Mine Subsidence in Indiana

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Extent of Subsidence

In Indiana the first shaft for the underground mining of coal was sunk during 1850 near Newburgh in Warrick County. Since that time 900 million tons of coal has been produced in the state by underground mining. Because the average thickness of coal mined underground during the past 130 years is about 5 feet, the total undermined surface area is about 100,000 acres, or 150 square miles. Room-and-pillar mining, which commonly leaves 20 to 50 percent of the coal on a property as pillars for supporting the overburden, has always been the dominant method of deep mining in Indiana.

Peak annual production by underground mining of about 30 million tons was achieved in 1918. Soon after that date surface mining surpassed deep mining in importance, and by 1979 only about 800,000 tons of coal was being produced in Indiana from underground mines. Therefore, the problem of mine subsidence in this state is confined to old abandoned mines, since active operations affect a relatively insignificant area each year.

The undermined acreage in Indiana is concentrated in 12 southwestern counties (fig. 1). The most extensive underground mining has been in Vermillion, Vigo, Sullivan, and Knox Counties. There has been less activity in Parke, Clay, Greene, Daviess, Pike, Gibson, Warrick, and Vanderburgh Counties.

With a population of 130,000 people, Evansville is the largest urban area lying close to extensively undermined territory. Other cities include:

- Terre Haute ............... 61,000*
- Brazil ......................... 8,000*
- Princeton ..................... 9,000*
- Linton ......................... 6,000*
- Clinton ...................... 5,000*
*1980 population estimate

In the entire United States an estimated 25 to 50 percent of all undermined areas have already subsided to some extent, and most of the rest of the undermined land will also eventually be affected by subsidence (Breslin and Anderson, 1976).

Effects of Subsidence

Mine subsidence may create a variety of effects on the surface, including sinkholes, sags, and troughs. Sinkholes, which completely rupture the surface, are mostly relatively small in diameter but may be deep (fig. 2). Sags and troughs are more subtle settlements of the surface but may be large in diameter. Both sinkholes and troughs may accumulate surface water, and because only 4 inches of displacement may disrupt field tile and produce ponding, many sinkholes and troughs hinder or prevent agricultural cultivation where they occur (Wiram and others, 1973) (fig. 3). In some areas extensive subsidence may eventually create swampy conditions. Damage to aquifers and alteration of the flow of ground water also frequently result. Some local residents use sinkholes as trash dumps, and exceptionally deep or active holes are used for decades before they become filled.

Where homes or buildings are present, damage may range from hairline cracks in plaster and windows that tend to stick to complete destruction (Voight and Pariseau, 1970). Only an inch of subsidence can cause serious damage to foundations, and masonry structures tend to be damaged more than wooden ones (Paone, 1977). Undermined houses may lose some of their resale value even though subsidence has not yet taken place (Bise, 1980). Some states that still produce large quantities of coal by underground mining have established programs providing subsidence-damage insurance (Illinois State Geological Survey, 1980).
Figure 1. Map of southwestern Indiana showing location of major underground coal mines. Modified from Preliminary Coal Maps of the Indiana Geological Survey.
RECOGNITION OF SUBSIDENCE

Figure 2. Sinkhole near Linton showing complete rupture of the surface.

Cracks in streets and highways and breaks in gaslines and waterlines are other common forms of damage from subsidence.

Recognition of Subsidence
Where its effects are sudden and dramatic, such as sinkholes or severe damage to manmade structures, subsidence is easily recognized. But when troughs and ponds form in woodlands and pastures, they may not even be noticed by the property owner. Even large sinkholes, partly filled with soil or water, or overgrown with brush and trees, may not be noticeable to a casual observer several years after their formation. In residential areas damage is generally quickly repaired. Therefore, both in rural and urban areas damage from subsidence may pass unnoticed or soon become difficult to recognize, and many owners forget or are reluctant to mention such damage to prospective buyers. The problem of recognizing certain types of damage from subsidence is compounded by its similarity to damage created by unrelated causes. In many undermined areas, damage from poor construction, freeze-and-thaw cycles, differential settlement of foundations, and subsidence due to withdrawal of ground water cannot be differentiated from damage due to mine subsidence (Voight and Pariseau, 1970).

Old subsidence or subtle subsidence can be more easily recognized in some places by using aerial photographs than by observing from the ground. The season and the year in which the photograph was taken may be critical. Certain types of subsidence are made evident by moist conditions in the spring (Popp, 1977), while dry sinkholes filled with brush may be most evident in the winter when there is less vegetative cover.

