Subsidence from Underground Mining: Environmental Analysis and Planning Considerations

GEOLOGICAL SURVEY CIRCULAR 876

COVER PHOTOGRAPH:

Subsidence pits, troughs, and cracks above an abandoned coal mine in the western Powder River Basin, Wyoming. Photograph by C.R. Dunrud.

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By F. T. Lee and J. F. Abel, Jr.

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1983

United States Department of the Interior

JAMES G. WATT, *Secretary*

Geological Survey

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

Lee, Fitzhugh T.
Subsidence from underground mining.

(Geological Survey circular ; 876)
Bibliography: p.
1. Mine subsidence—Environmental aspects.
2. Mine subsidence. I. Abel, John F., Jr. II. Title.
III. Series.
QE75.C5 no. 876 557.3s [622] 82–600123 [TD195.M48]

Free on application to Distribution Branch, Text Products Section, U. S. Geological Survey, 604 South Pickett Street, Alexandria, VA 22304

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By F. T. Lee and J. F. Abel, Jr.[1]

ABSTRACT

Subsidence, a universal process that occurs in response to the voids created by extracting solids or liquids from beneath the Earth's surface, is controlled by many factors including mining methods, depth of extraction, thickness of deposit, and topography, as well as the in situ properties of the rock mass above the deposit. The impacts of subsidence are potentially severe in terms of damage to surface utility lines and structures, changes in surface-water and ground-water conditions, and effects on vegetation and animals. Although subsidence cannot be eliminated, it can be reduced or controlled in areas where deformation of the ground surface would produce dangerous or costly effects.

Subsidence prediction is highly developed in Europe where there are comparatively uniform mining conditions and a long history of field measurements. Much of this mining has been carried out beneath crowded urban and industrial areas where accurate predictions have facilitated use of the surface and reduced undesirable impacts. Concerted efforts to understand subsidence processes in the United States are recent. Empirical methods of subsidence analysis and prediction based on local conditions seem better suited to the current state of knowledge of the varied geologic and topographic conditions in domestic coal mining regions than do theoretical/mathematical approaches. In order to develop broadly applicable subsidence prediction methods and models for the United States, more information is needed on magnitude and timing of ground movements and geologic properties.

INTRODUCTION

The worldwide need for energy resources requires increased production of coal and other fuels. A large amount of this production will eventually come from underground mining in areas where surface mining is impractical or uneconomical. Past coal mining practice left much coal in the ground as pillars that are difficult to recover. Present-day emphasis is on improving extraction percentage. Because both the methods of extraction and the number of mines will increase overall subsidence risk, we must be able to accurately predict the surface and underground impacts of subsidence and, if necessary, to suggest means to lessen these impacts. It is clear from poorly controlled mining operations of the past that we no longer have the luxury of mining without regard to present and future land use.

The purpose of this circular is to give an overview of subsidence processes and their potentially harmful consequences, the methods of subsidence prediction, and methods to control and reduce subsidence impacts. The report is primarily intended to serve as an introduction and state-of-the-art review for those individuals or groups concerned with assessing the potential environmental effects of underground mining. The major emphasis is on coal mining.

The time to plan for subsidence impacts is well before mining begins, not after surface effects are noticed. Because subsidence due to underground mining may be inevitable, the relevant questions to be asked are how much, when, and where, and what abatement procedures are possible and might be necessary. The impacts of subsidence are broad, affecting water supplies, transportation and utilities, vegetation, and farming. In addition, in situ extraction techniques for coal gasification and oil shale retorting are supported by extensive, costly surface facilities. The success of these oper-

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ations may depend upon accurately estimating the extent of subsidence, both in area and strain magnitudes, so that surface plants are not damaged or located unnecessarily distant from the mining operations.

Recent Federal regulations implementing the Surface Mining Control and Reclamation Act of 1977 (Federal Register, 1977) will encourage increased consideration of subsidence effects prior to mining. At present, however, very few mining companies in the United States make routine leveling surveys of the ground surface. Increased surface monitoring is needed in order to implement current mining regulations.

To a greater or lesser degree each mining area is different, and no one subsidence prediction method will serve equally well for all cases. For example, the prediction scheme used in the United Kingdom with excellent results for longwall coal mining[2] does not work as well in other areas largely because of different geologic conditions. The great diversity of mining conditions in the United States partly accounts for the circumstance that subsidence prediction is not far advanced in this country. A systematic concentrated effort is needed to develop more broadly applicable and accurate methods of subsidence prediction in the United States. The more general and widely used analytical techniques are discussed here; the reader is cautioned that many circumstances will require specific expert advice.

The term "mining" as used in this report includes all extractive processes for recovering organic and inorganic resources. Thus, we are concerned with deformations caused by several mining methods in a variety of geologic environments. Most emphasis in this report, however, is placed on longwall and room-and-pillar mining of coal. It has been estimated that coal extraction is responsible for over 90 percent of worldwide mining-induced subsidence (Allen, 1978). Longwall mining currently accounts for less than 10 percent of the coal mined in the United States, although it has long been the most popular method in Europe. However, because longwall mining, which removes a complete tabular section of coal, is more efficient than room-and-pillar mining, it is being promoted increasingly in the United States. Also, longwall mining induces a generally uniform and contemporaneous surface subsidence that can be more accurately forecast than subsidence caused by room-and-pillar mining. The current state of knowledge of subsidence permits a more detailed discussion of longwall-induced subsidence than of the other forms.

[2]Technical terms used herein are defined in the glossary, p. 25.

OVERVIEW OF SUBSIDENCE PROCESSES

DEFINITION

Subsidence is a time-dependent process, either natural or man induced, in which there is a lowering of the ground surface in response to the removal of gas, liquid, or solid matter. Deformation of the rock mass may be by either elastic, plastic, or brittle processes or by any combination of these processes. Subsurface deformation leading to surface subsidence includes the local lateral and upward displacements of rock above unmined areas (near mine boundaries or barrier pillars) caused by the downward movement of overburden into mine cavities. Strains induced by mining and transmitted through intervening strata to the surface may be compressive or tensile and may have both horizontal and vertical components.

CONCEPTUAL DESCRIPTION OF SUBSIDENCE

The void created by the underground extraction of coal or other resources causes significant changes in the magnitude and orientation of the in situ stress field and results in deformations both in the remaining coal and in the surrounding rocks. In general, the sides of the excavated area move inward, the floor upward, and the roof downward. The initial deformations may be elastic, that is, they may disappear if the deforming forces are removed. Nonelastic deformations, however, occur with time and, as the region of cavity influence increases with continued extraction, rock strengths are exceeded and irreversible block movements take place. Large bending moments in the mine roof strata will ultimately cause local roof failure and collapse, and the mined-out area will fill with overburden materials. The downward movement of overlying rock will induce lateral movement of rock toward the cavity. These deformations are illustrated in figure 1. Rock outside the vertical limits of the mined area will also subside. The affected ground will lie typically 10°–35° outside the vertical limits of the mined area (angle of draw). Deformations eventually reach the ground surface and may form subsidence depressions, open fractures, pits, and troughs. Com-

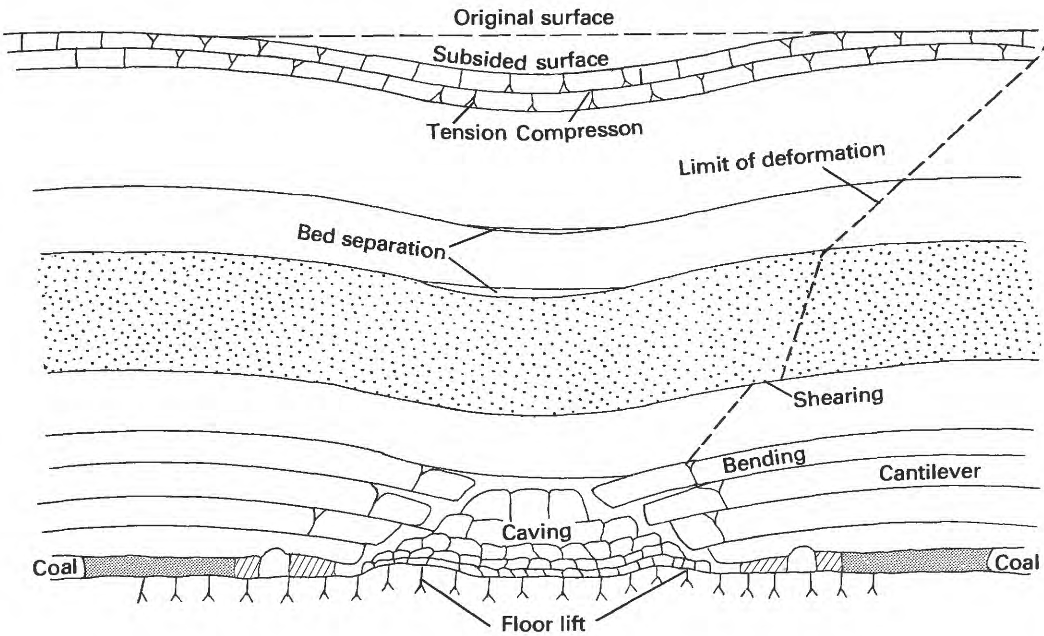


FIGURE 1.—Deformations produced in rocks above and below an extracted coal seam (modified from Shadbolt, 1978).

pression features including doming and thrust faulting have also been reported.

Depending upon several factors including mining methods and rock properties, the changes at the surface may occur almost concurrently with mining or they may be delayed and take place with dramatic suddenness more than 100 years after mining.

SUBSIDENCE PRODUCED BY LONGWALL COAL MINING

The mechanical aspects of the subsidence process in flat-lying coal bearing rocks mined by longwall methods are reasonably well known, compared to room-and-pillar mining, and are documented abundantly in the literature. This knowledge may be summarized as follows. When an underground coalbed of a given thickness is extracted over a wide area, the immediate roof will collapse. Rock displacements are transferred to the ground surface when the ratio of the width of the extracted material to the depth of overburden (*w*/*h*) exceeds a value which varies from 0.1 to 0.5 (Wardell and Eynon, 1968); the ratio value is controlled largely by the strength and structure of the rock overlying the mined-out area. Field measurements and theory support the concept that there is a stabilizing compression (or pressure) arch in the solid rock above and below the mined-out area. The duration of this arching effect is controlled by the height, width, and length of the mined opening, and subsidence will not begin until a critical void size is exceeded at which the arch will no longer span the excavated area. Consequently, there is often a delay between the onset of a change in state underground and the first appearance of land subsidence at the ground surface. The arching effect may be limited, however, by very weak overburden rocks or by poor mining practice that significantly weakens the overburden. Geologic conditions, mining depth, and seam thickness also affect arching behavior.

After subsidence has begun, it will develop progressively and continue so long as there is a progressive enlargement of the underground opening. Surface effects from longwall mining in mountainous terrain in New Mexico are illustrated in figures 2–4. These conditions occurred essentially contemporaneously with mining.

The concept of a "critical" area (width and length) of extraction is closely related to the ability of the strata above the excavated area to support loads across the mined openings. Assuming an infinite length for an extracted area (in practice

FIGURE 2.—Compression ridges produced contemporaneously with longwall mining near Raton, New Mexico.

a length equal to or greater than the depth of mining), there is a critical width of extraction for which the subsidence (vertical lowering of the surface) reaches a maximum value. Subcritical widths of extraction produce a trough-like subsidence area with vertical subsidence less than the maximum. At supercritical widths of extraction the subsidence area has an essentially flat bottom at approximately the maximum subsidence. These relations are illustrated in figure 5.

