Chapter 10.6
MINE SUBSIDENCE

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10.6.1 INTRODUCTION

Subsidence is an inevitable consequence of underground mining— it may be small and localized or extend over large areas, it may be immediate or delayed for many years. During recent years, with the expansion of urbanization and increased concern for the environment, it is no longer possible to ignore its aftermath. In the United States, mining companies have, therefore, begun to devote attention to the subject and study it in a methodical manner. Appropriate regulations have also been promulgated by various government agencies, depending on the needs of the region, in order to protect the public interest.

The problems associated with subsidence have been recognized since the inception of mining and mentioned in the literature as far back as Agricola's *De Re Metallica* in 1556. The initial "vertical theory" was modified by the researches of Coulomb, Toillez, Gonot, Rziha, and Fayol (Peele, 1952). Significant contributions may also be credited to Rucloux, Durmond, Callon, Goupilliere, Schulz, von Sparre, von Dechen, Hausse, and Jicinsky (Peele 1952). In the early part of the century, Briggs (1929) presented his comprehensive treatise on the subject. In the United States, the early investigations of Richardson (1907), Young and Stoek (1916), Rice (1923), Rutledge (1923), Crane (1925, 1929, 1931), and Allen (1934) are notable. The motivation behind these studies was the severe damage caused to structures, communications, and agricultural lands; the victims (mostly property owners) demanded compensation and restitution from the mine operators, and frequently resorted to court action. In order to defend against unjustified claims, measurements of ground movements were made. These data, along with theoretical concepts on the development of these movements, gradually evolved into the subject of *mine subsidence engineering.* Courses specifically devoted to the subject have been taught in German academies since 1931 and in US universities only since 1963. The major objectives of subsidence engineering are

1. Prediction of ground movements.
2. Determining the effects of such movements on structures and renewable resources.
3. Minimizing damage due to subsidence.

Thus it is evident that subsidence engineering not only entails the study of ground movements, structural geology, and geomechanics (both soil and rock mechanics), but also encompasses a knowledge of surveying, mining and property law, mining methods and techniques, construction procedures, communications technology, agricultural science, hydrology and hydrogeology, urban planning, and socioeconomic considerations.

Although the mining of all underground minerals may result in subsidence, most studies to date have concentrated on the extraction of flat bedded deposits—primarily coal. Hence throughout this discussion, reference to coal mining is made frequently. The information presented herein is, therefore, most pertinent to coal mining, although it generally applies to other bedded deposits. The principles may be also extrapolated to other mining methods, but the conclusions need validation by actual experience.

The pumping of geofluids, such as petroleum, natural gas, geothermal brines, and water, constitute "mining" in the strict sense and also cause subsidence. The effects of fluid withdrawal have been investigated at some length, although they are beyond the scope of this chapter. But the lowering of the water table in the region adjoining mining activity also induces ground movements, thereby causing surface damage, which must not be overlooked.

The term *subsidence,* as used in this chapter, implies the total phenomenon of surface effects associated with the mining of minerals and not only the vertical displacement of the surface as is sometimes inferred in the literature.

10.6.2 PRINCIPLES OF SUBSIDENCE

10.6.2.1 Development of Subsidence

Whenever a cavity is created underground, due to the mining of minerals or for any other reason, the stress field in the surrounding strata is disturbed. These stress changes produce deformations and displacements of the strata, the extent of which depends on the magnitude of the stresses and the cavity dimensions (Chapter 10.2). With time, supporting structures deteriorate and the cavity enlarges, resulting in instability. This induces the superjacent strata to move into the void. Gradually, these movements work up to the surface, manifesting themselves as a depression. This is commonly referred to as subsidence. Thus *mine subsidence* may be defined as ground movements that occur due to the collapse of the overlying strata into mine voids. Surface subsidence generally entails both vertical and lateral movements.

Surface subsidence manifests itself in three major ways:

1. Cracks, fissures, or step fractures.
2. Pits or sinkholes.
3. Troughs or sags.

Surface fractures may be in the form of open cracks, stepped slips, or cave-in pits and reflect tension or shear stresses in the ground surface.

When the area of surface collapse into the mine void is relatively small, the subsidence is termed a *pit* or *sinkhole;* generally, these are associated with shallow room and pillar mining. In Britain, the terms "crownholes," "chimneys," or "pipes" are also used to describe this phenomenon. In time, these pits may enlarge and coalesce to form trenches. Frequently, the walls of the pit intersect the surface precipitously, and the pit diameter increases with depth. The depth of pits is generally limited: 100 ft (30 m) in Pennsylvania (Gray et al., 1977), 165 ft (50 m) in Illinois (DuMontelle et al., 1981), or 10 to 15 times seam thickness, based on studies primarily in Colorado, Utah, and Wyoming (Dunrud and Osterwald, 1980).

When the mine void is of larger size due to longwall mining or eventual collapse of pillars, the collapsed strata fall into the excavation and bulk (i.e., broken material occupies a larger volume than in situ rock). This process continues until a height is reached of about three to six times the mined seam thickness (Singh and Kendorski, 1981), unless the material spreads or is transported to other parts of the mine by water. Cyclical wetting and drying of the debris could also induce greater compaction.

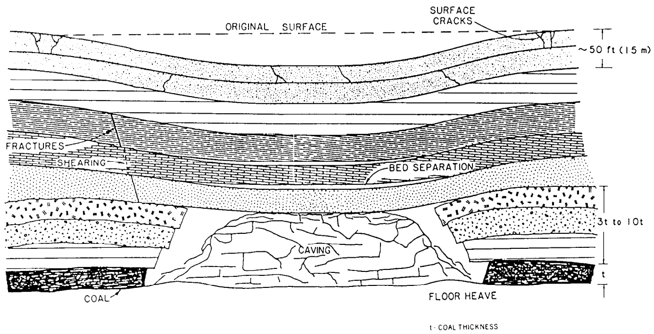

Fig. 10.6.1. Strata disturbance and subsidence caused by mining (Singh and Kendorski, 1981).

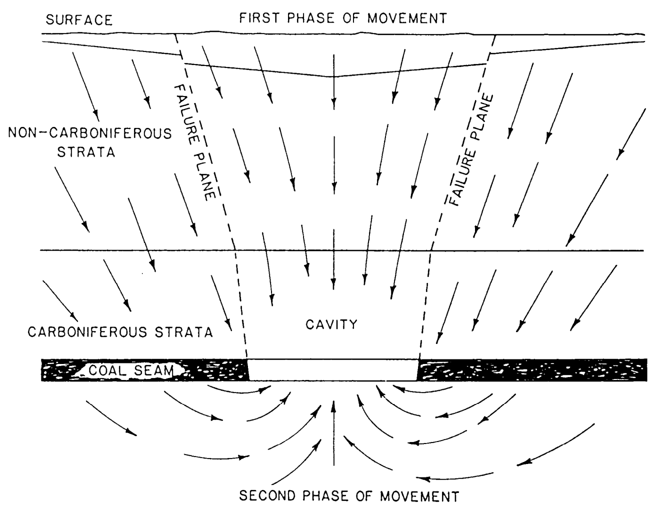

Fig. 10.6.2. Schematic representation of ground movements due to subsidence (Grond, 1957).

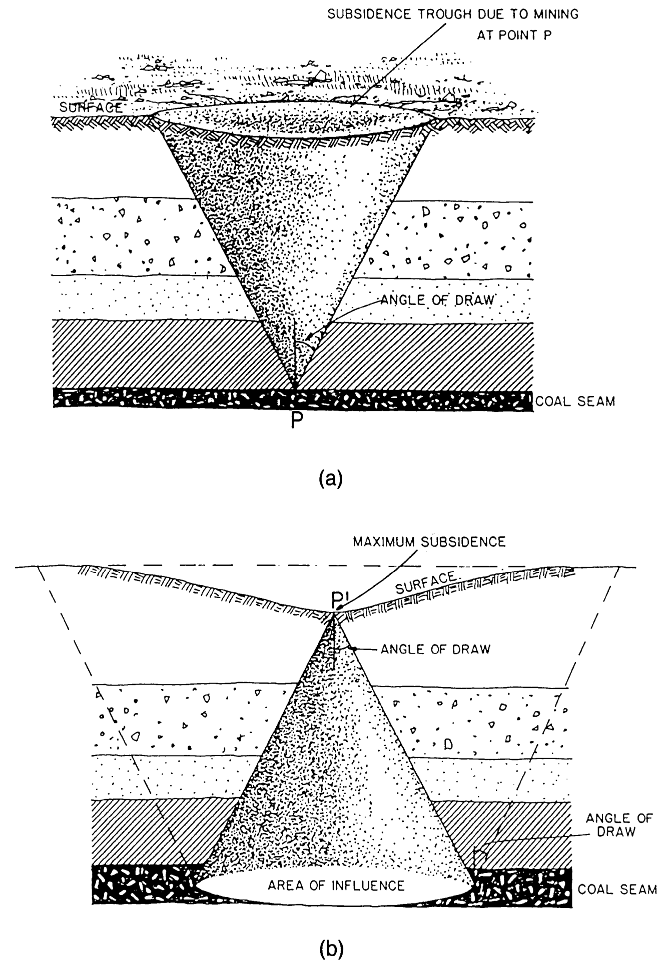

Fig. 10.6.3. Sketch depicting area of influence. (a) Effect on surface by mining at P. (b) Maximum subsidence at P′ by mining entire area of influence.

When the cavity is essentially filled with broken rock, the debris offers some support to the superjacent beds (Fig. 10.6.1). As these strata settle or sag, bed separation may occur because of the tendency for lower strata to subside more than the higher beds. Overall, as the various strata settle or subside, they sag rather than break and produce a dish- or trough-shaped depression on the surface. This type of feature normally covers a larger area than sinkholes, and is referred to as *trough* or *sag subsidence.* Trough subsidence may occur due to mining at any depth. The overall movements of the ground around the opening are depicted in Fig. 10.6.2; the direction of motion is not only vertically downward but also horizontal and, in some locations, upward.

The mining of a single point P (Fig. 10.6.3a) at seam level will affect a circular area on the surface, defined by the base of an inverted cone with P as the apex and the limit angle *g* as the semi-angle of the cone. If this cone is turned upright, then the mining of any part of its base will influence the subsidence of its apex P (Fig. 10.6.3b). Hence, this circular area is termed the *area of influence.* This implies that the diameter of the area of influence is given by $2D \tan g$, where D is the depth of the seam below the surface and g is the limit angle. (It may be noted that some authors use the complement of the limit angle, often termed the “angle of major influence.“) This diameter also defines the *critical width* of the workings, which is the minimum width that needs to be mined before the maximum possible subsidence is observed at the center of the trough. If the mined width is less than critical, it is termed *subcritical,* and the amount of subsidence that occurs will be less than the maximum. If a *supercritical* (i.e., larger than critical) width is excavated, the central portion of the trough will attain maximum subsidence, and a flat-bottomed depression will be produced (see Fig. 10.6.4).

If the vein being extracted is relatively flat and nearly horizontal, as is generally the case with coal and potash, the overburden and surface collapses or subsides forming a *depression* or *trough.* The surface area affected by mining is generally larger than the vein area excavated. Hence the angle of inclination between the vertical at the edge of the workings and the point of zero vertical displacement at the edge of the trough is termed the *limit angle* or *angle of draw.* It is evident that the limit of surface subsidence depends upon the precision with which the subsidence is measured. By convention, this is taken to be the contour of points that have subsided vertically by 0.01 ft (3 mm). It is also a function of the vein dip and the geology of the area.

