information on mine subsidence insurance. Nearly 5,000 claims were filed during the first 10 years of the fund's existence. Murphy et al. (1986) stated that only 16% of claims to IMSIF through 1985 were attributed to damage caused by coal mine subsidence.

Information Sources

Information on current or previous mine workings is available from the Illinois Department of Natural Resources, Office of Mines and Minerals, in Springfield and the Illinois State Geological Survey in Champaign. Uncertainty and undue fears can be dispelled by obtaining adequate information. Owners should seek advice as soon as possible after damage to a building is suspected. Agencies to contact for additional information are listed at the end of this booklet.

Illinois Mine Subsidence Research Program

Concerns about the effects of coal mine subsidence on other valuable natural resources of water and farmland prompted research. The Illinois Mine Subsidence Research Program was established in 1985 to develop guidelines for underground mining methods to maximize coal extraction while preserving the agricultural productivity of farmland. Specific research was necessary to determine the impact of Illinois' geologic conditions on subsidence characteristics. Modern subsidence information collected in Europe, the United Kingdom, and the eastern United States showed that differences in geologic settings and mining depths produced different subsidence effects. Furthermore, all had geology that was different from that of Illinois. By collecting Illinois data, including new and critical data about aquifers and crops, IMSRP researchers acquired a base of fundamental knowledge about coal mine subsidence in the Illinois. With this information, researchers were better able to develop the basis for sound solutions to social and environmental issues facing the coal and agriculture industries.

The research program was initiated at the request of the Illinois Coal Association and the Illinois Farm Bureau. It was directed by the ISGS. Projects funded under the IMSRP were studies of the subsidence process from the ground surface down through the floor of the mine. Participants in the research projects included the ISGS, Northern Illinois University, Southern Illinois University at Carbondale, the University of Illinois at Urbana-Champaign, and the Twin Cities Research Center of the U.S. Bureau of Mines. The full summary of this program can be found in the publication of Trent et al. (1996), and some findings are summarized here.

Effects of Planned Subsidence

Farmland The first priority of the IMSRP was to assess the impact on farmland of subsidence caused by high-extraction mining through two agricultural studies, the first on the impact of mining methods and the second on the effects of mitigation techniques. In 1985, aerial surveys and field sampling were used to assess the relative impacts of longwall and high-extraction retreat mining on corn yields. For 3 years, corn yields in subsided areas were statistically compared with yields from unmined areas under the same farm management. Aerial photos were used to locate and classify subsided areas (fig. 12). The comparative results showed that yields varied yearly because of weather, mining activity, and farm management and that the overall impact of subsidence on crop yield was slight. The average corn yield reduction on mostly unmitigated land was approximately 5% over longwall mines and 2% over high-extraction retreat mines (Darmody et al. 1988). These percentages are relatively low because it was found that the problem areas within the subsided panel area, such as ponding, were not extensive (1 to 2 acres per mine panel).

Figure 12 Aerial photos were used to locate subsided areas (circles) for study of the effects of unmitigated subsidence on corn yields.

Mitigation Another IMSRP agricultural study investigated the effectiveness of efforts by coal companies to mitigate subsided land. This study was designed to determine the impact of current subsidence mitigation practices on crop yields. Soil scientists compared corn and soybean yields from mitigated farmland with yields from comparable non-subsided areas. Again, subsided areas that had problems such as ponding were not extensive (1 to 2 acres per mine panel). Soil fertility and other characteristics also were tested and compared. Results were influenced by unusually dry weather in 1988 and unusually wet weather in 1990. Corn plants in mitigated soils were generally more sensitive to wet weather than soybean plants in mitigated soils. A 4-year study determined no significant differences in average soybean yields on mitigated soils. Corn yields per acre, however, averaged 21 bushels (or 19%) less. Mitigation significantly improved corn yields in subsided areas. Yield reductions of 42% to 95% were reported in other IMSRP studies for unmitigated subsided areas (the 1- to 2-acre problem areas) (Darmody et al. 1988). Results were very site-specific, and some sites had no significant yield differences. Increased soil wetness can be an asset in dry years, such as 1988, when corn yields were slightly higher in mitigated areas than in unmined areas.