The critical width of extraction is normally expressed in terms of the mining depth (fig. 5). In European coal fields it ranges from 1.0 h to 1.4 h, where h is the average depth of mining. This range has been attributed to differences in the types of overlying rock. Quantitative studies are meager; however, the lower values of the depth coefficient appear to be associated with overburden containing thick, strong sandstone and limestone beds whereas the higher values pertain to overburden containing a large percentage of thin-bedded shales, mudstones, siltstones, sandstones, and unconsolidated deposits. Maximum subsidence is also a function of the thickness of the extracted layer or the volume of material extracted, the mining methods, and several other factors discussed in the following sections.

SUBSIDENCE PRODUCED BY ROOM-AND-PILLAR COAL MINING

Room-and-pillar mining is the most frequently used mining method in United States coal mines. The coal is mined in entries (rooms) separated by pillars which may or may not be partially extracted later. Initially, a series of parallel entries

FIGURE 3.—Large open fissure associated with longwall mining in mountainous terrain near Raton, New Mexico. Such features can divert surface runoff, increasing landslide potential.

FIGURE 4.—Rockfalls and tension cracks produced during longwall coal mining near Raton, New Mexico.

are driven through the seam with interconnecting openings (breakthroughs) driven at right angles through the pillars between the rooms. Such a checkerboard pattern of openings is advanced through the coal seam to the limit of the area planned for mining. At this point approximately 50 percent of the coal will have been mined. The coal pillars between adjacent rooms may be fully or partially removed (robbed) during final, or retreat, mining. After full pillar removal, the rock above the mine collapses and the overburden gradually settles, creating surface fissures and subsidence.

The percent extraction by room-and-pillar mining depends upon several factors including the number and size of pillars deemed necessary to temporarily support the mine roof during retreat mining and the need to prevent or limit surface subsidence. In some sections of West Virginia and in other States where surface land is owned by the coal producer, nearly 100 percent of available coal can be mined using the room-and-pillar method. In States such as Illinois, however, where farm and industrial land are extremely valuable, only about 50 percent of the coal may be mined to prevent surface damage from subsidence.

Because of the several stages of coal removal and the slow pillar deformation and deterioration in room-and-pillar mining, surface settlement is not as uniform and immediate as it is in longwall mining; rather, it may be erratic, intermittent, and long delayed. Figure 6 shows a representative example of delayed subsidence features in Wyoming resulting from old shallow underground room-and-pillar mining operations.

SUBSIDENCE FROM MINING OTHER SEDIMENTARY RESOURCES

Other sedimentary resources which are extracted from considerable depth (hundreds of meters) include salt, potash, sulfur, trona, and phosphate. These minerals occur in bedded, usually

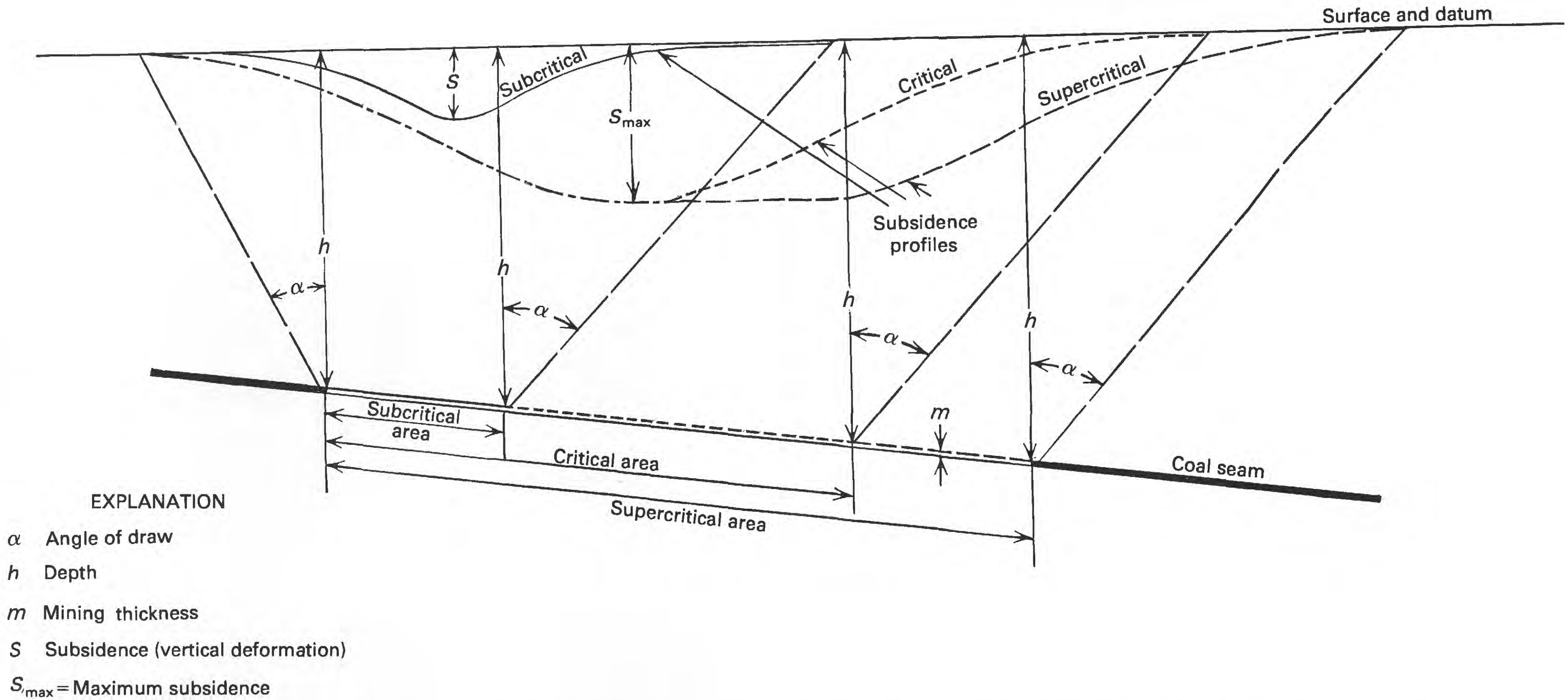


FIGURE 5.—Description of subsidence over longwall mining. Face advance direction is perpendicular to plane of page. (Adapted from National Coal Board, 1975).

flat-lying deposits, and have been mined by several methods: conventional room-and-pillar, longwall, and solution. Pillar and roof collapse and resultant surface deformations are typically delayed and difficult to predict. In solution mining of salt, for example, neither the time nor the location of subsidence can be predicted with confidence because salt deforms slowly in a complex manner and the deformations are different from those of overlying shale and sandstone. Furthermore, solution extraction of salt and other soluble evaporites is a specialized mining technique and the resulting subsidence causes unique problems (Marsden and Lucas, 1973). Drilling through aquifers and salt beds in search of oil, gas, and water has induced salt dissolution and subsequent subsidence (Fader, 1975). As Ege (1979) points out, the construction of highways, dams, and reservoirs over saline or gypsiferous rock has caused subsidence, water loss, and dam failures. A comprehensive discussion of subsidence associated with solution extraction of sulfur is given by Deere (1961).

The subsidence produced by room-and-pillar and longwall mining of potash, phosphate, and most

FIGURE 6.—Southeastward-looking aerial view showing the surface effects of past (room-and-pillar) and present (open pit) coal mining along the Tongue River in Wyoming (July 1977). Pits, troughs, depressions, and cracks have formed because of subsidence over the south part of the Acme mine. The mine was operated from the early 1900's until 1943. Overburden thickness ranges from 15 m in the middle ground to approximately 30 m in the foreground and consists of alluvium and soft interbedded shales, claystones, siltstones, and discontinuous sandstones. The dam in the right foreground across Hidden Water Creek ruptured because of subsidence. The water now is diverted into subsidence depressions, pits, and cracks upstream from the dam. Garbage from the town of Acme was dumped into the large pit at the left side of the photograph. Pits and troughs in the middle of the photograph are in alluvium. Note that the pits near the road and left of the draw do not occur in any noticeable depression; these pits are located above collapsed areas in haulageways of the Acme mine where adjacent coal pillars are strong enough to support the overburden. Alluvium is being removed at the Big Horn surface coal mine to extract the coal (background). Regrading is beginning near the river (right background). (From Dunrud and Osterwald, 1980.)

sedimentary rocks is grossly similar to that of mining coal, being dependent upon the thickness of the bed mined, the depth, the mining methods, and the properties of the overburden. The reader may want to consult Miller and Pierson (1958) for a discussion of subsidence over potash mines.

SUBSIDENCE FROM MINING CRYSTALLINE ROCKS

A very different type of subsidence is produced by the extraction of irregularly shaped metalliferous ore bodies by block caving or by leaching of disseminated deposits where the extracted width is small compared to the depth. A prominent collapse structure, as much as tens to hundreds of meters in depth, may develop rapidly. The subsidence mechanism in jointed crystalline rocks proceeds approximately as follows (Abel and Lee, 1980):

1. Rock collapses progressively upward from the mining horizon (undercut level) as ore is withdrawn from below.
2. The ground surface does not begin to subside measurably until the collapse has so thinned the intact rock above the mined-out area that it cannot support the load of the overlying rock (arching effect). The overlying solid rock will then deflect downward toward the collapsed rock. Lateral movement of adjacent rock into this collapsed rubble column is resisted by the active pressure of the rubble.
3. Further extraction of caved ore from below results in increased subsidence of the ground surface above and outside the area of extraction. This initial trough subsidence is similar in shape to the trough subsidence observed over coal mines.
4. Continued extraction of ore will result in breaching of the surface. The initial breach is typically in the form of a circular depression, or chimney, that is roughly centered over the mining area; it may be offset a minor distance because of preferential collapse along geologic discontinuities.
5. The rock adjacent to the chimney either slides along geologic weaknesses, such as joints or faults, or topples into the collapsing upper part of the chimney.
6. The final, or ultimate, angle of draw is located where either the flattest geologic weakness intersects both the ground surface and mining horizon or where the angle of repose of the broken rock mass is reached, whichever is flatter.

It is common practice to report an initial and final angle of draw for block-caving-induced subsidence. The initial angle of draw marks the extent of subsidence effects at the time the surface is breached. The final angle of draw occurs at the limit of measurable subsidence effects after mining ceases. Negative initial angles of draw, that is, those inside the mining area, have been reported; they were probably derived, however, from insufficient field measurements. Such a negative angle of draw refers to the angle between the vertical and a line connecting the side of the chimney with the nearest side of the mining level. Initial angles of draw in crystalline rocks range from $-5°$ to 40° and final angles of draw between 5° and 65°.

IMPACTS OF SUBSIDENCE

Damage from subsidence over underground mines has been a serious problem in urban areas for many years and will become more widespread as the demand for resources, particularly coal, increases. Continuing subsidence has recently posed hazards in parts of Colorado and Wyoming where urban areas have spread onto land underlain by abandoned coal mines. Delayed subsidence has caused extensive damage in urban areas established over coal mines in the Eastern States.

Economic impacts of subsidence in rural areas can also be significant. Fields must be regraded to eliminate ponding of water, and, as in urban areas, roads must be regraded and homes must be repaired. Water wells may become dry when aquifers are disturbed by rock movements. Gas mains are especially vulnerable to subsidence and, if ruptured, can catch fire and explode.