10.6.2.2 Movement of the Subsidence Curve

As subsidence occurs, there is a movement of surface points towards the center of the mined area. The amount of vertical

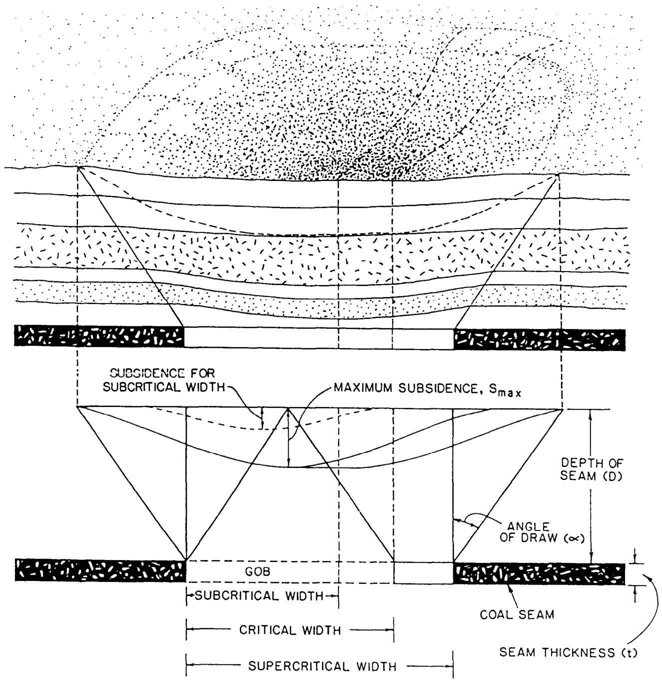

Fig. 10.6.4. Influence of extraction width on subsidence.

displacement experienced is greatest at the center while the horizontal displacements are least at the center and edges of the trough and maximum at, or close to, the edges of the mined area. Since these lateral movements are not uniform, there are changes in the lengths per unit length (i.e., strains), along any cross section of the mined panel. These strains tend to stretch the surface near the edges of the trough (i.e., these are tensile), and push inward within the boundaries of the extracted area (compressive strains; see Fig. 10.6.5). Both the tensile and compressive horizontal strains disappear at the center of the subsidence trough in the case of critical- and supercritical-width workings. Fig. 10.6.6a shows the progressive development of the mine working and the subcritical, critical, and supercritical widths being formed. As the mine workings progress, the horizontal tensile and compressive strain regions also move along (Fig. 10.6.6b). Hence these are also referred to as traveling strains.

The inclination to the vertical of the line connecting the edge of the mined area with the surface point exhibiting the maximum tensile strain is called the *angle of break* or *angle of fracture* (Fig. 10.6.7). These terms should not be confused with the draw or limit angle defined earlier. Generally, the angle of break is somewhat higher with subcritical-width workings than with critical- or supercritical-width workings for a given region.

10.6.2.3 Components of Subsidence

Subsidence consists of five major components, which influence damage to surface structures and renewable resources (see Fig. 10.6.7):

1. *Vertical displacement* (settlement, sinking, or lowering).
2. *Horizontal displacement* (lateral movement).
3. *Slope* (or tilt), i.e., the derivative of the vertical displacement with respect to the horizontal.
4. *Horizontal strain,* i.e., the derivative of the horizontal displacement, with respect to the horizontal.

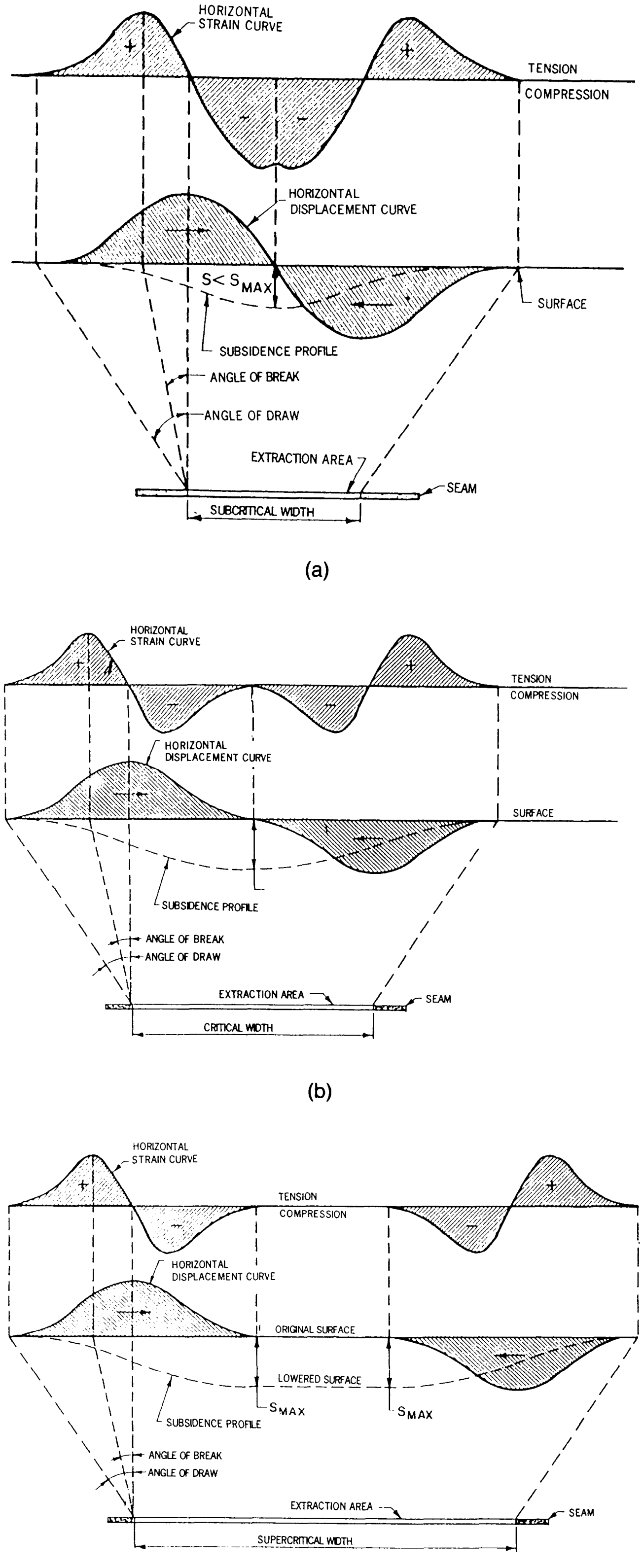

Fig. 10.6.5. Schematics of displacement and strain curves for various working widths. (a) Subcritical width. (b) Critical width. (c) Supercritical width.

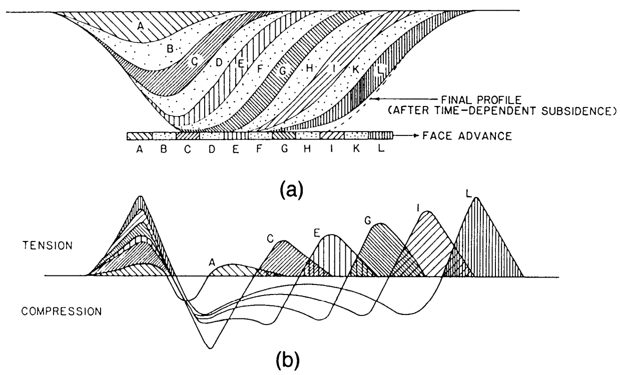

Fig. 10.6.6. Development of subsidence trough and strains with face advance (Rellensman and Wagner, 1957). (a) Subsidence development. (b) Traveling strain curve.

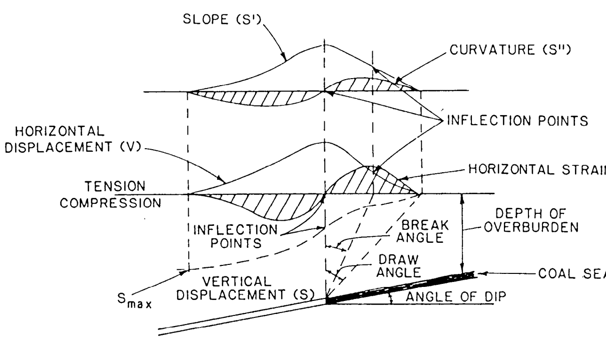

Fig. 10.6.7. Schematic of ground movements caused by subsidence (Singh, 1978).

5. *Vertical curvature* (or flexure), which may be approximated by the derivative of the slope, or the second derivative of the vertical displacement with respect to the horizontal.

Vertical displacements alone cause little structural damage. Examples of an observation tower having sunk 30 ft (9.2 m) in a coalfield, mining structures subsiding a similar amount around the sulfur mining areas off the coast of Louisiana, and a church in a potash mining district having settled 20 ft (6.2 m), all without significant damage, have been quoted in the literature. However, lowering of the land may cause some parts to be inundated, so that drainage patterns in agricultural areas may require redesign, flow through pipes may be disrupted or reversed, the groundwater circulation may be dislocated, and the grade of roads or railways may be altered.

Uniform horizontal movements of the ground surface also cause little damage to structures. But breaks in pipes, electric or communications lines, roads, and other features may occur.

Differential vertical settlements cause slopes to form and induce tilting. Maximum slopes in a subsidence trough generally range between 2×10^{-3} to 20×10^{-3}, but may reach 150×10^{-3} for multiple-seam extraction (Brauner, 1973). The formation of slopes may cause structures to tilt, the gradients of railroad tracks and highways to change, and tanks to overflow, and interfere with gravity drainage.

Surface horizontal strains cause most of the damage to structures located above mined areas. They cause tensile or shear cracks and buckling. Masonry structures withstand compression much better than tension. Strains may induce distortion, fractures, or failure. The weaker parts of the structure (e.g., openings) and the lower part of the frame are the first to show tension cracks. Pipes, cables, roads, railways, walls, and other building components buckle readily under compressive strains. Generally, the strains due to mining range between 1×10^{-6} and 10×10^{-6} (Brauner, 1973). The extent of strain transfer from the ground to foundations is not well established.

Curvature causes two types of distress on structures: (a) *shear strain*, which induces angular changes and tends to distort buildings out of square (distortion is generally proportional to structure height): and (b) *flexure* or *bending*, which causes strains in long load-bearing members. Concave curvature causes tension along the bottom and compression along the top of the building. The dimension of curvature is the inverse of length. Hence generally, the reciprocal of the curvature (i.e., radius of curvature) is quoted. For mine subsidence, this normally varies between 3200 ft (1000 m) and 6600 ft (2000 m), and seldom falls below 1600 ft (500 m) (Brauner, 1973).

10.6.2.4 Factors Affecting Mine Subsidence

Several geologic and mining parameters and the nature of the structure affect the magnitude and extent of subsidence that occur due to coal mining (Henry, 1956; King and Whetton, 1957; Sinclair, 1963; Cortis, 1969; Brauner, 1973; Chen et al., 1974; Anon., 1975).

Effective Seam Thickness: The thicker the seam extracted, the larger the amount of surface subsidence that is possible. In some cases, the entire seam may not be mined or some pillars or other nonminable coal may be left in place. Hence the effective seam thickness should be considered. In thick beds, the slenderness (height-to-width ratio) of the pillars is higher for a given extraction ratio. Slender pillars are normally more prone to failure.

Multiple Seams: Where multiple worked-out mining horizons exist, collapse could be initiated from any one of several levels, thereby increasing the likelihood of subsidence events, because the adjacent strata are disturbed. This is especially true when the prior mining was in an overlying seam.

Seam Depth: A school of thought exists that at greater depths, an arch is formed over the mine cavity, preventing surface subsidence. In recent years, this has been gradually refuted. Perhaps the time period that elapses before subsidence effects are observed at the surface is prolonged, but the total amount of subsidence does not appear to be changed; that is, subsidence is independent of depth (Orchard, 1964). Pit depths generally do not exceed certain limits, as discussed previously (see 10.6.2.1).

Dip of Seam: When the coal seam being mined is inclined, an asymmetric subsidence trough is formed that is skewed toward the rise; that is, the limit angle is greater on the dip side of the workings. The strains are also smaller toward the dip direction. Pillars in steeply dipping seams tend to be less stable.

Competence of Mine Roof and Floor: Since subsidence propagates from the mine level, the characteristics of the mine roof and floor are vital in the initiation of subsidence movements. Soft fireclay floors, especially if susceptible to further weakening due to moisture, induce pillar punching or heave. Weak roofs, composed of shales, siltstones, and limestones, permit falls that are accentuated if punching also occurs. Competent roof beds tend to support the overlying strata longer and hence delay the subsidence. Also, when these fracture, they occupy a greater bulk volume than weaker strata (which compact more). When both the roof and floor are strong, the pillars tend to spall and crush.

Nature of Overburden: Strong massive beds above the mine level tend to prop the overburden for a prolonged period and defer the occurrence of subsidence.

Near-surface Geology: The soils and unconsolidated rocks near the surface tend to accentuate subsidence effects. The geologic materials are less homogeneous and isotropic than the underlying strata, and often behave in an inconsistent manner. Cracks and fissures may initially form in a 50-ft (15-m) thick layer from the surface (Singh and Kendorski, 1981). Later, these may be filled by plastic deformation or material transportation by water. Occasionally, however, water flow may accentuate these fissures and form gullies. Structures and renewable resource lands are thereby adversely affected.

The composition of the rock/soil cover is important; if the material is of a fine, sandy nature containing large amounts of water, it may flow to a rock fracture and drop into the underground workings. Besides, water accumulating in the abandoned mine may seep upwards into the unconsolidated strata above through natural fissures and cracks in the rock and increase the potential for soil collapse.