Inspection of aerial photographs taken above 44 mines in Indiana where subsidence is known to have occurred reveals several basic types of features:

1. Shadowlike patterns created by standing water or water-saturated soil. These are generally most evident in cultivated fields (fig. 4A), although at least one good example occurs in a wooded flood plain along Busseron Creek in Sullivan County (fig. 4B). These are easily attributed to subsidence when the pattern consists of regularly spaced, rectangular dark spots that correspond to aspects of the mine layout. Some of the dark patterns are more irregular and diffuse, and these may be confused with patterns created by causes other than subsidence.

2. Ponds. Ponds occurring in a line (fig. 4C) or clusters of ponds that have clearly interfered with the cultivation of fields (fig. 4D) strongly suggest formation by mine subsidence.
Figure 3. Large trough near Linton.

(3) Furrowlike patterns. This distinctive pattern does not mimic any naturally occurring features and reveals exact details of some mine plans (fig. 4E). It characteristically occurs where overburden is thin, and it is the least common of the four basic patterns.

(4) Craters created by the formation of sinkholes. A few areas in Indiana appear on aerial photographs similar to the lunar surface (fig. 4F). Where such severe damage occurs, much of the land is allowed to become overgrown in trees and brush, and the effects of subsidence may soon become difficult to detect on aerial photographs.

The patterns described in 2 and 4 above are evident as clusters of ponds or depression contours on some 7\(\frac{1}{2}\)-minute topographic quadrangle maps published by the U.S. Geological Survey.
MINE SUBSIDENCE IN INDIANA

June 28, 1937

May 31, 1949

Figure 5. Aerial photographs taken above the Baker No. 28 Mine before and after subsidence. Mining of the area occurred in the late 1940's.

Using satellite imagery to detect subsidence has been tried (Amato and others, 1974), but this method has limited potential in Indiana. Using aerial infrared imagery, which accentuates moist areas, could aid in determining the location and extent of many previously undiscovered subsidence sites.

Even though the effects of mine subsidence may be obscure and difficult to recognize, they can be persistent. Some sinkholes or troughs that are evident today can be recognized on aerial photographs taken more than 30 years ago (fig. 5), and some may be as much as 80 years old. A large sinkhole that formed near Terre Haute (Vigo County) in 1979 was partly filled by weathering a year later, but the slope of the hole remained essentially vertical (fig. 6).

The Indiana Geological Survey has identified 44 abandoned mines in six counties where subsidence can be recognized (fig. 7). These areas affected by subsidence altogether contain hundreds of sinkholes and troughs. The most extensive damage observed to date is near Linton (fig. 8) and Brazil. About 6,600 acres of the total area shown in figure 8 have been undermined. Damage from subsidence recognized to date covers about 850 acres, or about 13 percent of all undermined areas. Much mining in the Linton district was at shallow depths, and sinkholes are prevalent. The proximity of large surface mines to the underground works may also have contributed to the extent and the severity of subsidence in the illustrated area.

Factors Affecting Subsidence

Among the factors recognized as affecting subsidence are: (1) time elapsed since mining, (2) depth of the mine, (3) presence or absence of water in the abandoned mine, (4) type and thickness of rocks and sediments overlying the mine, and (5) method and plan of mining.

In modern mining, inducing complete and uniform subsidence during mining is often tried. Damage is often negligible or does not occur, and the property owner need not worry about unpredictable subsidence in the distant future. In the old abandoned room-and-pillar mines of Indiana, however, subsidence may occur many years after the mine is closed. Subsidence may occur above certain parts of mines during or shortly after mining, but subsidence above other parts of the same mine may be delayed. Gradual deterioration, first of the timbers used for temporary
support within the active mine and then of
the coal pillars, may result in subsidence
many decades (even a century or more) after
the mine is abandoned. As previously
mentioned, underground mining of coal in
Indiana reached its peak in 1918 and then
decreased to its present relatively insignificant
level of less than a million tons per year.
Therefore, 90 percent of undermined areas
were worked out more than 30 years ago, and
50 percent of these areas were worked out
more than 60 years ago (fig. 9). While
recurrent subsidence on a given property may
take place at widely spaced intervals of time,
one can expect the frequency of subsidence
for the state as a whole to decrease each year.
At mines identified by the Indiana Geological
Survey as having created severe subsidence
damage, subsidence occurred at least 20 years
to the 80 percent of the sites. During 1979
and 1980 only three new occurrences of
subsidence were reported to the Survey, but
estimating the number of occurrences that
were unreported or unnoticed is impossible.
Figure 7. Map of southwestern Indiana showing location of subsidence sites investigated by the Indiana Geological Survey.
Figure 8. Map showing areas with recognizable subsidence south of Linton.
Figure 9. Cumulative production of coal by underground mining in Indiana. Data from the Indiana Bureau of Mines.