The study showed that all types of mitigation (ditch, fill, or both) can be successful. Rainfall amounts and other site-specific factors must be added into calculations of yield response at any site, regardless of mitigation methods used. A set of practices to improve mitigation success were identified, including avoiding soil compaction, minimizing the number of trips over the field with tractors and other farm equipment, using deep tillage, improving drainage, and adding sufficient fill to low areas (Hetzler and Darmody 1992).

Soils In an additional study, agronomists from the University of Illinois evaluated the effects of planned subsidence on agricultural soils. Soils above active longwall panels were described and analyzed before and after subsidence. Researchers monitored the ways water moved through soils before and after subsidence. Some soil types responded to subsidence and subsequent ponding differently from others, and some soils were found to require different management practices after subsidence. Seasonal patterns of rainfall distribution, including how precipitation affected the timing and duration of ponding, were also investigated. In a field study, water movements were traced in soils using dye before and after subsidence. Subsidence cracks at the edge of the mine panel were recognizable up to 8 months after subsidence, whereas the center of the mine panel had no visible post-subsidence cracks (Seils et al. 1992).

The water table initially dropped after subsidence but recovered almost to its original elevation. Areas where fill has been used to address closed depressions may benefit from installation of subsurface drain tile to improve discharge of subsurface water and prevent saturation of soils. A tracer substance used to evaluate water movement was found to move more rapidly through the soil after subsidence.

Overburden and Groundwater
Another priority of the IMSRP was to document the impact of planned subsidence mining techniques on the overburden (all the earth materials overlying the mine). The ISGS scientists monitored the hydrology and, indirectly, the amount and location of fracturing in bedrock over several active mining areas. A high-extraction retreat panel and several longwall panels were studied. Various types of instruments were used, including automatic recorders to measure water levels in test wells. Other equipment was used to document vertical and horizontal movements and possible fracturing in the overburden. Geologic information from drill holes was then correlated with data collected from instruments and analyzed before and after subsidence. At one site, a grid of monuments and other instruments was used to document three-dimensional surface movements during active subsidence; the instrumentation was arranged to simulate the dimensions of a residential foundation (Van Roosendaal et al. 1992). This was the first time some of this information was collected in Illinois.

The IMSRP was also concerned with the potential effect of subsidence on water resources. Geologists from Northern Illinois University and the ISGS monitored water levels in deep and shallow test wells before, during, and after subsidence (Trent et al. 1996, p. 43–49). The bedrock water-bearing aquifers in southern Illinois are not used as water sources because of their high saline content. Nevertheless, water levels in these units and in shallow aquifers were checked continuously by electronic recorders, and water chemistry and quality were evaluated. Results over several deep longwall panels showed that rural wells ending in glacial materials (sand, clay, and silt) were unaffected by subsidence. In settings where water-bearing bedrock was fairly extensive, water levels in test wells were temporarily lower, but recovered several months after mining (Booth 1992). When the aquifer was a small discontinuous body, the water levels did not recover because there was no large source of water to fill the newly formed porosity (small fractures) in the aquifer. The drop in water levels occurred because the volume of water filled more void space, created in the aquifer by the longwall subsidence wave moving through the bedrock.

Overburden, groundwater, and soils studies were conducted concurrently at the same active mining locations. This practice allowed researchers to compare and correlate information from the mine level to the ground surface. For example, information collected about fracturing in the overburden after subsidence helped to explain groundwater fluctuations. Scientists found that the water yield of bedrock aquifers was enhanced by longwall subsidence; however, this enhancement depended on the site-specific geologic factors that controlled the occurrence of groundwater. At the study sites, subsidence-induced fracturing improved the way water flowed through bedrock and enhanced the storage capacity of the bedrock aquifer.

Mine Design Another part of the IMSRP involved the study of the strength characteristics of the mine floor and pillars. Mine stability problems associated with weak floor conditions were addressed by on-site strength testing by researchers at Southern Illinois University at Carbondale. Researchers also monitored elevation changes of the ground surface over floor-squeeze areas of a room-and-pillar mine. Results of these investigations are applicable to all types of mines. These data led to the design of a computer model to predict movements of the mine floor and pillars on the basis of material properties.