Geologic Discontinuities: The existence of faults, folds, and the like may increase subsidence potential. Mining disturbs the equilibrium of forces in the strata and may trigger movement along a fault plane, due to ease of slippage, causing either settlement or upthrust at the surface, which may appear as a series of step fractures. The effects of the other parameters may need to be discounted in areas of adverse geological conditions.

Lateral movements concentrate near the fault, but the strains may become immeasurable on either side. Structures that straddle fault planes tend to be severely damaged, but nearby buildings remain relatively intact. Joints and fissures in the strata affect subsidence behavior in a manner similar to faults but on a smaller scale.

Fractures and Lineaments: Natural fractures and lineaments affect surface subsidence, but a strong correlation has not been established to date.

In Situ Stresses: High horizontal stresses tend to restrain surface subsidence by forming a ground arch in the immediate mine roof (Lee and Abel, 1983). The arch height and stability are sensitive to the ratio of vertical to horizontal stresses. Highly stressed arches may fail violently (e.g., the Urad molybdenum mine, Colorado). Roof instability and floor heave, resulting from high horizontal stresses and their orientation, need to be taken into account when laying out coal mines in the Allegheny Plateau (Aggson, 1978).

Degree of Extraction: Lower extraction ratios tend to delay subsidence. It is less prevalent in areas superjacent to first mining, since sufficient pillar support is generally available without crushing of pillars. In second mining, the cross section of the pillars is reduced by splitting and slicing. Localized stress buildups promote crushing, and excessively wide roof areas exposed between pillars stimulate roof failure. Third mining is almost invariably followed by roof collapse in the workings. Surface manifestations are a function of time, dependent on the rate of upward propagation of settlement.

Surface Topography: As may be anticipated, sloping ground tends to emphasize downward movements because of gravity. Tensile strains may become more marked on hilltops and decrease in valleys. Surface effects are influenced accordingly.

Groundwater: Deformation of the strata around mined areas may alter drainage gradients, resulting in the formation of surface or underground reservoirs (in aquifers). Low-lying areas, such as in central Illinois, may become flooded. Rocks may be weakened by saturation. Erosion patterns could change, and in limestone areas, caverns or karst areas may be created over a period of time.

Where surface runoffs from precipitation or water from leaky mains are allowed to accumulate, water may percolate down through the soil to the fractures and fissures in the bedrock, and finally into the mine openings. The erosion and lubrication effects induce failure.

Water Level Elevation and Fluctuations: Water reduces the strength and stiffness of pillars and the roof and floor markedly. Periodic changes in mine humidity promote deterioration of all these members. Floor softening permits punching, resulting in instability and subsidence. Flow through fissures cause seepage pressures, endangering the stability of the rock mass. Cleavage and bedding planes are lubricated by water, inducing movements.

Mined Area: The critical width needs to be exceeded along both the lateral and longitudinal axes to achieve maximum subsidence. This is especially important if competent strata present in the overburden tend to bridge across the panel and decrease subsidence when the panel width is less than the critical width, even though the length of the panel is greater.

Method of Working: The type of initial subsidence experienced, namely pit or trough, depends on whether room and pillar or longwall mining is being practiced. With room and pillar mining, the eventual collapse of pillars may lead to trenching or sagging of the surface. The displacements and strains over short distances, when they start appearing on the surface, are significant. Nearly immediate but predictable subsidence occurs with longwall mining. Harmonic mining, either by working adjacent longwalls in the same seam or superposed panels in different seams, can be effectively utilized to neutralize compressive and tensile strains and thereby protect surface structures. However, the method is not readily applied and is restricted for use only where mining costs become subservient to historical or social demands.

Rate of Face Advance: Surface subsidence follows the face as it progresses in the panel. If the coal extraction rate varies markedly, the traveling strains also fluctuate. This results in large differential settlements. A fairly rapid, even rate of face advance is best (Legget, 1972).

Backfilling of the Gob: Partial or complete backfilling of the gob reduces, but does not eliminate, subsidence. The amount of subsidence that occurs depends upon the type and extent of backfilling adopted. Thus, for example, hand packing is not as good as pneumatic stowing or hydraulic backfilling.

Time Elapse: The amount of subsidence observed is a function of time. In room and pillar operations, no surface effects may be noted for some time after the mining is complete until the pillars deteriorate or punch into the floor. In longwall mines, the surface may start sagging almost immediately after the face passes below an area. However, the occurrence of massive beds in the overburden could delay this. With longwalls, surface movements are complete within a few years, but when pillars are left intact for support, this may take decades. Room and pillar mining with removal of pillars may produce surface effects similar to longwall mining, with the degree of similarity dependent upon the amount of coal left as fenders or stumps (see also 10.6.3.4).

Structural Characteristics: The extent of damage to a structure is dependent on the type of structure and its size, shape, age, foundation design, construction materials and techniques used, standards of maintenance and repair, and purpose (Chen et al., 1974). The surcharge due to building loads may induce soil compaction, generating instability. Tall structures cannot tolerate much tilt, poorly constructed or older buildings are more readily damaged, and a large edifice is more liable to crack because of the strains and curvature induced by subsidence.

10.6.3 SUBSIDENCE PROFILES

10.6.3.1 Measurement of Subsidence

In order to make subsidence measurements, it is essential to erect monuments that will undergo the same vertical or horizontal displacements as the ground. Several designs of monuments have been used, some of which are depicted in Fig. 10.6.8. Whichever design is selected for use, it should be stable and firmly anchored about 5 ft (1.5 m) below the ground surface so as not to be affected by frost or other surface effects.

The choice of measuring instruments that may be used for subsidence measurements depends on a number of parameters (Panek, 1970):

1. Objectives of the investigation.
2. Area to be covered.
3. Topography of the region.
4. Profiles along which monuments are installed.
5. Spacing and number of monuments or observation stations.
6. Total cost that can be tolerated.
7. Duration of the investigation; survey frequency.
8. Labor requirements for surveying and data reduction.

The horizontal distance between monuments depends on the subsidence gradient. Generally, however, a compromise has to be reached between placing the monuments too close, which increases installation and measurement cost, and too far apart, which does not give enough readings to depict the measured variables adequately. The British National Coal Board (NCB) (Anon., 1975a) has recommended a monument spacing of $0.05D$, where D is the depth of the mined bed. In the United States, the tendency is to increase this distance (Deere, 1961; Gentry and Abel, 1978), and spacings of $0.05D$ to $0.1D$ have been advocated (Panek, 1970). The accuracy of the measurements should be such as to detect strains of 10^{-4}, which is about 1/10th the strain-level for structural damage. The method of measurement and the precautions necessary depends on the distance between monuments and may be obtained from any text on surveying (see also Chapter 8.2; Panek, 1970; O'Rourke et al., 1977).

Vertical displacements may be measured by trigonometric leveling (precision optical or laser), differential leveling, or tilt measurement. When using the theodolite, vertical angles must be measured correct to ½ second of arc. With precise leveling, a micrometer direct reading to about 0.005 ft (1.5 mm) should be employed. An inclinometer with a sensitivity of 10 seconds of arc is generally adequate for subsidence measurements. Second-order subsidence surveys with geodetic level and invar scale or equivalent, should close within $0.035(M)^{1/2}$ feet, where M is the circuit length in miles (Moffitt and Bouchard, 1975), an accuracy of 0.01 ft (3.3 mm) over a 1000-ft (305-m) line. In mountainous or swampy areas, third-order control with a closure of $0.052(M)^{1/2}$ ft may be used, an accuracy of 0.02 ft (6.5 mm) in 1000 ft (328 m). Tiltmeters for use in long-term (several years) subsidence surveys have been developed (e.g., Jacobsen et al., 1975; Holzhausen, 1986).

Automatic data acquisition systems (ADAS) for subsidence have also been used. One device employs one angular displacement transducer to measure tilt and another with an invar wire between monuments to ascertain linear displacement (Schmechel et al., 1977).

10.6.3.2 Subsidence Prediction

Existing subsidence prediction techniques fall under two basic categories, empirical and phenomenological (Voight and Pariseau, 1970; Brauner, 1973; Singh, 1978). The empirical theories are principally based on observations and experience from field subsidence studies. Some of the empirical methods have proved sufficiently reliable for subsidence prediction, at least for a given region. Many of these have been successfully applied in a number of countries, especially in Europe. Phenomenological techniques are based on equivalent material modeling principles where the subsiding strata are mathematically represented as idealized materials that obey the laws of continuum mechanics. Unlike empirical methods, the procedures used in the latter category have not achieved much success to date, mainly due to the difficulty of representing complex geologic properties of the strata in simple mathematical terms.

Promising empirical methods for prediction of subsidence over underground mines consist of the following:

1. Graphical.
2. Profile functions.
3. Influence functions.

Graphical Method: This simply involves displaying subsidence data in the form of graphical charts or nomographs, whereby subsidence magnitude and the associated parameters may be directly obtained for a specified set of mine parameters. This method is adaptable in areas where considerable subsidence data exist, and its applicability is generally restricted to relatively few, geologically similar regions. This technique has seen considerable use in the United Kingdom (Anon., 1975a).

Profile Functions: This involves the derivation of a mathematical function that can be used to plot a complete profile of the subsidence trough at the surface. It differs from a phenomenological approach in that the constraints employed in the profile function are empirically derived from observed data. This method can be readily applied to geologically dissimilar conditions by modifying the constant values. Profile functions have been successfully applied in several countries abroad such as Poland, Hungary, the Soviet Union, and currently in the United States (Gill, 1971; Brauner, 1973; Munson and Eichfeld, 1980; Adamek and Jeran, 1981; Hood et al., 1981; Peng and Cheng, 1981; Wardell, 1982). Selected profile functions are given in Table 10.6.1.

Influence Functions: This principle for subsidence prediction is based on the extraction of infinitesimal elements of area. Subsidence at any point on the surface is obtained from the sum of the influence of each extracted element, using the principle of superposition. Unlike profile functions, influence functions cannot be found directly by measurement. In addition, this method assumes a homogeneous, isotropic overburden material and, therefore, has limited accuracy. In general, influence functions have been found to be especially suitable for subsidence prediction over underground workings with irregular or complex geometries. This method has received considerable attention in Europe, and to a limited extent in this country (Sinclair, 1963; Gill, 1971; Brauner, 1973; Adamek and Jeran, 1981; Hood et al., 1981; Karmis et al., 1981; Peng et al., 1986). Table 10.6.2 depicts a few influence functions.

Phenomenological Methods: These are primarily based on the principles of continuum mechanics and assume the media to be elastic (Salamon 1963–4; Berry, 1969; Plewman et al., 1969; Crouch, 1973), viscoelastic (Marshall and Berry, 1967), plastic (Pariseau and Dahl, 1970), and elastic-elastoplastic (Dahl and Choi, 1974). Only the elastic-plastic model has been used with success in the United States (Dahl and Choi, 1974; 1981). Recently an elastic, frictionless, laminated model has been proposed (Salamon, 1989). Subsidence predictions using these various approaches are demonstrated in the following example.