Above shallow underground mines (20 to 100 feet deep), collapse of roof strata is almost certain to reach the surface (Wiram and others, 1973), but sinkholes seldom develop where overburden is greater than 150 feet. Below 150 feet the amount of subsidence, which generally takes the form of sags or troughs, depends largely on the geometry of the mine (Hunt, 1978). Although subsidence has occasionally been reported above mines as deep as 600 feet, the U.S. Bureau of Mines has estimated that only 10 percent occurs above mines more than 400 feet deep. At 450 feet the King’s Station Mine (Gibson County) was the deepest mine in Indiana’s history. But mining in Indiana has mostly occurred at an average depth of less than 150 feet. As a result, much of the undermined area of the state is subject to the most severe forms of subsidence damage, such as sinkhole formation. Depths of the 44 mines investigated by the Indiana Geological Survey range from 15 to 385 feet and average 100 feet.

Interesting to note, a misconception arose among the property owners and other investigators soon after the sinkhole diagramed in figure 6 was formed. What appeared from the surface to be a rock ledge in the bottom of the hole seemed to indicate that the actual mine workings had been exposed, and some feared that methane gas might be escaping from old works. Geologic records later revealed that the mine itself lay more than 100 feet below the bottom of the hole.

Some underground mines remain dry after abandonment, and others fill with water. Circulating ground water can seriously deteriorate pillars, weaken roof strata, and promote caving of the overburden to the surface (Panek, 1973). The occurrence of many sinkholes in Illinois coincides with the presence of water in mines (Hunt, 1978). River and stream flood plains in Indiana, such as those along Busseron Creek in Sullivan County, are especially prone to subsidence (Amato and others, 1974). Pumping water from an abandoned mine can greatly increase the chances of subsidence (Glover, 1977), and such pumping was formerly common. Some underground mines, such as the Miami No. 10 (Vigo County) and the Submarine Mine (Vigo County), were connected to older water-filled mines and were required to pump water out of the older works to prevent flooding of the active operations. Some abandoned mines provided useful water for active operations. For example, the Linton Supreme No. 23 Mine, a surface mine in Greene County, abutted some old underground mines from which water was used for operating a coal washery. The Talleydale Mine, an underground mine in Vigo County, pumped water from the neighboring Submarine Mine to provide cooling water for an air-conditioning system. In other places drainage of abandoned mines may occur unintentionally, as in 1962 when the Laughlin-Beck Mine (Greene County) accidently broke into the abandoned Vandalia No. 6 Mine and was flooded and forced to close. The owner of some property overlying the Vandalia No. 6 noted that several acres of pasture became marshy shortly afterward. Even today some active surface operations abutting underground mines must pump large quantities of water from abandoned works.

The material overlying a mine can be broadly divided into two categories: (1) stratified rock (bedrock) and (2) unconsolidated sediments (surficial deposits). Most of the bedrock overlying mines in Indiana consists of shales and siltstones. Substantial thicknesses of sandstone may also occur, but
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limestone beds are a relatively small part of the overburden. But when a thick bed of limestone or sandstone does occur above a mine, it may be sufficiently strong to prevent caving of the strata.

Except for a few underground mines in extreme southern Indiana, nearly all underground mines in the state are also overlain by surficial sediments. These sediments are primarily glacial or glacially derived, but some mines have also worked under sediments deposited by modern streams and rivers. These sediments may vary greatly in thickness over short distances, and the most severe subsidence occurs where the ratio of surficial to stratified overburden is large (Popp, 1977). As the Wick Mine (Pike County) drove under the Patoka River, the thickness of solid material was reportedly as little as 10 feet in some places. Breakthroughs to the surface or to water-bearing unconsolidated sediments occurred at the Binkley No. 10 Mine (Vigo County), the Submarine Mine (Vigo County), the Dresser Mine (Vigo County), and undoubtedly at other mines as well.