Damage from surface subsidence can be caused by changes in surface slope, differential vertical displacements, and horizontal strains. Planners must know whether these changes are complete or in progress, permanent or temporary; further mining may restore the original slope or close tensile fractures thereby rendering some remedial measures unnecessary or even harmful. The magnitude of structural damage in buildings and manmade structures will depend to a large extent upon details of design and materials; therefore any damage classification must be a general one.

EFFECTS ON SURFACE STRUCTURES

The effects of subsidence on surface structures are controlled to a large extent by the mining method. The long-term, delayed nature of subsidence over room-and-pillar mines can make the task of repair and maintenance of surface facilities intermittent and not predictable. Longwall mining, however, is associated not only with greater recovery of coal but with increased surface stability after mining and, hence, earlier construction or resumption of previous surface activities.

Many accounts exist of severe surface deformations that occurred, often abruptly, long after mining ceased. With only a few exceptions, the notable delayed residual subsidence has taken place in room-and-pillar mined areas rather than in longwall mined regions. At Farmington, W. Va., intermittent episodes of subsidence occurred because 2-m to 3-m high coal pillars were gradually forced into the weak claystone mine floor (Gray and others, 1977). Surface deformation that damaged dozens of homes and buildings began while the mine, which was 85 m below the surface, was active. Subsidence movements continued intermittently for more than 4 years after mining stopped until the mine was injected with coal waste. At the Geneva coal mine in Colorado, compression features such as fractured bulges and small anticlines formed in massive sandstone 274 m above a mined-out area about 1½ years after mining was completed. Measurements showed that the ground surface was shortened locally by as much as 0.92 m (Dunrud, 1976).

Damage to surface structures over room-and-pillar mines has been particularly noteworthy in those Eastern States underlain by extensive coal deposits. Surface developments overlie room-and-pillar coal mines in Pittsburgh, Pa., and Birmingham, Ala., as well as many smaller cities and towns in 17 States (Allen, 1978). For example, at Scranton, Pa., $29 million worth of property, including 2,000 homes, 50 commercial and office buildings, 2 hospitals, several schools, and various utility lines have either been damaged by or are being threatened by subsidence many years after the mines were abandoned. The total cost of surface stabilization of this area by hydraulic mine backfill is estimated to exceed $8 million (Dunrud, 1976). Subsidence occurred dramatically in 1974 in Lafayette, Colo., above a coal mine abandoned for several decades when a pit 4.5 by 5.5 m wide and 7.3 m deep developed in 24 hours in a then unoccupied part of a trailer court (Ivey, 1978).

Engineers in Poland classified structures into four categories, on the basis of importance and sensitivity to surface movement, and designated acceptable values of tilt and normal strain for each category (Hutchings and others, 1978, table 4). A classification of subsidence damage based on structural length changes and horizontal ground strain caused by longwall coal mining was developed by the British National Coal Board (NCB) and is given in table 1. The NCB has also developed a useful nomogram for estimating deformations of surface structures in the United Kingdom (fig. 7).

Figures 2–4 show surface effects produced by longwall mining in mountainous terrain in New Mexico. Because subsidence is an inevitable consequence of high-extraction mining, planners must be able to forecast its impact not only on surface activities but also on subsurface structures such as aquifers.

HYDROLOGIC IMPACTS

Subsidence depressions and associated fractures may disrupt surface and underground water flow, causing diminished well production, aquifer contamination, and decreased property values. In the dry areas that typically overlie western energy resources, the loss of springs and other surface water is especially critical (fig. 6). Proper planning and development of underground mining will lessen these detrimental effects. Few detailed studies exist to adequately document the effects of mining on the hydrologic regimen. Hydrologic changes may be more subtle than other mining effects; for example, subsurface aquifer disruption may occur because of displacement of rocks above mined-out areas without visible surface manifestation. Some shallow wells in Pennsylvania have experienced reduced production. In one instance, a mine face passed within 30 m of a 20-m-deep well which went dry. The well was deepened by 12 m and a good water supply was encountered (Sossong, 1973).

Of great importance in many areas is the potential hazard that surface waters present to mining. In Pennsylvania a longwall panel having 200–215 m of overburden was successfully mined directly below a reservoir (Sossong, 1973). Normal mining conditions were encountered with $63–190 \times 10^{-5}$

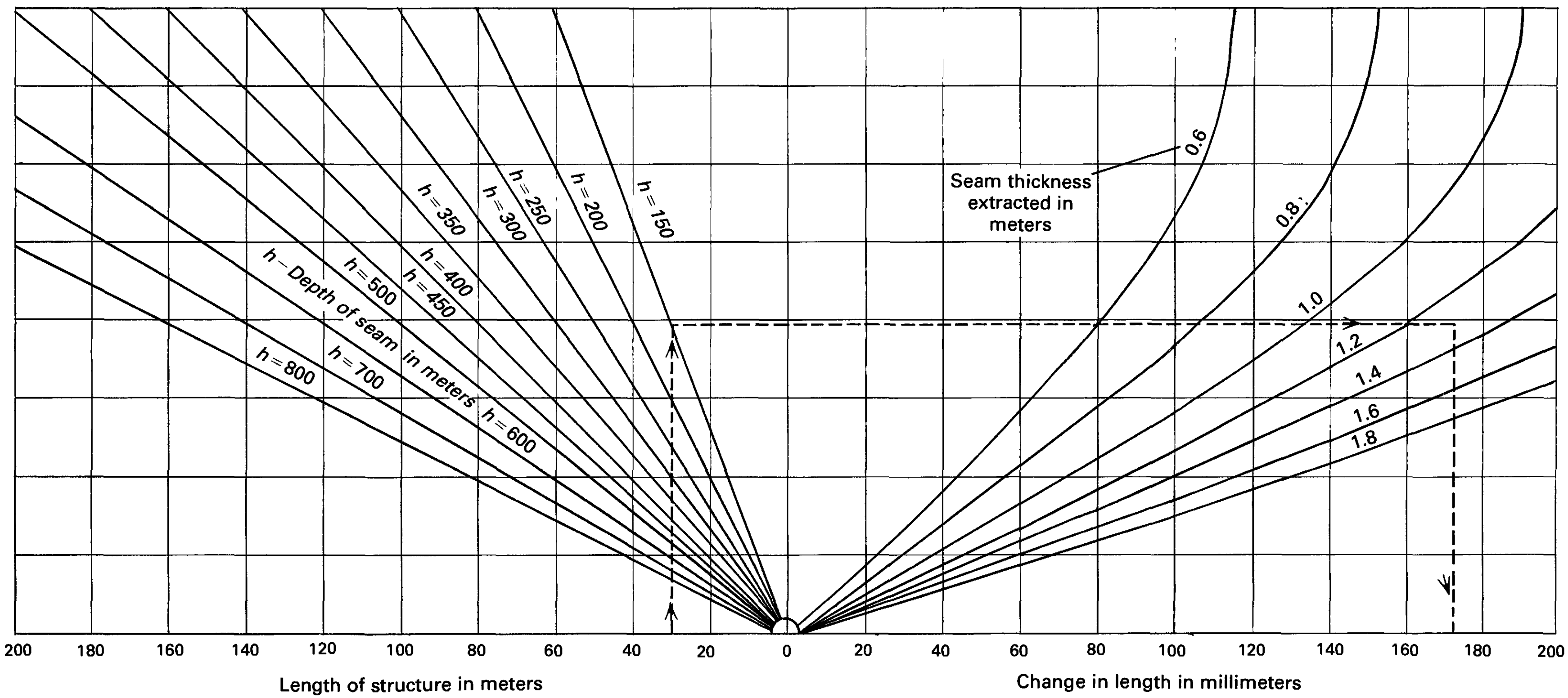


FIGURE 7.—Nomogram for the estimation of change of length of a surface structure for various mining conditions. Example given (dashed line) is for structure with length of 30 m, depth of coal seam of 150 m, and seam thickness of 1.3 m, which results in change of 172 mm in length of structure. (Modified from National Coal Board, 1975.)

TABLE 1.—*Subsidence damage classification for horizontal ground strain and changes in length of manmade structures[1] from longwall mining*

[με = microstrain; 1 ft = 0.305 m]

Class of damage	Change of length of structure	Description of typical damage
Very slight or negligible (example: 15-m long building extended 50 με).	Up to 0.03 m	Hair cracks in plaster. Perhaps isolated slight fracture in the building, not visible on outside.
Slight (example: 33-m long building extended 1,600 με).	0.03–0.06 m	Several slight fractures showing inside the building. Doors and windows stick slightly. Repairs to decoration probably necessary.
Appreciable (example: 27-m long building extended 3,700 με).	0.06–0.12 m	Slight fracture showing on outside of building (or one main fracture). Doors and windows sticking; service pipes may fracture.
Severe (example: 67-m long apartment house compressed 2,300 με).	0.12–0.18 m	Service pipes disrupted. Open fractures requiring rebonding and allowing weather into the structure. Window and door frames distorted; floors sloping noticeably; walls leaning or bulging noticeably. Some loss of bearing in beams. If compressive damage, overlapping of roof joints and lifting of brickwork with open horizontal fractures.
Very severe (example: 55-m long apartment house extended 6,000 με).	More than 0.18 m	As above, but worse, and requiring partial or complete rebuilding. Roof and floor beams lose bearing and need shoring up. Windows broken from distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of the roof and walls.

[1]Modified from National Coal Board, 1975.

m^3/s (10–30 gal/min) of water developed from the entire 183-m-wide panel. Maximum subsidence induced by an adjacent panel not under the reservoir was 0.65 m or 47 percent of the 1.37-m mining thickness with an average width/depth ratio of 0.85. Numerous shallow workings have taken place under large bodies of water. Many of these workings are essentially dry, although some mined coal seams were less than 30 m below water or saturated alluvium (Orchard, 1973). In the United Kingdom, undersea longwall extraction is permitted with a minimum cover of 105 m and a maximum tensile strain of 0.01.

We have discussed the development of increased rock mass permeability through mining-induced fracturing and the structural and lithologic characteristics that may be important determinants of subsidence. The significance of these factors is increased when mining under bodies of water or under productive aquifers; in such circumstances an adequate monitoring program is essential to warn of a possibly hazardous water inflow.

Guidelines for mining near surface and underground bodies of water have been published by the U.S. Bureau of Mines (Babcock and Hooker, 1977).

In addition to conventional coal mining, the underground coal gasification process and in situ retorting of oil shale can also affect ground-water supplies in complex ways. When ground water reenters a gasified coal bed, the residual reaction products (coal ash, tars, and gases) may undergo leaching, dissolution, and hydrologic transport

(Mead and others, 1978). Subsidence effects such as extensive fracturing or mine roof collapse may cause contaminants to find their way into aquifers that lie above the mined zone. Any meaningful evaluation of this potential hazard must be based on long-term monitoring of typically slow flow rates. As a consequence of the sorptive properties of the rocks associated with coal, the contaminants may move more slowly than the ground water and they may react chemically with each other and with the rocks, potentially lengthy and poorly understood processes.

EFFECTS ON VEGETATION AND ANIMALS

As we have noted previously, collapse over deep mine cavities may induce tension fractures in nearby overlying beds and at the ground surface. Methane gas may leak out of shallow coal seams or mines through these fractures and kill trees and woody plants, leaving only grasses unaffected. Garner (1974) found that certain bacteria in the soil use methane to produce hydrogen sulfide and nitrous oxide. These gases disrupt the root transpiration of woody plants, ultimately killing them. Noxious or toxic gases may also overcome animals grazing on the surface.