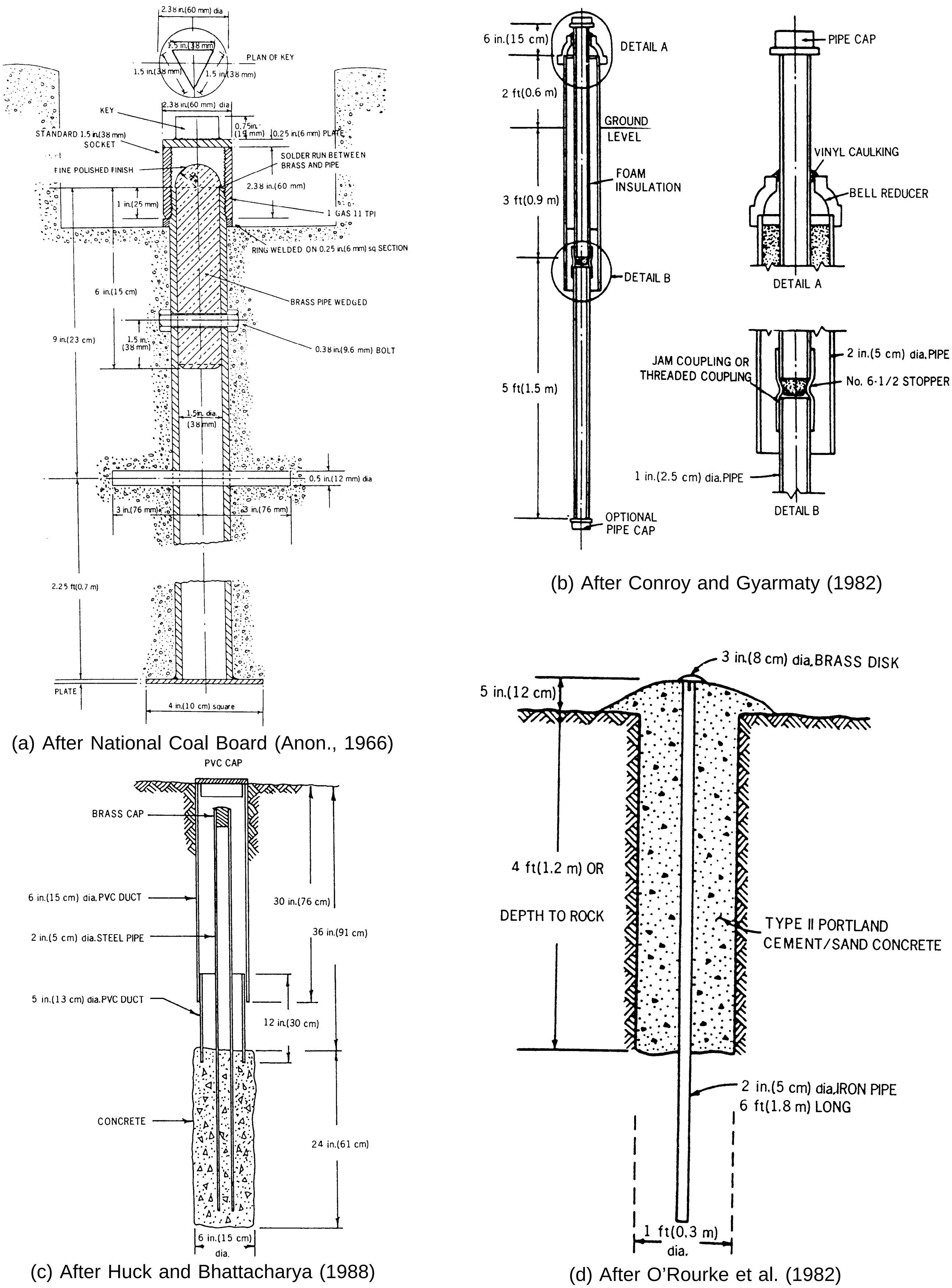

Fig. 10.6.8. Various subsidence monument designs.

Table 10.6.1. Profile Functions

Name	Function	Country/Area	Reference
Critical Extraction:			
Hyperbolic	$S(x) = \frac{1}{2} S_{max} \left[1 - \tanh\left(\frac{cx}{B}\right)\right]$	UK	King and Whetton (1957) Wardell (1965) Cherny (1966)
Error	$S(x) = \frac{1}{2} S_{max} \left\{1 - \left[\frac{2}{(\pi)^{1/2}} \int_{O}^{(\pi x/B)} exp(-u^2)du\right]\right\}$	Poland/ Upper Silesia	Knothe (1953)
Exponential	$S(x) = S_{max}\, exp\left[-\left(\frac{1}{2}\right)\frac{(x+B)^2}{B^2}\right]$	Hungary	Martos (1958) Marr (1958–59)
	$S(x) = S_{max}\, exp\left[-\left(\frac{cx}{B}\right)^d\right]$	US/Appalachia	Peng and Cheng (1981)
Trignometric	$S(x) = \frac{1}{2} S_{max} \left[1 - \left(\frac{x}{B}\right) - \left(\frac{1}{\pi}\right)\sin\left(\frac{\pi x}{B}\right)\right]$	USSR/Donets	General Institute of Mine Surveying (Anon., 1958)
	$S(x) = S_{max} \sin^2\left[\left(\frac{\pi}{4}\right)\left(\frac{x}{B} - 1\right)\right]$		Hoffman (1964)
Subcritical Extraction:			
Trignometric	$S(x) = S_{max}\,(n_1, n_2)^{1/2}\left[n^2\left(1 - x + \frac{\sin 2\pi x}{2\pi}\right) + \frac{1-n^2}{4}(1 + \cos \pi x)^2\right]$	USSR/Donets	General Institute of Mine Surveying (Anon., 1958)
Hyperbolic	$S(x) = \frac{1}{2} S_{max}\left[\tanh\frac{2(x+w)}{B} - \tanh\frac{2x}{B}\right]$	Poland/ Upper Silesia	Knothe (1957) Wardell and Webster (1957)
		US/Appalachia	Peng (1978)

x = horizontal distance
c = arbitrary constant
B = radius of critical area of excavation
u = integration variable
w = panel width
$S(x)$ = profile function
S_{max} = maximum possible subsidence
n_1, n_2 = coefficients related to width/depth
n = n_1 or n_2 depending on side of panel

Source: Updated from Brauner (1973) and Hood et al. (1981).

Example 10.6.1. Mine M, located in the Appalachian coalfield, is worked by the longwall method and has the following dimensions for a panel:
Depth of seam D = 213 m (700 ft)
Extraction height of seam h = 1.83 m (6 ft)
Panel width w = 152 m (500 ft)
Panel length L = 1219 m (4000 ft)

Solution.

(1) *Graphical Method (NCB)*

The National Coal Board (NCB) procedure has been selected as an example of the graphical method because of its wide use in this country in the past. The method is, however, becoming less popular in the United States, and thus the graphs presented by the National Coal Board (Anon., 1975a) are not reproduced in the interest of space. Reference is made instead to the figures in the original publication.

Step 1: From NCB, p. 9, Fig. 3, for w = 152 m (500 ft) and D = 213 m (700 ft), the subsidence factor, a = 0.68.

Hence the maximum possible subsidence,

$$S_{max} = ah = 0.68 \times 1.83 \qquad (10.6.1)$$
$$= 1.24 \text{ m } (4.1 \text{ ft})$$

Step 2: Since $\frac{w}{D} = \frac{152}{213} = 0.71$, from NCB, p. 13, Fig. 5, the values of $\frac{x}{D}$ (i.e., distance x from the center of the panel, in terms of the depth D) can be read off at various subsidence ratios, 1.00 S, 0.95 S, 0.090 S, . . . (see Table 10.6.3a).

For D = 213 m (700 ft), the values of distance d may be computed, as in Table 10.6.3a.

Step 3: From these data, the subsidence profile, $S(x)$, may be plotted (Fig. 10.6.9).

Step 4: Based on prior experience, the method assumes that the point of inflection occurs at 0.5 S_{max} = 0.62 m (2.05 ft), i.e.,

Table 10.6.2. Influence Functions

Function	Reference
$\phi(r) = \dfrac{S_{max}}{\pi\{\sin\gamma \cos\gamma + [(\pi/2) - \gamma]\}} \dfrac{B^3 \tan^3 \gamma}{r(r^2 + B^2 \tan^2 \gamma)^2}$	Bals (1932–33)
$\phi(r) = \dfrac{3\, S_{max}}{\pi\, B^2}\left[1 - \left(\dfrac{r}{B}\right)^2\right]^2$	Beyer (1945)
$\phi(r) = \dfrac{n\,(2)^{\frac{1}{n}}\, S_{max}}{\pi B \Gamma\,(1/2n)\, r}\, exp\left[-4\left(\dfrac{r}{B}\right)^{2n}\right]$	Sann (1949)
$\phi(r) = \dfrac{2\, S_{max}}{(\pi)^{3/2}\, Br}\, exp\left[-4\left(\dfrac{r}{B}\right)^2\right]$ when $n = 1$	
$\phi(r) = 0.216\, \dfrac{S_{max}}{Br}\, exp\left[-4\left(\dfrac{r}{B}\right)^6\right]$ when $n = 3$	
$\phi(r) = \dfrac{n\, S_{max}}{B^2}\, exp\left[-n\,\pi\left(\dfrac{r}{B}\right)^2\right]$	Litwiniszyn (1957)
$\phi(r) = \dfrac{S_{max}}{B^2}\, exp\left[-\pi\left(\dfrac{r}{B}\right)^2\right]$ when $n = 1$	
$\phi(r) = \dfrac{2\, S_{max}}{B^2}\, exp\left[-2\,\pi\left(\dfrac{r}{B}\right)^2\right]$ when $n = 2$	
$\phi(r) = \dfrac{4.6\, S_{max}}{\pi\, B^2}\, exp\left[-4.6\left(\dfrac{r}{B}\right)^2\right]$	Ehrhardt and Sauer (1961)
$\phi(r) = \dfrac{n\, S_{max}}{2\pi\, r_o^2\, \Gamma(2/n)}\, exp\left(-\dfrac{r}{r_o}\right)^n$	Kochmanski (1959)
$\phi(r) = \dfrac{7\, S_{max}}{B^2}\, exp\left(-6.65\, \dfrac{r}{B}\right)$ when $n = 1$ and $B = 6.65\, r_o$	

r = radial distance from reference point
B = radius of critical area of excavation
γ = angle of draw
n = parameter for characterizing strata conditions
$\phi(r)$ = influence function
S_{max} = maximum possible subsidence
Γ = gamma function
r_o = independent parameter

Source: Brauner (1973); Hood et al. (1981).

from Table 10.6.3a (or NCB, p. 13, Fig. 5), $\dfrac{x}{D}$ 0.36 so $x = 0.36 \times 213 = 76.7$ m (251.6 ft).

Step 5: The slope curve may be drawn from the subsidence profile by taking slopes at various points and plotting.

From NCB experience, the maximum slope is given by

$$2.75\,\frac{S_{max}}{D} = \frac{(2.75 \times 1.24)}{213} = 16.0 \times 10^{-3} \quad (10.6.2)$$

Step 6: The maximum values of extension and compression may be read off from NCB, p. 29, Fig. 15.

For $\dfrac{w}{D} = 0.71$, these are

$+E = 0.67\,\dfrac{S}{D}$, i.e.,

$+E = \dfrac{(0.67 \times 1.24)}{213} = 3.90 \times 10^{-3}$, and

$$-E = 0.83\,\frac{S}{D} = -4.83 \times 10^{-3}. \quad (10.6.3)$$

Now from NCB, p. 25, Fig. 12, the values of horizontal strain may be read off in terms of $\dfrac{x}{D}$ and then converted to x, as in Table 10.6.3b.

Step 7:

$$\text{Curvature } r = \frac{(\text{bay length})^2}{\text{differential of the strain}} \quad (10.6.4)$$

(i.e. second differential of subsidence)

Bay length is generally the distance between monuments. These are computed along with the curvature in Table 10.6.3b.

NOTE: All of the above calculations assume that both the seam and the surface are flat. If the surface is sloping, the adjustment in horizontal strain may be obtained from a nomograph (NCB, p. 31, Fig. 18). If, however, the surface is level, but the seam is dipping, the correction in the tensile strain is given in a table (NCB, p. 32, Table 6). The tensile strain on the dip side increases and that on the rise side decreases.

(2) *Profile Function*

A hyperbolic function has been demonstrated to fit well the subsidence characteristics of US mines (Peng and Chyan, 1981; Hood et al., 1981; Karmis and Jarosz, 1988), i.e.,

$$S(x) = 0.5\, S_{max}\left[1 - tanh\left(\frac{cx}{B}\right)\right] \quad (10.6.5)$$

where $c = 1.8$ for critical and supercritical widths, and $c = 1.4$ for subcritical widths (Karmis et al., 1986), and

$$B = D \tan\gamma \quad (10.6.6)$$

the radius of major influence.