Researchers also assessed the effectiveness of present mine designs. Understanding the current practices and problems found in Illinois underground mines was basic to creating a workable predictive model. Geologists and engineers from ISGS and Southern Illinois University surveyed several mines to identify geologic, mining, and operating conditions and procedures for the design of stable partial-extraction and high-extraction mines. Interviews were conducted with mine company staff, and observations were made underground. This information was then compared with map information and with other data provided by the mine operators. The findings were that many mines could benefit from more extensive pre-mining drilling and selected geotechnical studies of exploration cores to analyze potential ground stability problems more productively. In most mines, operators were extracting at rates consistent with the coal and immediate floor strata strengths. More analysis of conditions for shallow mines may lead to higher extractions of coal while maintaining a stable mine design.

Structures Research was also conducted on the effects of planned subsidence on foundations of buildings intentionally left in place and not protected from subsidence movements.

Several foundations were constructed and undermined by high-extraction retreat; another old home left in place was undermined by a longwall panel (Awasthi et al. 1991, Bennett et al. 1992). This research investigated practices used in other parts of the world, such as trenches filled with compressible materials around foundations, footings resting on compacted sand overlain with plastic sheets, and heavily reinforced foundation footings. Study participants include the Twin Cities Research Center of the U.S. Bureau of Mines, the University of Tennessee, the ISGS, the Illinois Mine Subsidence Insurance Fund, the Island Steel Coal Company, and the Old Ben Coal Company. Results indicated that those practices used elsewhere did not greatly reduce damage to the foundations in the Illinois setting. Therefore, the general practice of the coal companies is to rebuild the foundations (fig. 10).

Advantages of Planned Subsidence

The main advantage of planned subsidence is that subsidence is immediate and predictable. Additionally, the longwall system allows high extraction, even at great depth, allowing companies to produce more coal more efficiently from a given area.

Immediate and Predictable Subsidence Planned subsidence occurs immediately after mining in a predictable, manageable way. Subsidence due to older partial-extraction methods is unplanned and unpredictable and often occurs years or decades after companies have gone out of business. Coal companies are required to repair the effects of planned subsidence shortly after mining and into the future. An advantage of planned subsidence for the coal company is that a potentially smaller surface acreage is affected per ton of coal mined because high extraction removes more coal per given area.

Improved Mine Productivity An ISGS study concluded that Illinois coal producers needed to reduce the delivered cost of coal to customers to remain competitive (Bhagwat 1987). Illinois coal was losing markets throughout the United States because of its high delivered price and a sulfur content that is higher than that of coals from other parts of the nation. Increased mine productivity was shown to be the best way to lower the price. Longwall mining reduced some unproductive activities associated with room-and-pillar mining, such as moving equipment (shuttle cars, bolters, and continuous miners), roof bolting in production areas, and maintenance. These efficiencies increased productivity while maintaining a safe working environment. Since 2000, longwall mine productivity has been 40% higher per employee hour than room-and-pillar mines (Weisdack and Kvitkovich, 2005). Longwall mining concentrates equipment and workers to increase mine productivity, achieving better economic results for the coal companies and thus keeping them in business. The trend in the Illinois coal industry today is toward longwall mining, as it is throughout the United States and in other countries. Higher extraction rates also make better use of coal found in low-sulfur deposits because a greater percentage can be extracted, thus avoiding abandonment of one-half or more of this valuable resource.

Damage and Repair

The effects of subsidence from longwall mining depend on the topography of the land and the position and type of surface structures. As mentioned earlier, coal mine operators are now required by law to restore the land to its pre-subsidence capabilities and repair, replace, or compensate for subsidence damage to buildings. Repairs to land affected by longwall mining can be planned more easily than repairs to land that has randomly occurring depressions caused by older room-and-pillar methods. With planned subsidence, procedures to avert possible damage are established before mining begins.

Land As discussed earlier, subsidence can affect agriculture by changing the original topography of the land surface. After subsidence, closed depressions may form and pond water. The effects of ponding are weather-dependent. Crops can be damaged if surface water stands for significant periods in closed depressions. In dry years, however, these lower areas may actually benefit crops by retaining rainfall. Operators of coal mines using planned subsidence methods restore the land either by recontouring, improving drainage, or both. Soil material may be moved from nearby areas to fill in depressions, most commonly by constructing surface and subsurface drainage structures to remove excess surface water. With the consent of the landowner, a farm pond may be built if sufficient borrow material is required to fill the subsided areas.