Another source of damage to plant life and associated wildlife is the trough-like subsidence areas formed over areas of longwall mining. Unless drainage is maintained, these depressions may fill with water, creating swampy, tree-killing conditions and new types of habitats. Conversely, in some western areas (for example, North Dakota) collapse pits may be the only places wet enough to sustain the growth of cottonwoods and willows. Collapse pits and open fractures may trap animals or interrupt their migration patterns.

Losses of soil water or water in deeper aquifers through fractures created by subsidence could be equally harmful to plant and animal life, especially in semiarid areas.

COAL MINE FIRES

Coal mine fires are an indirect result of coal extraction and contribute to long-term subsidence. According to Dunrud and Osterwald (1980) several fires are burning in long-abandoned underground mines near Sheridan, Wyo. Many of the fires appear to have been started by spontaneous ignition when air and water were introduced through subsidence cracks, pits, and unsealed mine openings. Combustion is supported by the drawing in of oxygen and the exhaustion of smoke, steam, and noxious gases through subsidence cracks and pits. As the coal burns, more cavities are created causing more cracking and collapse which allows greater access for air, thereby accelerating coal burning. This uncontrolled "in situ gasification" process is destroying a valuable resource. In addition, gaseous combustion products locally pollute the air; soil changes are produced, and vegetation is retarded or killed by near-surface fires.

FACTORS GOVERNING SUBSIDENCE

The magnitude, rate of development, and surface expression of the subsidence process are controlled by several factors, most of which are interdependent. These include mining method, depth of extraction, size and configuration of openings, rate of advance or extraction, seam thickness, topography, lithology, structure, hydrology, in situ stresses, and rock strength and deformational properties. We point out the significance of these factors, if only in a cursory fashion, because, taken collectively, they demonstrate the complexity of the subsidence process.

MINING METHOD

Although any underground void will potentially induce subsidence, the manner in which a resource is extracted exerts a large influence on surface deformations. Thus, room-and-pillar, longwall, and in situ extraction techniques will affect the surrounding rock differently; pillar layout, cavity shape, and the volume of material removed govern the timing and configuration of surface expressions. For example, longwall mining generally produces contemporaneous subsidence, whereas room-and-pillar mining may prolong or delay the deformation of walls and roofs for many years. Compulsory recording of mine workings was not introduced in the United Kingdom until 1872, and there are at least 30,000 unrecorded shallow workings, some over 400 years old, where even today gradual deterioration of coal pillars leads to pillar collapse and uneven surface subsidence (Littlejohn, 1979).

MULTIPLE SEAM MINING OF COALBEDS

The sequence in which individual coalbeds of a multiple-seam deposit are mined determines the stress concentrations elsewhere in the mining area, in beds both above and below the bed being mined. According to Dunrud (1976) mining beds from top to bottom generally is safer and more efficient than other procedures, particularly if the final geometry is uniform; uniform geometry prevents stresses from being concentrated in isolated pillars and barriers and transmitted to underlying coalbeds. Several exceptions exist, however, to this generalization. If the stratigraphic interval is 7.5–15.0 m between two coal beds, for example, concurrent, uniform extraction of both beds may be the safest and most efficient mining procedure. Mining from bottom to top might be less hazardous and more productive in those areas where water or methane are present because mined voids in upper beds may store large amounts of these substances, later to become hazardous if tapped by subsidence fractures induced by mining lower beds.

DEPTH OF EXTRACTION

Because rocks are not perfectly elastic and do not deform as homogeneous, intact bodies but as a jointed or layered media, the depth of extraction governs subsidence development, particularly in room-and-pillar mines. The deeper the mining level, the greater the length of time required for rock deformations to reach the surface; thus the earliest surface deformation occurs above the shallowest coal mines. This phenomenon is frequently observed in areas of level topography underlain by dipping coal beds. In the Boulder-Weld County coal field in Colorado, for example, subsidence problems began in the 1860's when room-and-pillar mining of shallow coal started. Subsidence was relatively complete above these shallow mines. Today, many years after mining ceased, the effects of deeper mining continue to create new surface hazards. However, poor information as to the amount of pillar support that remained after mining and the dates of mining make it difficult to accurately estimate the potential for further subsidence.

RATE OF ADVANCE

The British National Coal Board has found that for longwall coal mining the time taken for subsidence to occur depends primarily on the time it takes for a coal face to be worked through the critical area. This time in turn is controlled by the depth and the angle of draw (because these factors determine the critical area) as well as by the rate of advance. Typical longwall advance rates are 0.3–1.2 m per day, and "high-speed" longwall face advance in coal is about 1.5 m per day (Whetton and King, 1961; National Coal Board, 1952, 1963). The maximum longwall face advance reported was approximately 5.5 m per day in a bedded quartzite in South Africa (Cook, 1967). Several studies indicate that subsidence is transmitted rapidly from the workings to the surface. For instance, when mining ceases for holiday periods subsidence stops almost instantaneously; subsidence continues as soon as mining resumes. A smooth, consistent rate of advance promotes consistent, predictable surface settlement.

THICKNESS OF SEAM OR DEPOSIT

In some mining areas the relationship of seam thickness and overburden depth to vertical displacement of the ground surface is well established. A compilation of more than 150 measurements made above longwall mines in the United Kingdom showed that a maximum depth of the subsidence basin of 0.9 times the seam thickness is reached when the span of the void (the area of complete extraction) exceeds 1.4 times the depth of the deposit (National Coal Board, 1975). The depth of the subsidence basin is less for thinner seams or for shorter void spans. For example, the maximum subsidence for a void span of 0.7 times the mining depth is 0.45 times the seam thickness. These relations were derived from empirical observations gathered by the NCB, and although they are voluminous and have been verified repeatedly, their applicability to other geologic environments and different mining methods has not been demonstrated.

LITHOLOGY AND STRUCTURE

The strength and deformational properties of rock masses are largely controlled by rock type and structural features such as joints, faults, and bedding and foliation planes. These geologic conditions are responsible for significant variations in subsidence development and particularly affect the surface extent and timing of subsidence. Knowledge of geologic conditions in advance of mining can aid in subsidence prediction and in the development of a monitoring plan. For example, the angle of draw changes with the dip angle, and this effect can be readily estimated (National Coal Board, 1975, p. 16–18). In addition, monument line layout can be shifted down dip according to the dip magnitude.

A gradual lowering of the surface is associated with weak overburden rocks whereas violent, often delayed, collapse is more typical of strong overburden rocks. The presence of through-going faults or dikes may limit the lateral growth of a surface depression, particularly in crystalline rocks (Lee, 1966; Crane, 1931). Such discontinuities apparently act as barriers because of lateral contrasts of rock properties.

Several examples of the role of lithology and structure may be cited. In the county of Lanark (Lanarkshire) in Scotland, room-and-pillar mining had ceased 118 years before sandstone beds collapsed abruptly over workings that were only 16 m deep. At the surface, structural damage to apartment buildings was so severe that the tenants were evacuated and several blocks of buildings were demolished (Thorburn and Reid, 1978). Orchard and Allen (1965) noted that 9 percent of total potential subsidence occurred during a 6-year period after a 166-m-deep longwall face advance stopped at Peterlee in the United Kingdom. A thick dolomitic limestone bed apparently retarded complete subsidence.

According to Kent (1974) roof falls in the Pittsburgh, Pa., room-and-pillar coal mines show two distinct patterns. In some mine areas where shale directly overlies the coal, nearly all roof falls occur along northeast-trending mine passageways parallel to the butt cleat (joint) direction in the coal. In other mine areas where shale overlies the coal but where thick sandstone lenses overlie nearby coal, severe and frequent roof falls may occur in the shale roof with no consistent orientation relative to the joints or passageways. Regional jointing appears to control the first type of roof fall, and sandstone channel deposits control the second type. The joint spacing is governed by the rock type: joints in the coal are well developed and closely spaced; joints in shale are less well developed and have a spacing of less than 0.3 m; and joints in sandstone are typically more than 0.3 m apart and are well developed. Through careful mine layout it may be possible to control roof falls and to more accurately predict the nature and timing of subsidence.

At a longwall mine in New Mexico, surface subsidence fractures indicated that the overburden was breaking primarily along the major east-west joint system and to a lesser degree along the secondary north-south joint set (Gentry and Abel, 1978). These tension fractures started to close when the mining face was only 20 m past the fracture.

In fractured crystalline rocks, the final angle of draw is typically controlled by faults and joints and is usually located where the flattest geologic weakness intersects the mining level and the ground surface.

IN SITU STRESSES AND OTHER GEOTECHNICAL FACTORS

High horizontal stresses, which are common in many shallow crustal rocks, act to inhibit the development of a surface depression by maintaining a strong ground arch in the immediate mine roof. Arch height and stability, however, are very sensitive to the ratio of vertical to horizontal in situ stresses. A highly stressed arch may fail violently as a result of progressive thinning as happened at the Urad mine in Colorado (Kendrick, 1973). At that mine, a molybdenum ore body in country rock of rhyolite and coarse-grained granite was mined by block caving. Horizontal stresses near the mine average 10.2 megapascals (MPa) (1,478 lb/in^2) which is 4.6 times greater than the horizontal stress induced by gravity loading (Hooker and others, 1972). These "anomalous" stresses may have caused the extreme difficulty in breaking down the arch and initiating caving even though very high powder factors were used. An unsupported stable arch 100 by 150 m existed approximately 100 m below the surface. The caving occurred spontaneously and violently; an airblast from rock bursting penetrated 60–75 m of broken muck and was still strong enough to knock people down. The entire back came down breaking through to the surface and forming a "glory hole" 150 m in diameter and 30–100 m deep. Similar violent deformations have been reported in other brittle, highly stressed rocks including sandstone, quartzite, and coal.

In many room-and-pillar mines little or no subsidence is anticipated, and surface use is planned accordingly. Most pillars deteriorate and deform with time, however, and depending upon bulking, deformation may extend to the surface. Lack of knowledge of the physical properties and rock stresses can lead to poor mining practices which in turn create stress problems in other parts of a mine, bringing about further uneven extraction procedures. In some mining regions of the United States, particularly those in the West (Dunrud, 1976), concentrations of earth stresses cause rock bursting and coal bumps which induce roof falls and pillar failures. These rock failures have forced changes in mining plans or abandonment of mine areas before mining is completed in a uniform manner, causing greater subsidence damage because of uneven mine geometry. Knowledge of pillar rock strength and creep properties is most critical in areas of high potential impact. In Allegheny Plateau coal mines, for example, high in situ horizontal stresses and the orientation of the maximum horizontal stress are related to roof instability and floor heave, making mine layout a major concern (Aggson, 1978).

TOPOGRAPHY

Several investigators have noted the complicating effects of topographic variations on subsidence development. In contrast to a level ground surface where the stresses produced by overburden on subsurface rocks are uniform, regions with irregular topographic relief will have irregular stress distributions that vary with the height of the column of rock above a particular underground point. Measurements made above three panels at the York Canyon mine in New Mexico, a longwall operation, show that maximum subsidence occurs under ridgetops and minimum subsidence under draws or topographic lows (Gentry and Abel, 1978). Subsidence decreased from 25 to 30 percent of the maximum under a draw; subsidence was only 1.6 m or 50 percent of the seam thickness mined. Peak subsidence of 2.0 m occurred below a ridgetop. At the same mine, greater horizontal ground movement resulted when the direction of mining was in the downslope direction than when mining was in the upslope direction. This behavior disagrees with the calculations of Kapp (1973), who showed by geometrical considerations that horizontal strain would be greater when the ground surface rose in the direction of mining and less when the ground surface fell in the direction of mining. More field measurements should help resolve this discrepancy.