For mine *M*, take $g = 25°$; hence $\tan g = 0.4663$, $D = 213$ m (700 ft). So $B = 99.3$ m (325.7 ft). Since the panel width is 152 m (500 ft), it is subcritical.

$$G(x) = S'(x) = -\frac{1}{2}\, S_{max}\, \frac{c}{B}\, sech^2\left(\frac{cx}{B}\right) \quad (10.6.7)$$

$$\rho(x) = S''(x) = \frac{c^2}{B^2}\, S_{max}\left[sech^2\left(\frac{cx}{B}\right) tanh\left(\frac{cx}{B}\right)\right] \quad (10.6.8)$$

For a flat seam, the horizontal displacement $u(x)$ and horizontal strain $\epsilon(x)$ are similar but related by a constant b, so that

$$u(x) = -\frac{1}{2}\,\frac{bc}{B}\, S_{max}\, sech^2\left(\frac{cx}{B}\right) \quad (10.6.9)$$

$$\text{and } \epsilon(x) = \frac{bc^2}{B^2}\, S_{max}\left[sech^2\left(\frac{cx}{B}\right) tanh\left(\frac{cx}{B}\right)\right] \quad (10.6.10)$$

Table 10.6.3. Computations for Ex. 10.6.1. Graphical Method

$S(x)$	0.00	−0.05	−0.10	−0.20	−0.30	−0.40	−0.50	−0.60	−0.70	−0.80	−0.90	−0.95	−1.00
Subsidence, $S(x)$	0.000	−0.062	−0.124	−0.248	−0.372	−0.496	−0.62	−0.744	−0.868	−0.992	−1.116	−1.178	−1.24
x/D	1.05	0.60	0.49	0.39	0.33	0.29	0.25	0.21	0.18	0.14	0.10	0.06	
Distance, x	223.65	127.80	104.37	83.07	70.29	61.77	53.25	44.73	38.34	29.82	21.30	12.78	0.00

Distance, x	175.73	116.09	93.72	76.68	66.03	57.51	48.99	41.54	34.08	25.56	17.04	6.39
Differ Vert Displ	−0.062	−0.062	−0.124	−0.124	−0.124	−0.124	−0.124	−0.124	−0.124	−0.124	−0.062	−0.062
Spacing	95.85	23.43	21.3	12.78	8.52	8.52	8.52	6.39	8.52	8.52	8.52	12.78
Slope, $G(x) \times 100$	−0.065	−0.265	−0.582	−0.970	−1.455	−1.455	−1.455	−1.941	−1.455	−1.455	−0.728	−0.485

(a) Subsidence and Slope Data

e/E	0.0	0.2	0.4	0.6	0.8	1.0	0.8	0.0	−0.2	−0.4	−0.6	−0.8	−1.0	−0.8	−0.6	−0.4
Strain, $\epsilon(x) \times 100$	0.000	0.078	0.156	0.234	0.312	0.39	0.312	0.000	−0.097	−0.193	−0.290	−0.386	−0.483	−0.386	−0.290	−0.193
x/D	1.05	0.65	0.55	0.48	0.44	0.38	0.33	0.25	0.23	0.20	0.17	0.14	0.08			
Distance, x	223.65	138.45	117.15	102.24	93.72	80.94	70.29	53.25	48.99	42.60	36.21	29.82	17.04			

Distance, x	181.05	127.80	109.70	97.98	87.33	75.615	61.77	5.12	45.80	39.41	33.015	23.43	8.52
Strain Diff	0.078	0.078	0.078	0.078	0.078	−0.078	−0.312	−0.097	−0.097	−0.097	−0.097	−0.097	0.097
Spacing	85.20	21.30	14.91	8.52	12.78	10.65	17.04	4.26	6.39	6.39	6.39	12.78	17.04
Curvature, $\rho(x) \times 10$	9.31	0.58	0.29	0.09	0.21	−0.15	−0.09	−0.02	−0.04	−0.04	−0.04	−0.17	0.30

(b) Strain and Curvature Data

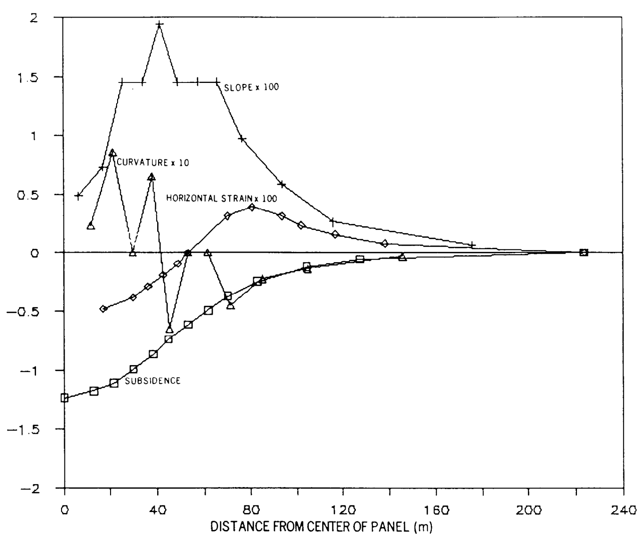

Fig. 10.6.9. Plots of results of Example 10.6.1, using the graphical method.

Peng et al. (1986) have found the horizontal displacement coefficient $b = 0.12$ in Appalachia.

Also, since $S_{max} = 1.24$ m (4.1 ft), $c = 1.4$, and $B = 99.3$ m (325.7 ft),

$$S(x) = 0.5\,(1.24)\left[1 - tanh\left(\frac{1.4x}{99.3}\right)\right]$$

$$G(x) = -0.5\left(\frac{1.4}{99.3}\right)(1.24)\;sech^2\left(\frac{1.4x}{99.3}\right)$$

$$\rho(x) = \left(\frac{1.4}{99.3}\right)(1.24)\;sech^2\left(\frac{1.4x}{99.3}\right)tanh\left(\frac{1.4x}{99.3}\right)$$

$$u(x) = -0.12 \times 0.5\left(\frac{1.4}{99.3}\right)(1.24)\;\mathrm{sech}^2\frac{1.4x}{99.3}$$

$$\epsilon(x) = 0.12\left(\frac{1.4}{99.3}\right)(1.24)\;sech^2\left(\frac{1.4x}{99.3}\right)tanh\left(\frac{1.4x}{99.3}\right)$$

These values are presented in Table 10.6.4 and plotted in Fig. 10.6.10.

(3) *Influence Function*

The influence function, commonly referred to as the Budryk-Knothe function (Knothe, 1957), has been successfully used in the United States for predicting mine subsidence, viz.,

$$f(x) = \frac{1}{B}\,exp\left[-\pi\left(\frac{x}{B}\right)^2\right] \qquad (10.6.11)$$

where x is the distance from the origin, located at the inflection point, and B is the radius of major influence = D tan g

Hence the subsidence at the surface point due to the extraction of a unit element Δx is

$$S_a = f(x)\cdot\Delta x \qquad (10.6.12)$$

So when the extraction extends from $-x_1$ to $-x_2$ for an effective mining height h, the surface subsidence at any point A is given by

$$S_A = \frac{ah}{B}\int_{-x_1}^{+x_2} exp\left[-\pi\left(\frac{x}{B}\right)^2\right]dx \qquad (10.6.13)$$

By definition, $S_{max} = ah$.

Integrating, using the probability density function, $\phi(x)$,

$$S\left(\frac{x}{B}\right) = \frac{S_{max}}{2}\left[\phi\left(\pi^{0.5}\,\frac{x}{B}\right) + 1\right] \qquad (10.6.14)$$

Hence the surface slope

$$G\left(\frac{x}{B}\right) = S'\left(\frac{x}{B}\right) = \frac{S_{max}}{B}\,exp\left[-\pi\left(\frac{x}{B}\right)^2\right] \qquad (10.6.15)$$

Table 10.6.4. Computations for Ex. 10.6.1, Profile Function Method

Distance, x	150	140	130	120	110	100	90	80	70	60	50	40	30	20	10
Subsidence, $S(x)$	0.0178	0.0235	0.0309	0.0407	0.0534	0.0698	0.0908	0.1175	0.1513	0.1929	0.2434	0.3032	0.3724	0.4497	0.5332
Slope, $G(x) \times 100$	−0.0495	−0.0650	−0.0851	−0.1110	−0.1440	−0.1857	−0.2374	−0.3002	−0.3745	−0.4592	−0.5515	−0.6460	−0.7347	−0.8081	−0.8570
Curvature, $\rho(x) \times 10{,}000$	0.1354	0.1752	0.2279	0.2923	0.3711	0.4646	0.5712	0.6859	0.7983	0.8921	0.9448	0.9306	0.8274	0.6250	0.3384
Horizontal displacement, $u(x) \times 10$	−0.0593	−0.0779	−0.1021	−0.1331	−0.1728	−0.2228	−0.2848	−0.3602	−0.4494	−0.5511	−0.6518	−0.7751	−0.9816	−0.9598	−1.0284
Horizontal strain, $\epsilon(x) \times 10$	0.1625	0.2115	0.2734	0.3508	0.4453	0.5575	0.6855	0.8231	0.9580	1.0705	1.1337	1.1167	0.9929	0.7513	0.4061
Subsidence $S(x) - S_{max}$	−1.2222	−1.2155	−1.2091	−1.1993	−1.1855	−1.1702	−1.1492	−1.1224	−1.0887	−1.0471	−0.9956	−0.9368	−0.8575	−0.7903	−0.7058

Distance, x	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
Subsidence, $S(x)$	0.6200	0.7068	0.7903	0.8676	0.9368	0.9966	1.0471	1.0887	1.1224	1.1492	1.1702
Slope, $G(x) \times 100$	−0.8741	−0.8570	−0.8081	−0.7347	−0.6460	−0.5515	−0.4592	−0.3745	−0.3002	−0.2374	−0.1857
Curvature, $\rho(x) \times 10{,}000$	0.000	−0.3384	−0.6260	−0.8274	−0.9306	−0.9448	−0.8921	−0.7983	−0.6859	−0.5712	−0.4646
Horizontal displacement, $u(x) \times 10$	−1.0489	−1.0284	−0.9698	−0.8816	−0.7751	−0.6618	−0.5511	−0.4494	−0.3602	−0.2848	−0.2228
Horizontal strain, $\epsilon(x) \times 10$	0.0000	−0.4061	−0.7513	−0.9929	−1.1167	−1.1337	−1.0705	−0.9580	−0.8231	−0.6855	−0.5575
Subsidence $S(x) - S_{max}$	−0.6200	−0.5332	−0.4497								

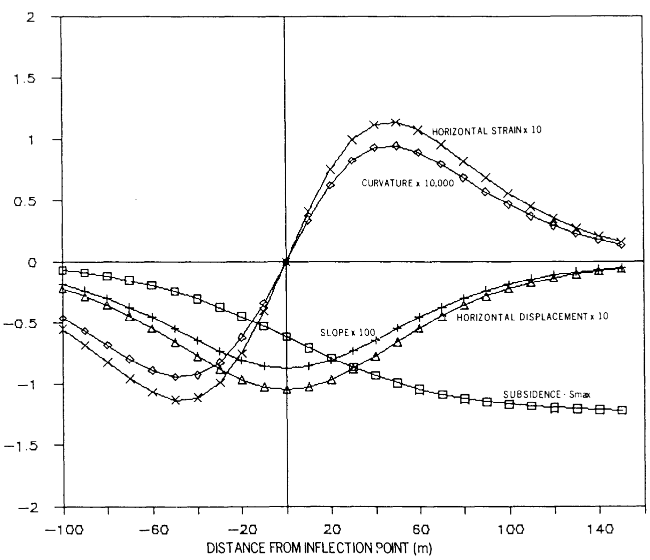

Fig. 10.6.10. Plots of results of Example 10.6.1, using the profile function method.

and the curvature

$$\rho\left(\frac{x}{B}\right) = S''\left(\frac{x}{B}\right)$$
$$= \frac{2\pi}{B^2} S_{max}\left(-\frac{x}{B}\right) exp\left[-\pi\left(\frac{x}{B}\right)^2\right] \qquad (10.6.16)$$

For a flat seam, the horizontal displacement profile $u(x)$ and the horizontal strain $\epsilon(x)$ are similar to the slope and curvature respectively, and related by the strain correlation coefficient b, i.e.,

$$u\left(\frac{x}{B}\right) = b\,\frac{S_{max}}{B}\, exp\left[-\pi\left(\frac{x}{B}\right)^2\right] \qquad (10.6.17)$$

$$\text{and } \epsilon\left(\frac{x}{B}\right) = b\,\frac{2\pi}{B^2}\left(-\frac{x}{B}\right) exp\left[-\pi\left(\frac{x}{B}\right)^2\right] \qquad (10.6.18)$$

Also we know that $B = D \tan g = 213 \tan 25° = 99.3$ m (325.7 ft) and $S_{max} = ah = 1.24$ m (4.1 ft).

For the Appalachian coalfield, $b = 0.12$ (Peng et al., 1986), so

$$S\left(\frac{x}{B}\right) = 0.5\, S_{max}\left[\phi\left(\pi^{0.5}\,\frac{x}{B}\right) + 1\right]$$
$$G\left(\frac{x}{B}\right) = \frac{1.24}{99.3}\, exp\left[-\pi\left(\frac{x}{B}\right)^2\right]$$
$$\rho\left(\frac{x}{B}\right) = \frac{2\pi}{(99.3)^2}\left(\frac{x}{B}\right) exp\left[-\pi\left(\frac{x}{B}\right)^2\right]$$
$$u\left(\frac{x}{B}\right) = 0.12 \times \frac{1.24}{99.3}\, exp\left[-\pi\left(\frac{x}{B}\right)^2\right]$$
$$\epsilon\left(\frac{x}{B}\right) = 0.12 \times \frac{2\pi}{(99.3)^2}\left(-\frac{x}{B}\right) exp\left[-\pi\left(\frac{x}{B}\right)^2\right] \qquad (10.6.19)$$

Since $B = 99.3$ m (325.7 ft), we generate Table 10.6.5 and plot these data as Fig. 10.6.11.