The amount and character of subsidence also depend on the system used in mining. The type of resulting damage may vary from one part of the mine to another. Severe damage is more likely to occur where the mining pattern is irregular, where the extraction ratio is high (that is, where less than 40 percent of the coal was left in the form of pillars), and where the width of rooms or sets of rooms (panels) was large (Hunt, 1978). Before 1900, mining in many places was highly irregular and haphazard (fig. 10). The mine entries tended to wander, turning or deflecting whenever the slightest problem was encountered in mining, such as increasing seam hardness or roof instability. This unsystematic exploitation not only wasted coal resources but also created a greater potential for subsidence by leaving small or irregularly shaped pillars. Such exploitation could even endanger the existence of the operation by weakening the roof strata above vital haulageways or causing collapse of the shaft. In 1881 the state mine inspector noted that many operators ruined their mines by crowding large numbers of men into the mine where "... they are gouging and robbing the coal around the bottom of the shaft" (Indiana Inspector of Mines, 1882?, p. 73). Serious subsidence often occurs near the shafts of old mines, such as those prevalent in Clay County.
As coal mining in Indiana became more concentrated in large companies that employed engineers and experienced coal operators, the scientific exploitation of coal properties was emphasized more. Patterns of mining became more regular and systematic (fig. 11), and by World War I most coal produced in Indiana came from mines where greater adherence to predetermined mine plans was attempted.

Access to a block of coal was generally gained by driving two parallel tunnels referred to as “main development entries” (fig. 12). For ventilation these main entries had to be connected by short crosscuts at regular intervals. Most main entries were relatively narrow, and closely spaced timbers supported the roof. Containing track and serving as the main haulage routes, these entries had to have a long life. In Indiana mines each main entry was generally only 12 to 18 feet wide, and wide barrier pillars (typically greater than 18 feet) on both sides provided additional support for the roof. From the main entries cross entries were driven perpendicularly at regular intervals, and as these cross entries advanced, rooms were developed perpendicular to the cross entries. The room began as a narrow neck (only about 6 feet wide) to ensure the stability of the cross entries. After about 9 to 15 feet the rooms were widened to their standard width. The optimum width and length of rooms were arrived at by trial and error; wider and longer rooms were possible where the roof was stronger and stabler. In most Indiana mines room widths ranged from 20 to 30 feet, but wider rooms were possible in some mines under exceptionally good conditions. Room lengths varied widely and generally ranged from 175 to 400 feet, though some exceptionally favored mines had rooms 600 feet long. Narrow pillars, 6 to 23 feet wide, were initially left between the rooms, and the entire panel or set of rooms would be expected to cave in within a short time. On many mine maps these areas were designated as “worked out” (fig. 13). The number of rooms that could be turned off a given set of cross entries also depended on the natural stability of the roof. In Indiana this number ranged from 10 to 32.

Above the panels, particularly when pillars were removed, subsidence could be expected to occur during or soon after mining, and once it had occurred, a recurrence was not
Figure 14. Section showing the relationship of large shallow troughs to a panel within the underlying mine. Note that the area affected on the surface may be larger than the area of the panel. The depth of the mine may exceed 150 feet, and the surface displacement will be less than the original height of the rooms.

Likely, subsidence above these areas is characterized by large shallow depressions (fig. 14) that are particularly evident in flood plains and that may occur in areas with relatively thick overburden.

Where overburden is shallow and pillars have not been removed, the caving of entire panels may give rise to the furrow type of pattern.
width of opening typically 14 to 40 ft

weathering of coal creates wider opening

total height of initial rock fail may be 2.2 ft

unconsolidated sediments

sharified rocks

water table

unconsolidated sediments
Figure 15. Cross sections and photograph showing possible stages in the formation of a sinkhole. A, Initial condition of the mine opening, with a stratified roof and a soft clay floor. B, Development of roof instability accompanied by weathering of the coal pillars and squeezing of the clay floor into the opening. C, Initial catastrophic failure of the roof strata. The cavity at the top of the rockfall is smaller than the original mine opening. D, Cleanup of the rockfall. If the fall occurs in an active part of the mine, the miners may remove the broken rock and create an extremely large cavity. E, Additional rockfalls may occur after the mine is abandoned, but if the cavity is large, swelling of the broken rock will not fill the cavity. F, Upward migration of the cavity by successive rockfalls may be permanently halted by a thick, strong rock stratum (generally limestone or sandstone). G, Photograph showing that upward migration of the cavity may be terminated by successive rockfalls if the cavity is filled by swelling of the broken rock. Photograph was taken at an active surface mine in northern Clay County. H, Breakthrough of the cavity to the surface. If the mine is not too deep and if no unconsolidated sediments are present, a depression may form on the surface. I, If thick unconsolidated sediments are present on the surface, a deep sinkhole may form as the loose material is washed down through the broken rock and into the mine. The depth of the sinkhole may greatly exceed the height of the original cavity as sediment washes into the mine. J, If the water table is undisturbed, only a small sag may form at the surface.
The formation of deep sinkholes long after a mine is abandoned apparently tends to be more prevalent above the main development entries or around the edges of the mine. Narrow, heavily timbered, and protected by barrier pillars, the main development entries were designed to be long lived, and it may take many years for subsidence to work its way to the surface.