The natural stability of steep slopes may be affected by subsidence-induced deformations, triggering landslides. The definition of stress distributions related to topography is necessary for accurate slope-stability assessment prior to mining.

TIME

The time factor in mining-induced subsidence has been investigated in the past, mainly as applied to coal mining. It has long been known that the deeper the seam, the longer the duration of surface movement, although the reasons are not well understood.

In longwall mining, the subsidence of a point at the surface theoretically begins when a longwall face enters the "critical area" (fig. 1) and ceases when the face leaves the critical area. The surface point actually continues to subside (residual subsidence) for a variable period, perhaps months, although over 90 percent of the total subsidence occurs while the face is within the critical area. Most investigators point to rate of advance and depth of mining as the factors governing the rate and timing of surface subsidence. As we have stated earlier with respect to the areal limits of subsidence, geological/geomechanical properties influence strain rates and modes of deformation. Orchard and Allen (1974) contend that when the face advances out of the "critical area," further ground movements occur because of complex time-dependent stress redistribution processes in the overlying rocks. The influence of depth of mining and face position on time-dependent subsidence becomes more significant in room-and-pillar mining primarily because of the difficulty of predicting deterioration of pillars.

SUBSIDENCE ANALYSIS

The objectives of subsidence analysis are to predict the occurrence, timing, and magnitude of vertical and horizontal components of surface deformation induced by underground resource extraction. The analysis should consider the likelihood of and the consequence of the impacts discussed in the previous section. Depending on present and future land use plans, how much subsidence is tolerable and, in light of resource conservation, how much of the resource should be extracted? Although it is desirable to recover the total deposit, this can rarely be done; recent United States underground coal mining practice extracted only approximately 57 percent of the coal (Lowrie, 1963).

The person concerned with assessing subsidence potential should determine whether subsidence has occurred previously in the area and its severity. Is future subsidence from old mining a possibility? We have mentioned some of the many factors that control subsidence, and each of them should be evaluated in a comprehensive analysis in order to determine the likelihood of significant harmful environmental impact.

DATA REQUIREMENTS

The following discussion is intended as an overview of the broad data needs for subsidence analysis rather than as an attempt to specify a complete suite of geotechnical properties. Considerable latitude is necessary to allow for site-specific needs. Knowledge of premining conditions is needed for prediction of disturbances that may be caused by mining.

GEOLOGIC DATA

Geologic maps, sections, and core logs are necessary to define topography, depth of mining, rock types and thicknesses, jointing, faults, and variations in the attitudes of beds, including folds. A drilling program should include at least one hole drilled to below the coal seam in the vicinity of the surface monuments and the panel. This drilling should be done for the first panel of a new mine and for one panel in an operating mine. The hole should be logged from the surface. Rotary drilling is satisfactory if cuttings are collected and identified for every 1.5 m of the drill run and if the hole is geophysically logged to produce an electrical resistivity (lithologic) log of the rock overlying the panel. The location of any methane gas in coal beds should be defined as well as the rank of the coal and its composition, including sulfur content. Knowledge of premining seismicity of an area is needed to determine the likelihood of complications such as severe bumps and roof falls.

HYDROLOGIC DATA

Studies should be done to define premining surface-water and ground-water volumes, flow rates, and quality. Aquifers and aquicludes should be identified. It is very important to identify all surface springs, streams, or bodies of water. Well data for the region should be systematically analyzed throughout the mining period. The sorptive properties of the rocks may be closely related to subsidence-induced ground-water changes that were discussed previously.

GEOTECHNICAL DATA

Two categories of rock-behavior data are needed for subsidence analysis. One category deals with the behavior of the underground mine and the surrounding rock and water environment. The other category deals with the behavior of the ground surface above the mine.

The first category includes rock strengths, cohesion, angle of internal friction, and elastic properties including, for example, Young's modulus and Poisson's ratio. Creep behavior data for the overburden materials are needed to forecast delayed subsidence. Knowledge of in situ stresses, especially the magnitude and direction of the horizontal stresses, is needed for planning a safe and efficient mining operation and for applying realistic limits to mine deformation and subsidence calculations. The second category includes horizontal and vertical strains and displacements and their magnitudes, locations, and duration.

MINING PLANS

A proposed mining plan is necessary for early input to the subsidence analysis. The plan should be based not only on geologic, hydrologic, and geotechnical data but also on mining methods, extraction location and sequence, location of panels, barrier pillars, and, in the case of multiple-seam deposits, the seams to be mined and the proposed sequence. The mining plan should anticipate the magnitude, location, and timing of surface disturbance. If the plan is revised, initial subsidence predictions may be altered.

ANALYTICAL TECHNIQUES FOR SUBSIDENCE PREDICTION

BACKGROUND AND STATE-OF-THE-ART

The accuracy of subsidence prediction varies from country to country, and is controlled mainly by knowledge of geologic and topographic conditions and the length of mining experience. In the United Kingdom, for example, data has been collected over a long period of time from more than 150 coal mines in similar geologic environments. The results of these observations have been presented as empirical formulas and procedures for prediction of the nature, areal extent, and severity of subsidence and related events. Subsidence-induced surface deformations can be predicted and described but only under conditions similar to those of the original observation. Particularly in Europe, new methods of extraction such as harmonic mining and stepped-face layout have been developed to minimize surface deformations and reduce damage to structures. It has been possible through integrated systems of prediction, mining techniques, and monitoring procedures to control the development of subsidence basins so that shallow mining may proceed under buildings and even towns.

In the United States, methods of subsidence control and estimation are less well developed. Subsidence theory developed in Europe has not been used extensively in the United States because room-and-pillar mining, rather than the longwall panel system, is the more common mining method in the United States. Although longwall mining is increasing in the United States, empirical methods such as that of the NCB have not found widespread application in U. S. mining because of dissimilar and varied geologic conditions.

We will briefly discuss the current methods of subsidence prediction and some of their limitations. Subsidence prediction techniques fall into two broad groups: empirical methods and mathematical models. Researchers have cited field and laboratory studies to support both approaches.

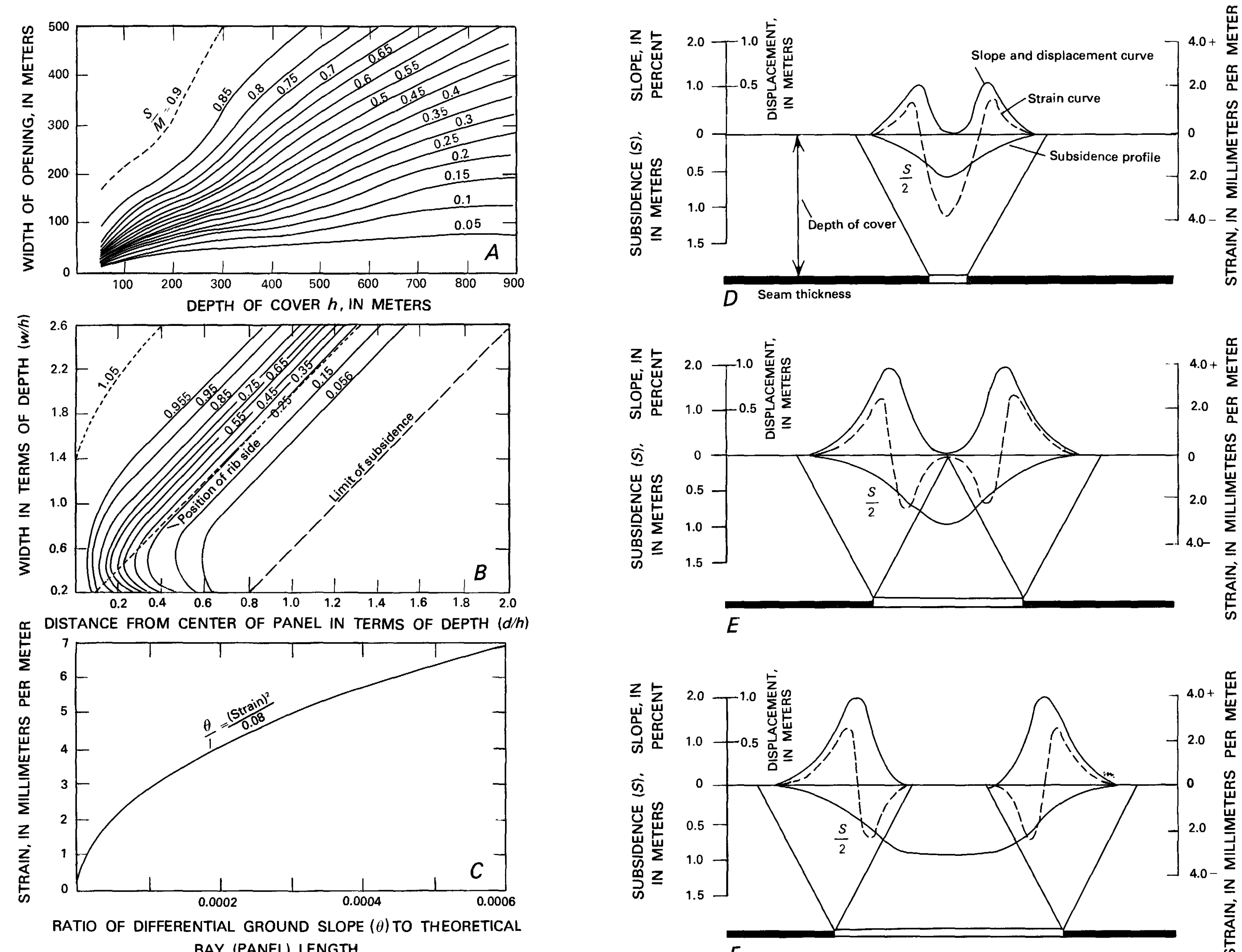
BRITISH NATIONAL COAL BOARD METHOD

This empirical subsidence calculation method was developed in the United Kingdom for the prediction of the vertical component of surface displacement or subsidence (S) and the horizontal component of surface strain (ϵ) associated with trough-like subsidence caused by the longwall method of coal extraction (National Coal Board, 1975). This relatively simple method is based on the subsidence data obtained from mining seams that dipped less than 25°, were 0.6–5.5 m thick (m), and ranged in depth (h) from 30 to 792 m. The face or panel width (w) ranged from 30 to 457 m and the panel width to depth ratio (w/h) ranged from 0.05 to 4.0. These observations were made where the panels contained no zones of special support, and the panel width was averaged if the sides were nonparallel. The NCB system provides for correction of horizontal strain estimates where the ground surface is sloping and where the coal seam is dipping.

Subsidence analysis using the NCB method proceeds as follows. The ratio of S to m is derived from the planned width and depth of the workings (fig. 8*A*). Subsidence at various points on the predicted subsidence profile is found as a proportion of S based on the ratio of w to h (fig. 8*B*). These points are then related to the position of the rib side for a given value of w/h and the predicted subsidence profile for the subcritical width of extraction is plotted (fig.8*D*). From the subsidence profile the values of subsidence for points at recommended intervals of $h/20$ are tabulated. Values of ground slope, differential ground slope (ϕ), and the ratio of S to the distance between stations are calculated. Figure 8*C* shows the empirical relationship between panel length, ground slope, and horizontal strain in a curve where the strain (ϵ) is read directly. The subsidence profiles and associated slopes and strains for critical and supercritical widths of extraction are plotted (figs. 8*E* and 8*F*). NCB experience shows a range in the angle of draw from 25° to 35°. Probably because of geologic and topographic factors, the angle of draw varies much more when worldwide measurements in a variety of host materials are considered.