NOTE: In the NCB graphical method, the inflection point of the subsidence curve is assumed to be at the face. Generally, this is a short distance in the gob and can be empirically determined (Brauner, 1973; Kohli and Jones, 1986). In the solutions to the example above, subsidence is considered negative, extension is positive.

10.6.3.3 Prediction Methods Used in the United States

Many of the methods referred to in the earlier sections have been applied to US coalfields, yielding varying levels of success. The most favored technique until recently has been the use of the empirical charts developed by the National Coal Board (Anon., 1975a). Comparison of US subsidence data with NCB predictions highlight the following shortcomings:

1. With the possible exception of Illinois, maximum subsidence factors observed in US coalfields are less than predicted by NCB (O'Rourke and Turner, 1979; von Schonfeldt et al., 1979; Karmis et al., 1981). Probably the large proportion of competent strata in the overburden of most US coalfields is the cause of the discrepancy.

Table 10.6.5. Computations for Ex. 10.6.1, Influence Function Method

Distance, x	150	140	130	120	110	100	90	80	70	60	50	40	30	20	10
Subsidence, $S(x)$	−1.24	−1.24	−1.24	−1.24	−1.24	−1.23	−1.22	−1.21	−1.19	−1.16	−1.11	−1.04	−0.96	−0.86	−0.74
Slope, $G(x) \times 100$	−0.0010	−0.0024	−0.0057	−0.0127	−0.0264	−0.0516	−0.0946	−0.1625	−0.2621	−0.3966	−0.5631	−0.7500	−0.9374	−1.0993	−1.2096
Curvature, $\rho(x) \times 10{,}000$	0.0074	0.0174	0.0383	0.0783	0.1494	0.2652	0.4373	0.6681	0.9428	1.2228	1.4467	1.5417	1.4452	1.1298	0.6216
Horizontal displacement, $u(x) \times 10$	−0.0012	−0.0029	−0.0069	−0.0152	−0.0317	−0.0619	−0.1135	−0.1950	−0.3145	−0.4759	−0.6757	−0.9000	−1.1249	−1.3192	−1.4515
Horizontal strain, $\epsilon(x) \times 10$	0.0089	0.0209	0.0459	0.0940	0.1793	0.3183	0.5248	0.8018	1.1314	1.4674	1.7361	1.8501	1.7342	1.3558	0.7459

Distance, x	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
Subsidence, $S(x)$	−0.62	−0.50	−0.38	−0.28	−0.20	−0.13	−0.08	−0.05	−0.03	−0.02	−0.01
Slope, $G(x) \times 100$	−1.2487	−1.2096	−1.0993	−0.9374	−0.7500	−0.5631	−0.3966	−0.2621	−0.1625	−0.0946	−0.0516
Curvature, $\rho(x) \times 10{,}000$	0.0000	−0.6216	1.1298	−1.4452	−1.5417	−1.4467	−1.2228	−0.9428	−0.6681	−0.4373	−0.2652
Horizontal displacement, $u(x) \times 10$	−1.4985	−1.4515	−1.3192	−1.1249	−0.9000	−0.6757	−0.4759	−0.3145	−0.1950	−0.1135	−0.0619
Horizontal strain, $\epsilon(x) \times 10$	0.0000	−0.7459	−1.3558	−1.7342	−1.8501	−1.7361	−1.4674	−1.1314	−0.8018	−0.5248	−0.3183

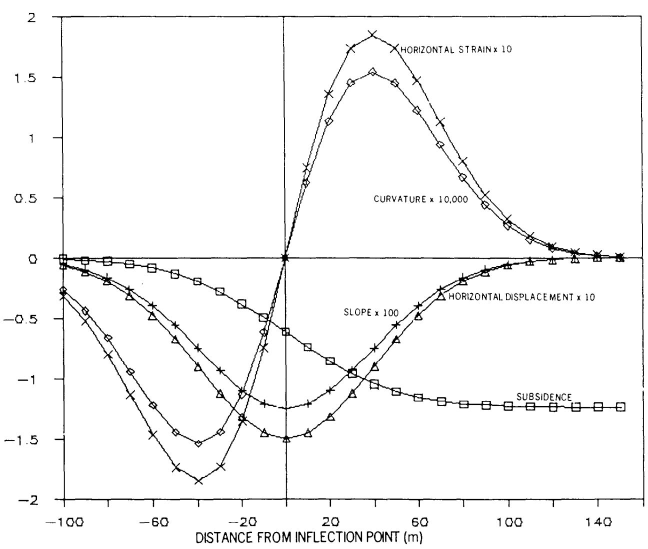

Fig. 10.6.11. Plots of results of Example 10.6.1, using the influence function method.

2. Limit (draw) angles in the US coalfields tend to be less than the 35º value generally accepted by NCB (Abel and Gentry, 1978; King and Gentry, 1979; von Schonfeldt et al., 1979; Bauer and Hunt, 1981; Karmis et al., 1981), because of the bridging effect of the strong strata in US coal measures. Typical draw angles for various countries and coalfields are given in Table 10.6.6.

3. The points of inflection of the subsidence profiles over US coal mines are generally closer to the panel centerline compared to the NCB profile (O'Rourke and Turner, 1981; Adamek and Jeran, 1981); this effect is dependent not only on the percentage of competent strata in the overburden but also on their locations relative to the ground surface and their thicknesses.

4. Surface strains and curvatures observed over US longwall panels have been shown to be significantly higher than NCB predictions, almost four times larger in many cases (O'Rourke and Turner, 1981; Adamek and Jeran, 1981; Moebs, 1982). It has been suggested that the presence of ancient workings, different in situ horizontal stress conditions, and the relatively unconsolidated nature of the surficial deposits above British mines may have resulted in the lower strain values (O'Rourke, 1983).

For the most part, the discrepancies in the observed values are a result of the differences in geologic characteristics between British and US coal measures. Most of the observations constituting the NCB charts were taken within relatively narrow geographical boundaries. Therefore, it may be expected that these data are inapplicable in the United States on a global basis. Only in areas where the geology is similar to that in the British coalfields can these charts apply. In other mining regions, these charts have to be modified prior to application.

In addition to the NCB-type subsidence predictive charts, studies have been undertaken to evaluate the potential of profile and influence functions for subsidence prediction in the United States. Among the profile functions that have been recommended (Munson and Eichfeld, 1980; Kohli et al., 1980a; Daemen, 1981; Hood et al., 1981; Adamek and Jeran, 1981), the hyperbolic tangent function appears the most promising. One drawback of profile functions is that their applicability is restricted to mine geometries that are simple, such as longwall panels. Most US coal mines are worked by room and pillar methods, rendering the profile function techniques less applicable. The use of influence functions is expedient in these instances since complex room and pillar layouts can be readily modeled. One application of influence functions is the zone area method, originally developed by Marr (1975). This method has been successfully used (Karmis and Haycocks, 1983; Karmis and Jarosz, 1988; Peng et al., 1986; Luo and Peng, 1989), since it lends itself to computer treatment.

Table 10.6.7 lists some computer programs currently available in the United States.

10.6.3.4 Time Effects

The duration of subsidence resulting from mining is composed of two distinct phases: (1) active and (2) residual. Active subsidence refers to all movements occurring simultaneously with the mining operations, while residual subsidence is that part of the surface deformation that occurs following the cessation of mining (or in the case of longwall mining, after an underground excavation has reached its critical width). The duration of residual subsidence is of particular importance from the standpoint of structural damage at the surface as well as from a legal perspective. The latter involves evaluating the extent of liability of underground mine operators for postmining subsidence.

Time spans during which surface subsidence may occur vary markedly with the mining method being used. Longwalls induce subsidence rapidly, beginning almost immediately after mining. With room and pillar systems, major occurrences of surface subsidence may be delayed for decades until the support pillars have substantially deteriorated and collapsed. The actual time involved depends on a number of factors such as the strengths of coal, roof, and floor; extent of fracturing; presence of water;

Table 10.6.6. Typical Values of Angle of Draw

Coalfield/Country	Reference	Angle of Draw (degrees)
Limburg/Netherlands	Brauner (1973)	35–45
Limburg/Netherlands	Pottgens (1978)	45
Northern France	Brauner (1973)	35
USSR	Brauner (1973)	30
Ruhr/Germany	Brauner (1973)	30–45
Ruhr/Germany	Kratzsch (1983)	55
Saar/Germany	Kratzsch (1983)	40
UK	ICE (Anon., 1977)	25–35
Midlands/UK	Orchard (1957), Wardell (1969), NCB (1975)	35
US:		
East — Anthracite	Montz and Norris (1930)	25
Southwestern, PA	Newhall and Plein (1936)	10–25
Appalachian	Cortis (1969)	15–27
Appalachian	Peng and Chyan (1981)	22–38
Northern Appalachian	Adamek and Jeran (1981)	12–17
Central — Illinois	Wade and Conroy (1977)	23–29
Illinois	Conroy (1979)	15–30
Illinois	Bauer and Hunt (1981)	12–26
Illinois	Hood (1981)	17–18 (long.)
Illinois		42–44 (trans.)
West — Raton, NM	Gentry and Abel (1977)	16
Deer Creek, Emery, UT	Allgaier (1988)	30
Somerset, Gunnison, CO	Dunrud (1984)	15–25
Salina, UT	Dunrud (1984)	8–20
Sheridan, WY	Dunrud (1984)	6–9

depth of workings; pillar size; and percentage extraction. Hence prediction of when or how much damage may occur becomes difficult.

Longwall Mining: The duration of residual subsidence movements above longwall panels is relatively short, typically varying between a few weeks and about 10 years. Further, the magnitude of these movements rarely exceeds about 10% of the total subsidence. The time spans reported in the literature are summarized in Table 10.6.8.

Empirical relations proposed to estimate the duration of residual subsidence include:

1. United Kingdom (Institution of Municipal Engineers, Anon., 1947):

$$\text{Time (mo)} = 6 + \frac{\text{mining depth (yd)}}{100} + \frac{\text{face advance (yd)}}{\text{rate of face advance (yd/mo)}} \qquad (10.6.19)$$

2. USSR, Germany (Brauner, 1973; Kratzsch, 1983):

$$s = 1 - e^{-ct} \qquad (10.6.20)$$

where s is ratio of instantaneous subsidence to final subsidence, c is overburden strata characteristic, t is subsidence time span, and e is base of natural logarithms.

3. USSR (Shadrin and Zamotin, 1977):

$$t = c[(1/q) - 1]^{1/2} \qquad (10.6.21)$$

where t is subsidence time span, c is overburden strata characteristic, q is a constant relating mining depth, panel width, and structure and hardness of overlying rock, i.e., $1/[1 + (D/w)^n]$, D is mining depth, and w is width of workings. Nomograms have also been developed and used for this purpose.

None of the above quantitative relations are immediately applicable to US conditions because of the site-specific constants contained within each expression.

Room and Pillar Mining: *Mechanism of Subsidence Development*—In room and pillar mining without pillar recovery, the magnitude of active subsidence is generally small, and the ground surface may experience a variable frequency of subsidence incidents during this period. The coal pillars and the surrounding rock are usually relatively sound at this time with only minor deflections of the roof being transmitted to the surface.

Some time after mining, however, complete collapse of the abandoned pillars and the adjacent strata may occur as a result of natural causes or human activities. These processes are likely to continue until all the voids created by mining excavation have been filled by the caved strata. Consequently, in the case of room and pillar mining, the residual subsidence can be the major subsidence measured on the surface.

There have been some misconceptions among the US mining community that surface subsidence may be avoided if certain conditions are fulfilled:

1. Sufficient coal is left unworked to serve as load-bearing pillars (generally over 50%).
2. Mining is conducted at great depths.
3. Strata overlying the workings contain competent beds.

Recent studies, however, have shown that no matter how well-designed a room and pillar layout might be, the additional weight transmitted to the pillars due to excavations will cause measurable deformation on the pillars, and these movements will eventually be transmitted to the surface. Depending upon the extent of pillar loading and the characteristics of the pillars and the superincumbent material, the surface deflection may vary from considerable to negligible, and sometimes is nearly undetectable. The long-term stability of mine pillars is extremely difficult to determine.