When areas are mitigated, strategies learned from studies of soil replacement at surface mines are used to make decisions about moving soils in farming areas. Research has shown the importance of keeping the original topsoil as the top layer in reclaimed areas; soils with different chemical and physical makeup have been shown to be detrimental to growing crops. Consequently, when mitigation occurs after planned subsidence, the topsoil is generally removed and set aside. Then, the subsoil is filled in with soil from borrow areas to restore the drainage of the land. Finally, the original topsoil is replaced. This procedure ensures that the original chemical and physical makeup of the crop-growing medium is intact.

Any mitigated areas are subject to soil compaction problems from soil-moving machines; compaction may alter soil properties or diminish yields by inhibiting root growth. Again, technology and equipment to alleviate soil compaction are borrowed from soil replacement research at surface mines. The success of mitigation techniques in farming areas is related to managing compaction problems, replacing the original topsoil so that soil fertility and chemistry are maintained, and maintaining surface drainage so that ponding does not occur.

Structures Steps to avoid damage to structures during planned subsidence are usually taken before mining begins. For example, homes can be raised off foundations to a level position and then lowered after subsidence is complete. Installing flexible connections for water and utility service are examples. Measures taken to minimize subsidence effects depend on the position of the structure over the longwall panel and the building's stability, age, and materials. Structures generally are closely monitored during subsidence.

Roads, Railroads, and Pipelines State highways in Illinois have been successfully undermined by longwall operations many times. One of the first instances of Illinois highway undermining was extensively planned and monitored by the mining company and the Illinois Department of Transportation to ensure safety (Sneed and Sumner 1990). Traffic continued on the roads during and after subsidence, and final repairs to the roads were completed about one year after undermining. Roads have also been undermined in other states, where a similar process of planning, monitoring, and remediation is followed. Figure 13 shows before and after photos of a road that was subsided by longwall mining and was subsequently repaired. It is the responsibility of the mine to preplan with the road authority to coordinate such undermining and to pay for the repair. This same process applies to other infrastructure such as railroads (fig. 14).

In Illinois and other states, pipelines have been safely undermined without being taken out of service. From these experiences, pipeline operators and mining companies have outlined proper monitoring and intervention responses for successful pipeline undermining. Usually, the pipeline is exposed for monitoring and then covered again after subsidence (fig. 15).

Building Damage from Other Causes Homeowners who suspect their home is being affected by subsidence may notice the following signs: cracks in foundations, walls, or ceilings; cracks in the ground around the house; sticking doors and windows; chimney, porch, or steps separating from the house; and water or utility lines cracking or breaking (Bauer 2006).

Figure 13 Examples of a road subsided (a) over a longwall panel and (b) repaired.

Mine subsidence will trigger several of these symptoms in a short time, but other causes may be responsible if only one or two of these problems are occurring.

The shrinking and expanding of moisture-sensitive soils is a common cause of building damage that may be initially mistaken for mine subsidence. Murphy et al. (1986) found that the broad category of soil volumetric change accounted for 44% of the foundation problems investigated by researchers at the Illinois Mine Subsidence Insurance Fund. This category included soil problems such as shrink-swell, freeze-thaw, settlement by loading, hydrocompaction of fill, and settlement of uncompacted fill. Many decades of yearly cycles of shrinking and expanding soils, due to moisture changes, can build up pressure on foundation walls and cause cracking and other damage. Around a home, saturated soils caused by poor drainage or inadequate gutters and downspouts can also cause foundations to tilt or sink (Bauer 2006). More information