On the basis of the NCB curves, the greatest possible subsidence, S_{max}, is approximately 90 percent of the seam thickness and occurs at values of w/h greater than about 1.2. At values of w/h less than 0.2, the maximum subsidence is less than 10 percent of the seam thickness extracted. The method may be used to estimate the effect on subsidence of certain barrier pillar spacings and backfilling, both of which reduce subsidence. Further, the NCB method employs other empirical curves relating to surface horizontal strains to enable the computation of maximum tension, maximum compression, the extent of the tensile and compressive areas, and a complete strain profile. The NCB system is the most widely used prediction scheme, particularly to provide a general approximation of subsidence effects; it may be supplemented by other methods suited to local conditions. O'Rourke and Turner (1979) reported on their experience in applying the NCB method to longwall coal mining in Illinois. They found significant differences between longwall subsidence patterns observed in Illinois and those typical in the United Kingdom for similar conditions of panel width, depth, and excavated thickness of coal. Specifically, at the Old Ben No. 24 mine at Benton, Ill., they found the following conditions:

1. The subsidence profile was relatively narrow, as demonstrated by angles of draw that are approximately 10° less than those in the United Kingdom.
2. The maximum curvature of the subsidence profile was four times greater than that predicted by the NCB system.
3. Maximum horizontal surface strains of nearly



WIDTH OF OPENING, IN METERS
DEPTH OF COVER h, IN METERS
S/M = 0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
A
WIDTH IN TERMS OF DEPTH (w/h)
DISTANCE FROM CENTER OF PANEL IN TERMS OF DEPTH (d/h)
1.05
0.955
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.056
Position of rib side
Limit of subsidence
B
STRAIN, IN MILLIMETERS PER METER
RATIO OF DIFFERENTIAL GROUND SLOPE (θ) TO THEORETICAL BAY (PANEL) LENGTH
θ/l = (Strain)²/0.08
C
SUBSIDENCE (S), IN METERS
SLOPE, IN PERCENT
DISPLACEMENT, IN METERS
STRAIN, IN MILLIMETERS PER METER
Slope and displacement curve
Strain curve
Subsidence profile
Depth of cover
Seam thickness
S/2
D
E
F

2 percent, which are four times larger than those in the United Kingdom, were measured.

Although a few other measurements indicate similar gross trends (Gentry and Abel, 1978), insufficient observations have been made at other U.S. longwall mines to confirm or deny a general trend.

The NCB method is not relevant to mining in crystalline rocks or to in situ extraction techniques.

OTHER EMPIRICAL METHODS

Another empirical prediction method is based on the so-called "stochastic" or random media theory discussed by Voight and Pariseau (1970). The method is seriously restricted because it does not incorporate knowledge of material properties prior to mining but rather transfers field measurements from known areas to areas of new mining via an empirical procedure. This approach may result in the uncertainty of results, and an exceedingly large number of studies would be required to demonstrate the general validity of the method. The same difficulty applies to the NCB system. Statistical methods that treat a broad collection of data concerning geologic controls on subsidence are more broadly applicable. We have found, for example, that as the percentage of shale in the rock mass decreases and the amount of sandstone increases, the angle of draw and the area of potential subsidence decreases (Abel and Lee, 1980).

MATHEMATICAL TECHNIQUES

The mathematical approaches to subsidence prediction attempt to define the conditions that lead to subsidence and, hence, to develop general predictive models. In these approaches the rock mass surrounding the mined opening is assumed to be an ideal material that deforms elastically. Wide applicability and improved understanding are the main advantages claimed for these approaches (Voight and Pariseau, 1970). Included in this group are elastic, viscoelastic, and plastic idealizations. Finite-element analysis is widely used to manipulate elastic or viscoelastic continuum excavation models. As more realistic model properties and boundary conditions are defined, predictions should become more accurate. Voight and Pariseau (1970) were not able to reconcile field observations of surface displacements over British coal mines to subsidence profiles calculated on tne basis of isotropic theory. They did find, however, that transversely isotropic theory was in good agreement with field data.

In general, subsidence-prediction methods are most seriously deficient where subsidence deformations are controlled by structural discontinuities such as faults, joints, and folds, or by rock type.

SELECTION OF AN ANALYTICAL TECHNIQUE

The NCB method is based on the largest systematic analysis of subsidence data available. It is accurate enough to predict trough-like subsidence from longwall mining where the overburden rock is largely shale, siltstone, or marlstone, where it does not contain thick, strong beds of sandstone or limestone, and where the topography is subdued. Thus, the NCB method is applicable to many environmental impact analyses of underground mining.

Where coal is extracted by room-and-pillar methods, subsidence prediction will be very difficult, particularly where there is irregular room development, nonuniform barrier pillars, and poor definition of panels. Under such circumstances, frequently associated with old mining areas, it is usually impossible to predict the time, magnitude, or occurrence of subsidence.

In modern room-and-pillar coal mining, attempts are usually made to control subsidence by leaving a larger percentage of the coal in place, often 40 percent or more. In Illinois (Hunt, 1979), the magnitude, shape, and position of the subsidence profile is delineated on the basis of case-history comparisons in which extraction ratio, depth, panel width, and mining thickness are the principal factors. Where bedrock overburden is less than 50 m thick, smaller sinkhole features pre-

FIGURE 8.—British National Coal Board method of estimating subsidence. *A*, Relation between maximum subsidence, width, and depth. *B*, Lines of equal subsidence for various width/depth ratios. *C*, Strain prediction graph. *D*, Subsidence profiles and associated slopes and horizontal strains for subcritical width of extraction. *E*, Subsidence profiles and associated slopes and strains for critical width of extraction. *F*, Subsidence profiles and associated slopes and strains for supercritical width of extraction. (Modified from National Coal Board, 1975.)

dominate; if it is more than 50 m thick, subsidence is trough-like. Sinkhole development is also related to the hydraulic connection between the surface and the mined-out area. Caving of the roofs of shallow mines allows seepage of surface waters into the mine, decreasing roof and wall stability and promoting caving to the surface. The graphs in figure 9 show the relationship between percent subsidence and panel width for several extraction ratios in Illinois. These examples would be typical trough-like subsidence. Hunt (1979) has shown that where extraction is greater than 80 percent, the NCB method accurately predicts subsidence. Figure 10 indicates that surface tilting is directly proportional to subsidence and increases with the amount of extraction. The findings of Hunt contrast with those of O'Rourke and Turner. Again, more data from longwall coal mines in the United States is needed in order to assess applicability of the NCB method.

Pennsylvania's Bituminous Mine Subsidence and Land Conservation Act of 1966 provides for protection of certain structures including public buildings and residences. Protection is defined in terms of support provided by coal left in the ground. From April 1966 to January 1969 only 1 percent of the 5,500 protected structures were damaged by subsidence, and in 1977 only six cases of damage to the protected structures were reported (Bise, 1980). The formula by which these structures are

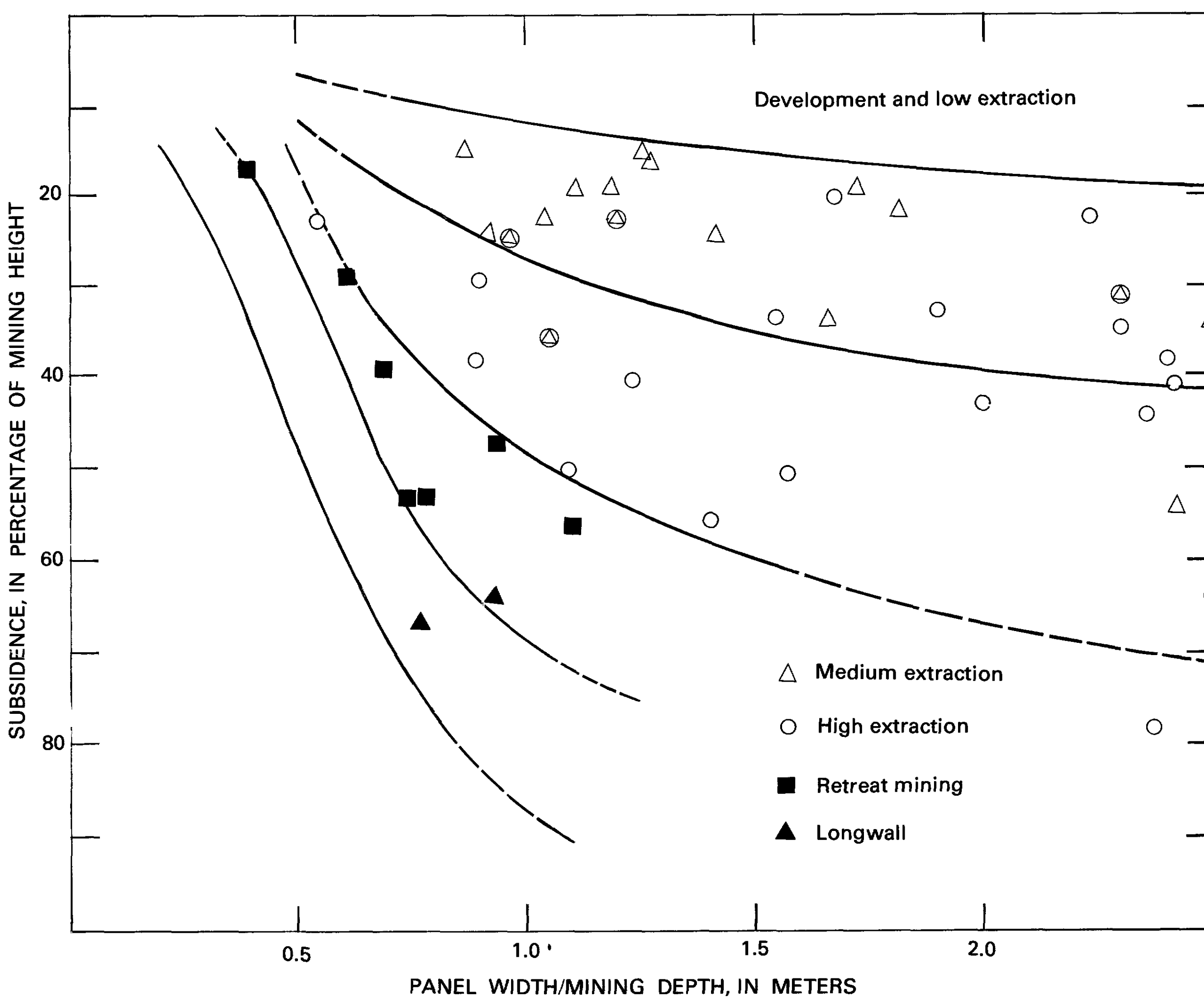


FIGURE 9.—General relation between percent subsidence and panel width to mining depth ratio. Curves indicate approximate range of control of mining method on subsidence. (From Hunt, 1979.)