Table 10.6.7. US Computer Programs for Subsidence Prediction

Program	Year	Developer	Basis	Output	Merits	Limitations	Comments
INTEX	1982	international Exploration, Inc.	Empirical—finite element	Max vert subsidence max horiz comp strain break angle draw angle	Accommodates joints and faults. Can model local conditions.	Requires knowledge of specific coal and rock properties, and mine layout.	Developed for anthracite coalfield
SPASID (subsidence prediction and system identification)	1983	Pennsylvania State University	Influence function (Knothe and elastic)	Vertical subsidence horizontal subsidence profile horizontal strain grid lines percentage subsidence with respect to face	Can determine optimum influence function from measurements. Usable as batch program. Permits modification of input to suit geology. Considers dip, gates, edge effects, time, asymmetric profiles of adjacent panels. 2-D and 3-D plots. Math co-processor not required.	Command-driven, slow. FORTRAN and subsidence knowledge required. Needs graphical software. Default parameters are from UK experience.	
SUBPRO (subsidence professional)	1985	USBM	Combined profile and influence functions	Vertical subsidence inclination curvature horizontal strain	Has variable coefficient to suit geology. Can accommodate actual overburden data or average. Computer or subsidence knowledge not required. Special hardware not needed.	Maximum profile is 300 ft on either side of panel edge. Cannot store input or computed data.	Restricted to northern Appalachian coalfield. Parameters cannot be modified. Requires BASIC software.
SUBSIDE 2.0	1986	Buelah Engineering	Influence function (Bals)	Subsidence strain profiles	Permits changing input. Different parameters for room-and-pillar, varied overburden, multiple seams, dip. Generates design load/safety factor for pillars. Panel/profile data interchangeable. Operates batch jobs. AUTOCAD tie-in. Menu driven. Works with limited input data.	Cannot accommodate discrete points. Automatically generated intermediate points may not align with input data. Knowledge of subsidence required.	Developed for Appalachia.
SDPS (surface deformation prediction system)	1987	Virginia Polytechnic Institute and State University	Profile function	Vertical subsidence location of inflection point panel subcritical, critical, supercritical	Easy to use. Plots profiles.	Cannot predict subsidence at specific points.	Developed for Appalachian coalfield, but used elsewhere.
			Influence function	Subsidence slope curvature strains at discrete points	Displays 2-D and 3-D plots. Can accommodate room-and-pillar mining, dip, flexibility in input parameter.	Need to exit program to access deformation indicies.	
			Zone area	Maximum subsidence	Cannot compute subsidence at discrete points. Cannot adjust subsidence parameter	Plots are 2-D and 3-D. Can adjust subsidence parameters. Needs math co-processor and knowledge of subsidence.	
CISPM (comprehensive, integrated subsidence prediction model)	1988	West Virginia University	Influence function	Subsidence horizontal displacement slope strain curvature	Can take data directly from total survey station or electronic distance meter. Parameters automatically recommended, but can be adjusted for geology. Can graph all solutions. Accommodates profiles and discrete points. Computer and subsidence knowledge not required. Menu-driven.	Needs math co-processor. Has six programs—LWSUB, SUBSDNC, DYNSUB, SURVEY, SUBDED, CONSULT.	Developed for Appalachian coalfield, but used elsewhere. Assumes surface subsidence complies with normal probability distribution.

Sources: Anon. (1982), Ingram et al. (1989), Luo and Peng (1989), Martin (1990). **Author's Note:** Subsidence computer programs are continually being revised, modified, and developed. This information may not reflect the latest version, nor does this table list all available programs.

Table 10.6.8. Residual Subsidence Duration Over Longwall Mines

Reference	Country/ Coalfield	Residual Subsidence Duration
Institution of Municipal Engineers (Anon., 1947)	UK	2 to 10 years
Orchard & Allen (1974)	UK	Several months to 3 to 6 years (strong overburden)
Collins (1977)	UK	2 to 4.5 years
Grard (1969)	France	6 to 12 months
Brauner (1973)	Germany	1 year (Cretaceous overburden) 2 years (sandstone overburden)
Brauner (1973)	USSR	2 years (shallow mines) 4 to 5 years (deep mines, > 1300 ft or 400m)
Shadrin and Zamotin (1977)	USSR	2 to 25 months
Gray et al. (1977)	US/Appalachian	Few months to few years
Hood et al. (1981)	US/Illinois	12 months

The three basic mechanisms responsible for residual subsidence over room and pillar mines include:

1. Collapse of roof beds spanning adjacent pillars.
2. Pillar failures.
3. Squeezes or crushes.

1. *Roof Collapse.* Over remnant pillars, this is perhaps the most prevalent failure mechanism associated with abandoned room and pillar mines. Depending on certain geometric and geotechnical factors, the caving process may be arrested at some point in the overburden or it may extend upwards to the surface. The surface expression of this process is generally in the form of a localized depression or pit.

The height to which the collapse process can take place is a function of

a. Volume of the original mine opening or room.
b. Bulking factor of the strata material.
c. Location and thickness of overlying competent strata.

Two basic modes of roof failure have been recognized, namely, shear and flexural failure (Morgan, 1973). The former usually initiates diagonal tension cracks near the junction of the mine pillar and the roof, and the latter causes tension cracks near the midspan of the roof. Both result in voids above the mine level. Dependent on the mechanism of failure of the individual roof beds and their tensile and shear strengths, a variety of geometric forms of collapse are possible, ranging from conical through wedge to rectangular. For a given width of mine opening, it can be demonstrated that, for each type of collapse, the height of collapse is a function of the overlying strata. The influence of competent strata in the overburden has been neglected in this analysis (Piggott and Eynon, 1977).

2. *Pillar Failures.* These occur due to changes in the environment or surcharged loading and may take place at the time of mining or after considerable delay. They result in trough-like subsidence.

In general, subject to pillar geometry, pillar failure does not ordinarily occur at shallow depths since the size of coal pillars left behind are usually much greater than that required to support the overlying strata or any additional loading from surface development. However, where very small pillars or "stubs" exist within a given mining section, these may fail and cause sufficient loads to be transferred to adjoining pillars by arching, resulting in extended failure.

In most instances, pillar failures coincide with some phase of mining, such as pillar robbing on the retreat, abandonment of a particular mining area, or working other seams in close proximity. Another common cause of pillar failure is the action of concentrated foundation loads, from pile foundations or otherwise, being transmitted onto the remnant pillars (Piggot and Eynon, 1977).

3. *Squeezes or Crushes.* When abandoned pillars punch into either the immediate roof or floor that might have been weakened or altered by the action of water or other weathering processes, squeezes (crushes) may result. Generally, the surface settles as a trough or basin.

The mechanism of failure in this case is not unlike the failure of building foundations as the load carried by the mine pillar is transferred to the floor (or roof). If the bearing capacity of either the roof or floor is exceeded, squeezing may occur. The following factors (Gray et al., 1977) favor bearing capacity failure:

a. Underclay mine floor.
b. High pillar stresses.
c. Flooded mine conditions.

Factors Influencing Duration of Residual Subsidence—The factors in room and pillar mines that govern the duration of residual subsidence have not been quantified as yet. Probably the following parameters play a role:

1. *Depth of Working:* Increased depth implies a longer duration for subsidence movements. Any instability caused at the mine level has to propagate through the overburden in order to reach the surface.

2. *Mine Geometry:* This may be expressed in terms of the following attributes:

a. Seam thickness.
b. Pillar width-to-height ratio.
c. Extraction ratio.
d. Presence of multiple panels.
e. Presence of multilevel workings.

Increased *seam thickness* increases the potential for instability of pillars and speeds up the subsidence process.

Both the *pillar width-to-height ratio* and *extraction ratio* reflect upon the safety factor built into the mine design. Pillar width-to-height ratios greater than 0.1 and extraction ratios of less than 50% have both been claimed to permit no surface subsidence. Although mines designed to these standards have been known to be stable for long periods of time, sometimes more than a hundred years, this is not strictly true.

Presence of multiple panels and *multilevel workings* generally result in a shorter residual subsidence phase since they increase the volume of underground voids.

3. *Strength and Deformation Characteristics of the Roof Floor, and Pillar:* Over the long term, these affect the duration of surface subsidence depending on the interrelationships of these structural members.

4. *Types of Roof Control:* Roof control practices in a mine influence the relative susceptibility of the roadways to collapse; for example, bolted mines tend to subside faster than those with cribs, steel supports, or other types of bracing.

5. *Character of the Overburden:* Significant aspects which profoundly govern the duration of subsidence movements are

a. Thickness of surficial soil beds.

b. Lithology.
c. Structural geology.

Soil thickness is important since the fractures propagate through it rapidly. Also granular materials (e.g., sands) offer less bridging capacity than fine-grained soils (i.e., clays).

Although the effect of *lithology* is poorly understood, weaker rocks (i.e., shales and siltstones) are generally unable to support their own weight and the strata above, and transmit subsidence movements to the surface in a short time span. Competent rocks (e.g., sandstones and limestones) effectively bridge over excavations and delay the residual subsidence period. Besides their relative competency, the thicknesses of these strata govern the duration of subsidence; massive beds inhibit the propagation of subsidence movements longer than thin, laminated formations. Also affecting the process are facies changes, lensing, pinchouts, and other lateral variations of geology that may alter the character of the overburden from one place to another. Joints occur even in competent strata, and some slippage along these may be expected with time. Thus even though some investigators suggest that a competent rock layer of thickness greater than 1.75 times the width of the workings will arrest the collapse (Piggott and Eynon, 1977), other studies (Thornburn and Reid, 1977; Gray et al., 1977) show that such competent beds merely delay the subsidence process.

Structural geology impacts subsidence in the same manner as lithology, by varying the ability to bridge excavated spans. Generally, surface geologic features (e.g., faults, photolineaments, stream valleys), and underground features (e.g., bedding planes, joints, fissures, cleat, folds, or other inhomogeneities) tend to shorten the subsidence period.

6. *Presence of Old Mined-out Workings:* Old workings in the vicinity of an active mine accelerate the rate of residual subsidence, since the surrounding strata are disturbed.

7. *In Situ Stress Field:* The existence of high horizontal stresses impacts the time for subsidence since the structural integrity of the mine supports is affected.

8. *Water:* The presence of water reduces the strength and stiffness of mine pillars, roof, and floor in flooded mines. Further, softening of the floor (e.g., underclay) encourages pillar punching, resulting in instability and subsidence. Flow of water through fissures causes seepage pressures in the rocks, endangering the rock mass stability. Generally, the formation of pits in shallow mines is promoted by these factors. Dewatering of flooded mines accelerates coal pillar deterioration by exposing submerged pillars to the damaging effects of air and removing the buoyant support afforded by the water.

Periodic *changes of humidity* cause the slow deterioration of pillars, roof, and floor, with similar results.

9. *Nonmining factors:* Those that affect subsidence include
a. Mine fires.
b. Earthquakes.
c. Tectonic movements.
d. Surface precipitation.

Although not common, *mine fires* accelerate the subsidence process due to degradation of abandoned pillars (Dunrud and Osterwald, 1980). *Earthquakes* and *tectonic movements* may destabilize otherwise stable areas. Experience indicates a direct relationship between increased *rainfall* and greater subsidence activity (Anon., 1975b; Gray et al., 1977).