Development of a sinkhole may follow one of several courses, depending on the character of the overburden. If a mine entry or room is initially driven too wide, failure of the roof may occur during or soon after mining. If the entry is initially driven narrow, it may gradually widen by deterioration and spalling of the coal in the adjacent pillar during the years after the mine is abandoned (fig. 15A and B). Kelly (1952, p. 10) noted that in the King's Station Mine (Gibson County) "... the average entry will widen at a rate of approximately one foot per year." If the entry becomes too wide or if there is a natural weakness in the rock constituting the roof, the rock strata will sag and then fall. The initial cavity in many mines is a few feet to 25 feet high (fig. 15C). When rock falls in the main haulage or ventilation entries of active mines, it must be cleaned up and removed (fig. 15D). Rock may fall repeatedly, and cavities reaching upward more than 25 feet are not uncommon (fig. 15E). After hours, days, or years, more rock may fall, and the cavity may gradually work its way upward to the surface. Caving may terminate at a thick limestone or sandstone unit sufficiently strong to bridge the cavity and support the overlying material (fig. 15F). Because broken rock tends to fill a larger volume than undisturbed rock, the broken material is said to swell. If the mine entry is small and deep, the entire cavity may eventually reach a stable arched configuration or may fill itself, and caving will cease (fig. 15G).

If the mine entry is shallow or initially large, the cavity may eventually reach the surface (fig. 15H). If no unconsolidated overburden is present, the surface displacement will always be less than the height of the original cavity because of swelling. But if unconsolidated material is present over the bedrock, large and deep sinkholes may form as the unconsolidated sediments are washed down through the broken rubble and into the mine workings (fig. 15I). Such conditions are encountered in some active mines. At the Dresser Mine Given (1935, p. 373) noted:

*Any roof breaks in the worked-out sections are quite likely to extend up to the wash, with resultant inflow of water and, in some cases, of the wash itself, which is sufficiently loose to flow readily through cracks of any size.*

In these places the depth of the sinkhole may be limited only by the thickness of unconsolidated overburden. If the mine is below the water table and already filled with water, the loose sediment cannot be washed downward, and only a relatively small sag will form at the surface (fig. 15J).

**Sources of Information**

Information concerning underground mines and potential subsidence at a particular locality is desired by many prospective purchasers of property or by many individuals planning to build houses or other structures. Original maps of some mines are available at county courthouses, but the most complete file is at the Indiana Bureau of Mines and Mining, 105 East Main Street, Washington, IN 47501. Most of these maps have been photographed and are on file at the Indiana Geological Survey, 611 North Walnut Grove, Bloomington, IN 47405. Maps of selected counties and quadrangles showing mined-out areas and providing information on age, depth, and other characteristics of the mines are also available at the Survey.

Aerial photographs covering most of the undermined areas in Indiana are available for study at the Indiana Geological Survey and at offices of the Soil Conservation Service in each county seat. Some photographs may be purchased from the U.S. Geological Survey, EROS Data Center, Sioux Falls, SD 57198.

Where expensive structures are being planned and where doubt exists concerning the extent of undermining, a program of drilling may be necessary to determine if a mine is present. Drilling must take into account possible unmined pillars of coal; the proper spacing of drill holes is critical to proper evaluation.

If a prospective building site is known to be
undermined, backfilling the mined-out space or using special construction techniques that could minimize any damage arising from future subsidence might be considered.

Summary
About 100,000 acres of southwestern Indiana are undermined, but there are no estimates of the total acreage of subsidence damage. Subsidence is indicated by the formation of sinkholes, ponds, and troughs, alteration of the flow of ground water, and damage to manmade structures. The effects of subsidence, which are long lasting in many places and may not be eliminated by natural processes for decades or centuries, may be difficult to recognize and must be studied in the field and on aerial photographs. The character and areal extent of subsidence, as well as the time elapsed before its formation, depend on the layout of a mine, the methods used in mining, the depth of a mine, the character of the rocks and sediments overlying a mine, the flow of ground water through the workings, and later human activity, such as surface mining.

Because the initial stages of subsidence are hidden and because so many factors are involved, predicting subsidence above abandoned room-and-pillar mines for a particular locality is impossible. But as more information is gathered, determining probabilities of subsidence for selected sites may be possible.

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