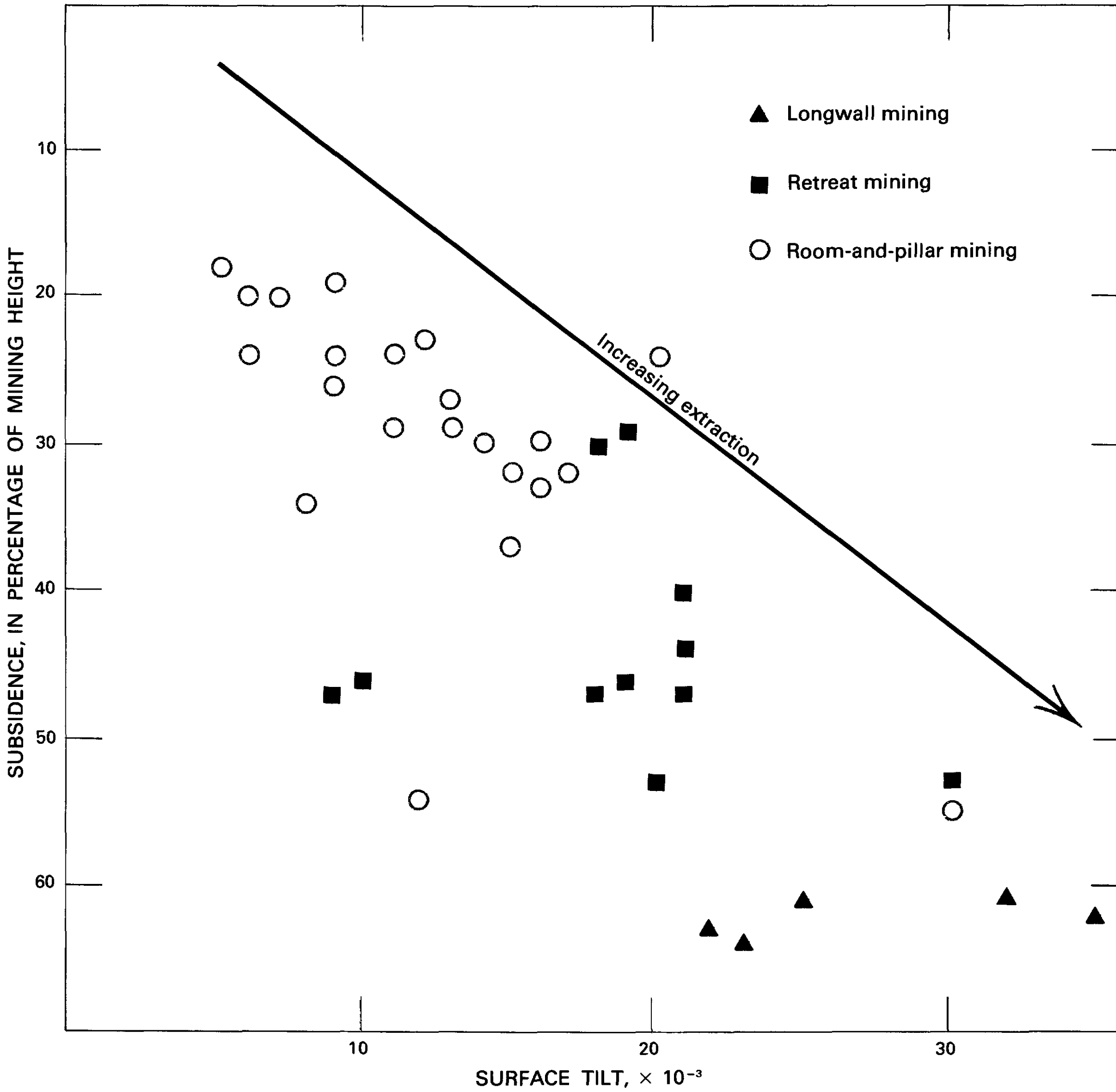


FIGURE 10.—Relation between subsidence and surface tilt (from Hunt, 1979).

protected was derived from many subsidence incidents over the Pittsburgh seam. We quote Bise (1980, p.1):

> Where a structure is located on terrain that is level or slopes less than 5%, the lateral distance (LD) of the support area from each side of the structure is equal to the tangent of 15 degrees (0.27), multiplied by the depth of cover (D), plus a safety factor of 4.6 m, or LD=(0.27)×(D)+4.6m. To find the total length or width of the support area, double the result found for LD and add the length or width of the structure.

This guideline deals only with defining the support area. Within this area, 50 percent of the coal must be left in place in uniformly distributed pillars which can be no smaller in plan than 6.1 by 9.1 m. In addition, no mining may be done where the overburden thickness is less than 30.5 m under a protected structure. Barrier pillars cannot be extracted where the pillar width is less than the cover. As Bise (1980) points out, however, this method fails to consider the effect of mining methods on subsidence and does not allow for recovery above 50 percent.

Studies done in Europe have resulted in general schemes for controlling subsidence damage in partial extraction mining. Orchard (1964) found that if both horizontal and pillar dimensions are equal to at least 10 percent of the mining depth, and if the pillars are uniformly spaced, subsidence will be negligible while allowing 50-percent recovery of the coal. Wardell (1969) presented data to show that there is a consistent relationship between the percent of subsidence and depth, extraction ratio, seam thickness, and pillar width. The findings of these researchers are in general agreement.

At the York Canyon mine near Raton, N. Mex., Gentry and Abel (1978) compared vertical and horizontal strains resulting from longwall mining with values calculated from the NCB method. Much of the overburden there is weak shale, grossly similar to the British coal fields. Maximum compressive and tensile horizontal strains determined at the mine were more than twice the predicted values. The NCB method predicted 25 percent less vertical tensile strain than was actually measured. The York Canyon mine subsidence profile was similar in shape, however, to the NCB model. Presence of a strong 12-m-thick sandstone, strong jointing, and mountainous terrain may account for some of the observed differences.

SUBSIDENCE MODELS FOR IN SITU ENERGY EXTRACTION

The subsurface voids remaining after in situ processes such as coal gasification and oil shale retorting will not closely resemble the voids created by coal mining. The change in load-supporting ability of the surrounding rock mass in such "partial extraction" processes may be difficult to determine, and until field measurements are available, the prediction of subsidence effects for in situ extraction will be based mainly on mathematical analyses such as computer solutions of finite element codes. Examples of current practice in this area are given by Langland and Fletcher (1976) and Advani and Lin (1977).

The mathematical solutions have several limitations. Among them are:

1. The solutions are valid only for geometrically simple openings.
2. The material is assumed to be isotropic, homogeneous, and elastic.
3. The effects of water and geologic strucure are not considered.

Mead and others (1978) discussed prediction and measurement of subsidence produced by in situ coal gasification. It is important that early monitoring be conducted to measure ground deformations produced by these types of mining operations so that their subsidence characteristics can be verified.

MONITORING METHODS

Geotechnical measurements are made in order to establish the validity of model predictions and to safeguard surface structures. The monitoring methods and types of instruments used must be carefully selected so that their data output is compatible with the data needed for subsidence calculations.

SURFACE INSTRUMENTATION

Our intent is to briefly describe current monitoring practice, rather than to present a specific set of guidelines. A premining survey should be made to identify geologic conditions or surface facilities that would warrant changes in a conventional monitoring scheme.

The most widely used and important type of subsidence-monitoring measurement is surface leveling. Monuments are installed before mining begins, and readings are taken until stability is reached after mining ceases.

A typical subsidence monitoring layout for a 762-m by 168-m longwall panel below mountainous terrain is shown in figure 11. In this example the seam thickness is approximately 3 m and the average overburden thickness is 107 m. One row of monuments was placed along the centerline of the planned panel and another row perpendicular to the centerline. Two diagonal lines were established radiating from the centerline at 45°. These lines were added to define subsidence effects above the corners of the longwall panel.

For monitoring most coal mine panels in flat terrain, three lines of surface monuments are adequate, two perpendicular to the long axis of the mining panel and one directly above the centerline of the panel. The cross-panel lines should extend 0.9 times the depth of the seam outside the panel on both sides and completely across the panel. The centerline monuments should also extend 0.9 times the depth of the seam outside the starting position of the panel and the same distance past the planned end of the panel. If the panel is terminated because of poor roof conditions or faulting, for example, the centerline monuments can be shortened accordingly. These recommendations

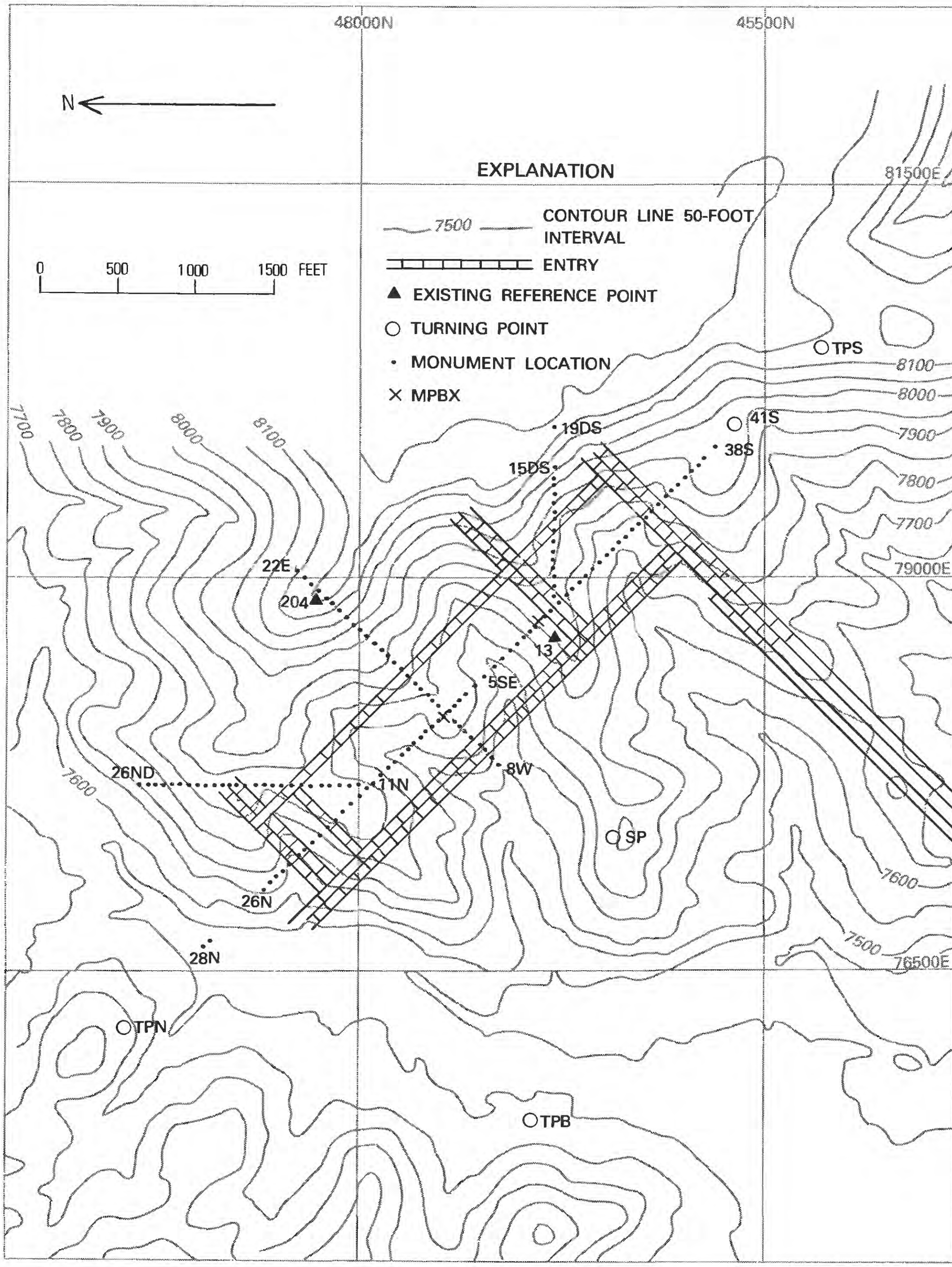


Figure 11.—Location of surface monuments, turning points, and reference points for part of the York Canyon mine, Raton, New Mexico (from Gentry and Abel, 1978).

are in general agreement with current practice in the United States (Wade and Conroy, 1980; Gentry and Abel, 1978).