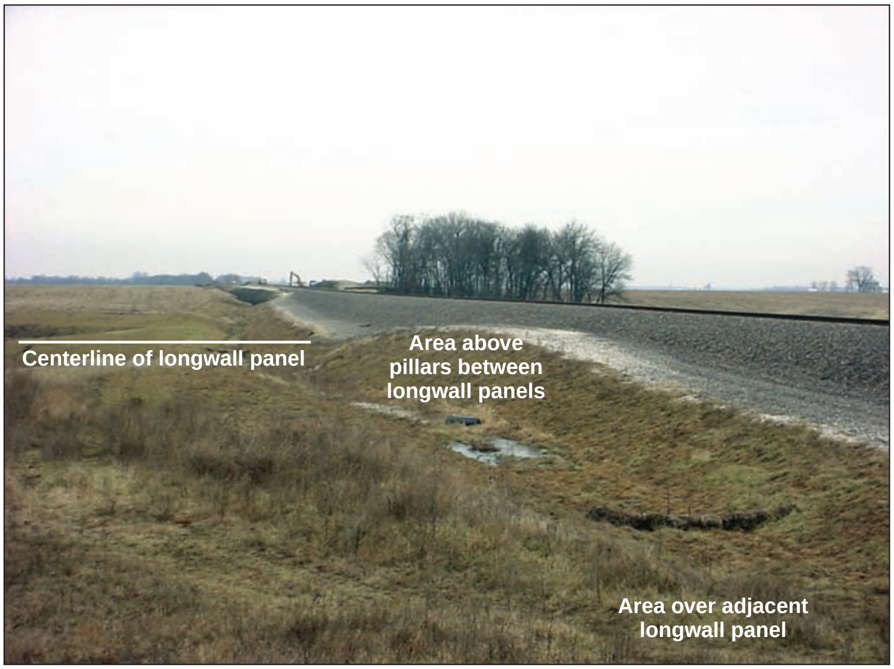

Figure 14 This railroad grade was re-established after longwall coal mine subsidence by increasing the vertical amount of crushed rock (ballast) below rails where longwall panels crossed under the tracks. (Photograph by Dan Barkley.)

Figure 15 This subsided pipeline (dip in pipeline) was successfully undermined by several longwalls. It was uncovered and monitored during subsidence.

about structural damage not due to coal mine subsidence is available elsewhere (Bauer 1983, 2006). Additional information about the effects of soils, geology, and weather on movements of survey monuments and other structures given by Bauer and Van Roosendaal (1992).

Market Competition

Illinois coal is not only losing markets because of its high-sulfur content but also because of its high delivered price. Increased productivity through longwall mining reduces mining costs per ton. Lower production costs for coal eventually result in lower electricity bills for consumers. Greater mining productivity can be achieved by optimizing the use of workers and machinery. High-extraction mining methods help companies to reach this goal. Also, a safer work environment is provided by the use of longwall mining equipment.

In the 2007 census of longwall mines, 52 longwall systems were operating in the United States; 4 of these systems were in Illinois (Fiscor 2007). The 2005 annual report of the Illinois Office of Mines and Minerals noted that the longwall method of mining accounted for 53% of the coal extracted by underground mines in Illinois. Nationwide, since 2000, longwall mine productivity has been 40% higher per employee hour than room-and-pillar mines (Weisdack and Kvitkovich 2005). Many persons view longwall mining as Illinois' best bet for staying competitive with other states that produce coal.

The effects of subsidence from longwall mining are immediate, planned, and known. The homeowner, farmer, and mining company can prepare for and manage these effects. By law, mining companies that have the right to subsided the ground surface and are using the planned subsidence method must plan for and repair damage to land and structures affected by subsidence.

Greater efficiency is achieved with longwall mining. Higher extraction rates allow companies to make the best use of low-sulfur coal deposits, a factor that became crucial because of the 1990 Clean Air Act amendments. Coal is a nonrenewable resource, and planned subsidence methods maximize the use of available coal reserves.

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Mined-out Area Maps, General Information
Illinois State Geological Survey
615 East Peabody Drive
Champaign, IL 61820-6964
217-333-4747
http://www.isgs.uiuc.edu/

Assistance with Abandoned Mine Subsidence
Division of Abandoned Mined Lands Reclamation
One Natural Resources Way
Springfield, IL 62702-1271
217-782-0588
http://www.dnr.state.il.us/mines/aml/index.htm

Mine Subsidence Insurance
Illinois Mine Subsidence Insurance Fund
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217-782-7500
and
100 W. Randolph, Suite 3-400
Chicago, IL 60601
312-814-7179
http://www.commerce.state.il.us/dceo/

Coal Industry Information
Illinois Coal Association
212 South Second Street
Springfield, IL 62701
217-528-2092,
http://www.ilcoalassn.com/

Active Mine Permit Information
Office of Mines and Minerals
One Natural Resources Way
Springfield, IL 62702
217-782-6791
http://www.dnr.state.il.us/mines/