SPACING OF MONUMENTS

The spacing of monuments directly influences measurement precision. Monuments that are spaced too closely may result in measurement of local anomalous ground movements caused, for example, by the displacement of individual joint blocks in which the monuments are anchored. Widely spaced monuments may reduce costs but could fail to adequately define the subsidence profile, particularly in mountainous terrain. The NCB (1975) suggests a spacing of 0.05 h (where h is equal to the depth of the overburden) or one-twentieth of the depth of mining. Panek (1970) recommended a monument spacing of 0.05–0.1 h.

The presence of critical surface structures may also dictate the location and spacing of monitoring positions. For most situations the monument spacing should probably not exceed 0.1–0.2 h. This relatively wide spacing allows determination of vertical ground movements and permits a rough check of the horizontal strain measurements obtained by extrapolation from the relatively smooth vertical subsidence profile. Spacing monuments more closely in order to better define horizontal deformations is probably not justified. According to Orchard and Allen (1965, p. 622), for example, "It is a fact that although levels taken before and after subsidence will usually produce a smooth subsidence profile, the strain diagram obtained from horizontal measuring between survey stations is often erratic." They attribute this situation to "irregularities" in the subsoil. At the York Canyon mine (Gentry and Abel, 1978), horizontal movement measurements were less reliable than vertical measurements, apparently because of shifting and tilting of the joint blocks on which the concrete monuments were anchored; movement of the joint blocks affected horizontal measurements more than vertical measurements. Additional details of generally accepted monument layout and construction are given by Wade and Conroy (1980) and Gentry and Abel (1978).

Monuments should be surveyed at least twice before starting panel extraction, and any discrepancies should be resolved by an additional survey. The frequency of readings is determined by the rate of movement of the face, seam thickness extracted, and monument spacing. The centerline monuments should be surveyed when mining of the panel has advanced 1.9 times the seam depth. Each row of crossline monuments should be surveyed when mining has progressed 1.0 times the depth past the crossline. All monuments should be resurveyed after panel completion and yearly until no further changes in monument positions are detected. Survey procedures and the need for long-term monitoring are addressed by Collins (1978). Gentry and Abel (1978) give detailed specifications for monument construction and monitoring equipment.

SUBSIDENCE CONTROL AND REDUCTION

An obvious conflict exists between minimizing subsidence and maximizing resource recovery. In some areas more surface settlement can be tolerated than in others. In urban areas, for example, less than 50 percent of the resource may be recovered in order to prevent subsidence. In many European coal fields where overburden thicknesses range from 60 to 900 m, deformation arches are stable within the overlying rocks, and subsidence does not reach the surface if the widths of mined-out areas are held from one-fourth to one-half of the overburden thickness (Zwartendyk, 1971). Much coal must be left in the ground in order to obtain this high degree of surface stability.

In the United Kingdom, a "panel and pillar" method has been used with success when mining beneath towns, factories, railroads, and utility lines. The panels were mined without backfilling, and little subsidence damage occurred. Subsidence ratios were less than 20 percent of the coal thickness above mined panels whose widths were about one-third the average overburden depth.

In sedimentary iron ore deposits of the Lorraine area of France, support pillars were left in a checkerboard pattern; this method was abandoned, however, because of subsidence problems associated with severe pillar bursts. The geometry of the mining plan was changed to create sturdy barrier pillars separating panels whose widths were 0.42 times the overburden depth. These pillars sustained the compression arch within the overburden, minimizing subsidence and allowing safe recovery of 60 percent of the total reserves.

Another mining technique developed in The Netherlands coal mines is known as harmonic mining. This technique involves mining in such a way that the final vertical and horizontal surface strains produced by mining in one area are canceled by strains produced by mining in another area. For example, mine extraction panels might be offset and mined concurrently so as to produce negligible final horizontal strain in the overburden or at the surface perpendicular to the mining panels. Several drawbacks exist, however, to this approach. Damaging transient strains and compression arches can be produced at the surface. The method might also cause high stress concentrations in the rock between coalbeds at the mine boundaries which could cause rock bursts and serious roof falls. Further, mining schedules must be very precise under this system to maintain the required geometry. Other factors that would lessen the effectiveness of this method are uneven topography and steeply dipping coal beds.

Backfilling of mined-out areas in room-and-pillar mines has been effective in preventing subsidence. This method is used primarily in mines below urban areas where surface stability is critical. Backfilling materials may be placed manually, hydraulically, or pneumatically and may consist of sand or larger grained mine waste. Hydraulic backfilling is generally most efficient, and maximum subsidence is frequently less than 10 percent of the seam thickness extracted. The example given previously of backfilling with coal waste at Farmington, W. Va., illustrates the effectiveness of this method.

DESIGN PRECAUTIONS

Buildings and other structures can be designed to resist or tolerate subsidence deformations. Very flexible structures remain intact (and conformable) despite subsidence-caused distortion and, alternately, very rigid foundations have been developed that can be releveled by the use of jacks as subsidence progresses. The design of support mechanisms for facilities built over old mine workings involves a careful appraisal of subsurface conditions. Support by fill, caissons, or piers using boreholes may be feasible.

CONCLUSIONS

Although the damaging surface effects of underground mining have been widely documented, little research has been carried out to determine accurately the effect of subsidence on surface structures under specific geologic conditions in the United States. Further, the potentially broad disruptive effects of mining on water supplies have been studied at only a few domestic locations.

Some of the factors that influence the development of ground movement cannot be quantified precisely. The differences in rock-mass behavior caused by site conditions alone would indicate that subsidence prediction and engineering cannot be treated in purely mathematical terms. Although the NCB has developed quantitative, practical assessments of mining effects in the United Kingdom, there is no generally applicable subsidence model for the United States, nor are there adequately tested, empirical models for any of the major U.S. coal fields: the Appalachian, Interior, or Rocky Mountain. The influence of local geologic environments and mining methods on subsidence in the United States will require the collection of large masses of data in order to construct several accurate prediction models. Virtually no data base exists from which to forecast the surface effects of the various proposed in situ extraction techniques.

The behavior of rock units above longwall operations has been shown to be more accurately predictable than for room-and-pillar mining. An accumulation of quantitative data in the United States similar to that of the NCB for longwall mining would be valuable in establishing sound domestic empirical or mathematical subsidence models. The tools, techniques, and knowledge exist to conduct a coordinated nationwide subsidence research program. If the development of subsidence technology can lessen costly environmental or structural damage, the cost of this development will be repaid.

GLOSSARY

Angle of draw. The angle formed by the vertical and a line drawn from the edge of the underground workings (rib-side) to the point of zero subsidence on the ground surface. *Also called* limit angle.

Arching effect. The mining-induced process by which the roof bows upward spanning the mined-out area and tending to prevent roof falls. The span width is controlled by many factors including depth, seam thickness, mining method, rock strength, structure, and in situ stresses.

Back. Roof of a mine or tunnel.

Backfilling. Placement of material in underground workings in order to retard collapse of roof and pillars and to reduce subsidence.

Barrier pillar. A solid block or rib of coal left unmined between two mine workings for protection against water inflow or squeezing conditions.

Bay. *See* panel.

Block caving. A stoping method of mining in which a thick block of ore is partly isolated from surrounding blocks by a series of drifts. The block is undercut by removing a slice from under the block causing it to cave under its own weight. The broken ore is removed from below, and as the caved mass moves downward, it is further broken by pressure and attrition.

Breakthrough. A passage cut through a pillar to facilitate ventilation from one room to another.

Bulking. The increase in volume, by virtue of increased void volume, of mined rock.

Butt cleat. The minor cleat system or jointing in a coal seam. *Also called* end cleat.

Chimney. Initial surface collapse above a mined-out area in crystalline rocks.

Cleat. A joint system in a seam along which the coal fractures. There are usually two cleat systems developed perpendicular to each other.

Critical subsidence profile. Subsidence profile drawn at the critical width.

Critical width. Width of extraction of coal seam at which the subsidence at the bottom of the trough has the maximum value.

Delayed subsidence. A variable amount of residual subsidence that occurs long after mining, usually controlled by lithologic properties. For example, a strong rock layer between the mine and the surface may retard the collapse process months or years.

Dip angle. The inclination from the horizontal of a seam or bed, measured perpendicular to the strike of the structure.

Extraction ratio. Ratio of mined-out area to the total planned mine area.

Face. A surface on which mining operations are in progress.

Face cleat. The major cleat system or jointing in a coal seam.

In situ. In the natural or original position; in place.

Leaching. The extraction of soluble metals or salts from ore by means of percolating water or other solutions.

Longwall. A method of mining coal or other resources in which the seam is removed in one operation by means of a long working face or wall. The workings (face) are advanced in a continuous line which may be several hundred meters long..

Mining Horizon. The level at which a deposit is mined.

Monument. A stake, rod, or concrete structure that is used to mark ground location points for mining surveys.

Overburden. The rock and (or) soil above a coal seam.

Panel. Areas of extracted coal, separated by long, solid barrier pillars.

Panel length. Dimension of a panel measured in the direction of face advance. *Also called* face length.

Panel width. Distance across a working coal face. *Also called* face width.

Pillar. Solid coal or ore left either temporarily or permanently to support the roof or prevent water inflow.

Powder factor. The amount of explosive used to mine a ton of rock or ore.

Percent recovery. The proportion of coal or other resource mined from a seam or deposit.

Residual subsidence. That amount of the total subsidence that occurs after the face leaves the critical area.

Retreat mining. A mining method by which a pillar of solid coal or ore is left until the final mining while pulling out of a room-and-pillar panel.

Rib. The side of a pillar or the wall of an entry.

Ribside. Edge of mine workings.

Room. An excavation driven from an entry from which coal or ore is produced.

Room and pillar. A method of mining coal or other resources in which the seam is mined in rooms separated by narrow pillars and in which 50 percent or more of the resource is removed during initial mining.

Solution mining. The in-place dissolution of mineral salts of an ore with a leaching solution.

Subcritical subsidence profile. Subsidence profile drawn at a subcritical width.

Subcritical width. Width of extraction of coal seam at which the bottom of the subsidence area is trough-like and has less than the maximum value.

Subsidence. Vertical component of ground movement.

Subsidence area. The entire surface area affected by subsidence over a high-extraction panel.

Subsidence basin. The depression at the surface above high-extraction mining panels.

Subsidence profile. A curve depicting subsidence of the ground surface on a section drawn parallel to the direction of advance of an underground excavation.

Supercritical subsidence profile. Subsidence profile drawn at a supercritical width.

Supercritical width. Width of extraction of coal seam at which the bottom of the subsidence trough is approximately flat at the maximum subsidence value.

Transition point. The point of transition between concave and convex curvature of a subsidence profile.

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