Prediction of Time of Subsidence—The wide variety of interrelated factors that may affect the duration of residual subsidence over room and pillar workings renders the task of accurate prediction of the time of subsidence difficult. Field observations of the time period of residual subsidence is further complicated by the fact that these movements generally continue over prolonged periods of time. Thorburn and Reid (1977) reported a case study

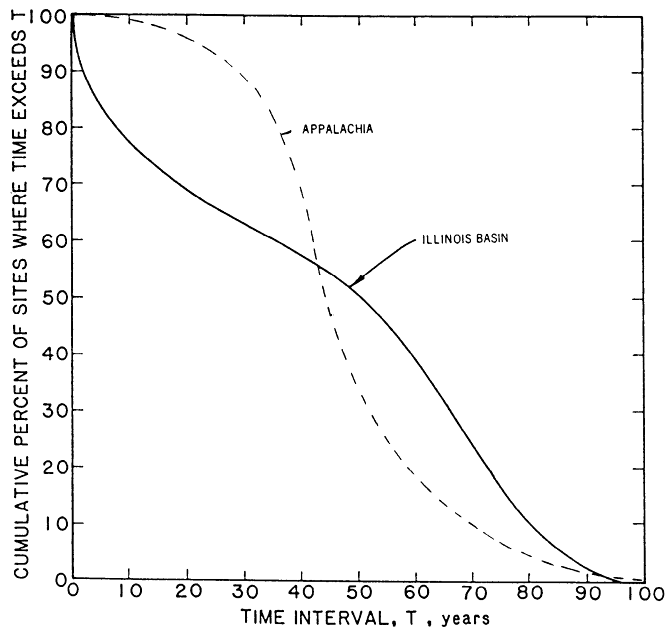

Fig. 10.6.12. Relationships for time interval between mining and subsidence. *Source:* Appalachia (Gray et al., 1977); Illinois data (Bauer and Hunt, 1981).

of a subsidence event occurring about 118 years following mine abandonment. Ivey (1978) observed subsidence in Colorado 73 years after cessation of mining. Dunrud and Osterwald (1980) concluded that surface subsidence is likely to occur for several years or several decades after mining and reported subsidence events over workings in Wyoming that were driven 25 to 80 years earlier. Mahar and Marino (1981) made similar observations in Illinois where mining had taken place several months to more than 100 years prior to the occurrence of subsidence. Based on data collected from subsidence incidents in Pennsylvania and Illinois, a common trend is not evident (Fig. 10.6.12). Investigations in Illinois (Bauer and Hunt, 1981) showed no direct relationship between depth of workings and the time period of subsidence; Pennsylvania data show similar scatter. Kratzsch (1983) developed an analytical relation between the time factor and parameters such as pillar size, shape, deformation behavior, and degree of backfilling, based on data from room and pillar salt mines. Its applicability to coal mines is unverified. A generalized model for subsidence prediction over partial-extraction mining is not currently available.

10.6.4 SUBSIDENCE-INDUCED DAMAGE

10.6.4.1 Surface Structures

Buildings: Damage to surface structures, especially buildings, is mainly caused by tilt, angular distortion, bending, and horizontal strain. Several distinct types of damage are evident as manifestations of tension, compression, angular distortion, shear, bending, and rigid body rotation and/or translation of the structure. Building deformations from ground movements usually begin at foundation level and propagate upward through the basement to the superstructure (Anon., 1975a; Bruhn et al., 1982). The transmission of the deformations from the foundation to the superstructure depends on the nature of the structure, in particular its continuity and attachment.

Tensile stresses developed by horizontal ground strain tend to produce vertical and steplike cracks in brickwalls, generally across and along the mortar-brick interfaces. Most of the extension cracks tend to be vertical, particularly near the base of the structure, and usually propagate from weak elements, such as doors, windows, or construction joints. These are generally uniformly open or more open at the bottom than the top. In the upper part of the structure, the cracks may become diagonal. Extension cracks on the basement floor are usually open and show little or no offset between the sides of the crack, usually appearing at right angles to the direction of the tensile stresses.

Compressive damage is characterized by bulging and bending failures of foundation cracks. Severe compression can cause the lower parts of the walls to move closer together and induce bending stresses in the structure that cause tensile cracks near the upper part of the walls and compressive failure at the lower part. In masonry structures, however, compressive stresses are usually not transmitted to the upper part of the walls due to the low shear resistance along mortar/brick contacts. In such cases, the induced cracks are generally restricted to the lower parts of the structure. Where the floor is especially weak, heaving of floor tiles or buckling failure may result.

Angular distortion related to differential settlement can cause vertical cracks in floor slabs that usually form closer to the side that has settled more. Walls subject to angular distortion exhibit diagonal cracks in the plaster or masonry walls which tend to extend toward the side with greater settlement. Angular distortion also causes binding of doors and windows.

Differential tilting or bending of a structure induces shear stresses in the walls and slabs. Under these circumstances, damage is characterized by horizontal and vertical cracks in the walls. Alternatively, shear and bending may act together to cause diagonal cracks in the walls.

These descriptions exemplify the effect of a single deformation mode acting alone on the structure. In actual practice, several of these forces may occur together and produce a complex pattern of cracking and distortion in various locations and directions. Furthermore, the damage descriptions provided above are limited to visible damage external to the structure. Damage caused to structural members or foundations is difficult to characterize in simple terms since the nature of the damage depends largely on the several variables including strength properties of the structural members, type of construction, zones of weakness, and previous deformation history.

In addition, the length of the structure has a major influence on the relative severity of the resulting damage. Studies have indicated that the longer the structure, the greater the damage severity (Anon., 1975a; Peng and Cheng, 1981a).

Damage Criteria—A number of damage classifications have been developed which correlate building damage to ground movements; only three are presented here. The scheme developed by the National Coal Board (Anon., 1975a) on the basis of direct observations of building damage in the United Kingdom is probably the best known (Table 10.6.9). A similar system has been developed for Northern Appalachian coalfields (Table 10.6.10), which relates damage to a severity index, based on the repairs required for building basements, instead of ground movements (Bruhn et al., 1982). Currently, a sufficient database does not exist to extend this nationwide. The results of a survey of a wide range of sources is presented in Table 10.6.11. A brief discussion of these and other classification systems is presented by Bhattacharya and Singh (1985).

Bridges: Damage may be caused to bridges by horizontal ground strain resulting in the movement of the supports of piers either towards or away from one another. Differential vertical settlement or distortions in the horizontal plane may bring about complex and often serious effects on the decking and arches (Anon., 1975a).

It is generally difficult to determine the location and nature of the ground movements based on visual observation of damage. Often compressive damage leads to crushing and spalling of concrete decks and plaster. Combined compression and extension due to bending may cause opening and closing of construction joints in abutments and plaster cracking. At the higher end of the scale, damage is characterized by distress in the superstructure, inward horizontal movement of abutments, jamming of beams and girders against the back wall of the abutments, and serious damage to the bearings (Moulton et al., 1982).

Damage Criteria—Few data on damage criteria for bridges are currently available. Results of a survey are presented in Table 10.6.12.

Miscellaneous Structures: Included in this category are dams, embankments, reservoirs, canals, locks, aqueducts, sewers, sewage disposal works, and other common types of structures. Very limited data are available on these structures.

Measurement of ground movements in the failure investigation of an earth dam due to extension cracks in the concrete embankment, revealed that the magnitude of horizontal strain developed was about 1×10^{-3} (Lee, 1976). Tensile strains greater than 1.5×10^{-3} resulted in damage to dams in the Kyushu coalfields of Japan (Nishida and Goto, 1969).

A failure criterion of 1×10^{-3} for limiting horizontal strain has been recommended in the design of two reservoirs at one location, and between 0.3 to 2.75×10^{-3} for another (Lackington and Robinson, 1973).

The consensus appears to converge upon a limiting horizontal ground strain of around 1×10^{-3}, applicable to a variety of surface structures. However, this should be regarded only as a first estimate, and site-specific analyses should be conducted prior to design recommendations.

10.6.4.2 Public Utilities and Communications

Roads and Airport Runways: The principal types of damage affecting roads and highways due to subsidence movements include:

1. Cracks on the road surface.
2. Deterioration of base course and/or subgrade.
3. Distortion of horizontal and vertical alignment.
4. Bumps or undulations on the road surface.
5. Damage to ancillary works such as sidewalks, drains, fences, curbs, and the like.
6. Water flooding.

Of these, the most common form of damage is the formation of tensile cracks on the road surface, usually coinciding with the position of the ribsides in the mine workings below. Altematively, compression ridges may occur near the center of the panels. Also common are severe local changes of gradient that may become a source of danger for high-speed traffic, especially if it causes surface water to stand in pools in affected areas.

Airport runways experience problems similar to those for high-speed highways.

Damage Criteria—It is generally accepted that highway bridges are more susceptible to ground movements than roadways. Hence damage criteria for bridges often are used to represent a conservative limit of such criteria for roads. Further, most public roads are protected by safety pillars and generate little interest for accumulating data. Besides, road damage can generally be repaired with tar or "cold patch" treatment, which is relatively inexpensive. Table 10.6.13 presents some available data.

Table 10.6.9. National Coal Board Classification of Subsidence Damage

Change of Length of Structure: *From*	*To*	Class of Damage	Description of Typical Damage
	Up to 0.1 ft (30 mm)	Negligible or very slight	Hair cracks in plaster. Perhaps isolated slight fracture in the building, not visible on outside.
0.1 ft (30 mm)	0.2 ft (60 mm)	Slight	Several slight fractures showing inside the building. Doors and windows may stick slightly. Repairs to decoration probably necessary.
0.2 ft (60 mm)	0.4 ft (120 mm)	Appreciable	Slight fracture showing on outside of building (or one main fracture). Doors and windows sticking; service pipes may fracture.
0.4 ft (120 mm)	0.6 ft (180 mm)	Severe	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.
Over 0.6 ft (180 mm)		Very severe	As above, but worse, and requiring partial or complete rebuilding. Roof and floor beams lose bearing and need shoring up. Windows broken with distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of roof and walls.

Source: Anon., 1975a.

Table 10.6.10. Subsidence Damage Classification for Northern Appalachian Coalfield

Class	Characteristic Basement Damage	Severity Index
I Slight	• Hairline cracks in one or more basement walls and possibly floor slab. • Some cracks in perimeter walls causing loss of water tightness. • Repointing required in some or all walls.	0
II Moderate	• Cracks in one or more basement walls and floor slab. • Some wall/footing reconstruction and floor replacement required, as well as local repointing.	1
III Severe	• Cracks in one or more basement walls and floor slab. • Possible wall instability and loss of superstructure support, requiring shoring and bracing. • Extensive repair work involving wall/footing reconstruction and floor slab replacement.	2
IV Very severe	• Cracks typically in all basement walls, as well as floor slab. • Possible instability of several walls and loss of superstructure support, requiring extensive shoring and bracing. • Possible significant tilt to home.	4
	• General reconstruction of basement walls, footings and floor slab required.	5

Severity Index is the relative cost of repairing basement. *Source:* Bruhn et al. (1982).

Railroads: One of the first effects of subsidence on railroad tracks is rider discomfort, which sometimes requires the reduction of maximum permissible speeds. At higher levels of ground strain, rail tracks have a tendency to "snake" or bend, and in more extreme cases, entire rails may be forced out of the track. Sometimes where the mine workings are located on one side of the track, differential lateral strains may occur and cause displacement of the tracks relative to one another. Changes in ground slope may adversely affect track performance by formation of localized depressions, or creating gradients greater than permissible for a given type of traffic.

One effect commonly observed over longwall panels is that, depending on the location of the coal working faces, reversals of stress and strain occur on the surface. A railway line might be subjected to tensile stresses at first, followed by a neutral stress period, and then by compressive stresses. This transition is generally the most damaging phase of movements from the point of view of rail tracks (Anon., 1977).

The extent to which a railway line is affected by ground movements is related to

1. Types of traffic involved.
2. Speed limits.
3. Types and construction of track.
4. Preventive and remedial works.
5. Nature and magnitude of ground movements.

Damage Criteria—Damage to railroads may be classified in terms of interruption of use or failure. Interruptions of use would refer to excessive track gradients or bumps on the track resulting in rider discomfort, reduction of permissible speeds, increased propulsion and braking forces, reduced payloads and train lengths, or impairment of orderly traction and shunting operations. Quantitative limits for this level of damage are difficult to assign due to the many variables involved. A railroad track may be deemed to have failed if the deformations are of such magnitude that it is incapable of sustaining traffic due to risk of derailment. Available data are given in Table 10.6.14.

Pipelines. Generally, pipelines are laid some distance below the ground surface. Buried pipelines are known to be more susceptible to damage from ground movement than those laid above ground. These move in response to ground movements due to friction and soil pressure between the pipe material and the

Table 10.6.11. Damage Criteria for Buildings

Building Category	Damage Seventy Level	Movement Type	Movement Limits	Country	Reference	Suggested Value
Brick and masonry/ brick bearing walls/ low-rise structures	Architectural	Angular distortion	1.0–2.0 $\times 10^{-3}$	Germany	Niemczyk (1949)	1.0 $\times 10^{-3}$
			0.5–1.0 $\times 10^{-3}$		Meyerhoff (1953)	
			1.0–2.0 $\times 10^{-3}$		Skempton and McDonald (1956)	
			1.0 $\times 10^{-3}$	USSR	Polshin and Tokar (1957)	
			1.0–2.0 $\times 10^{-3}$	US	Sowers (1962)	
			1.0 $\times 10^{-3}$	US	O'Rourke (1976)	
			1.0 $\times 10^{-3}$	UK	Attewell (1977)	
			1.2 $\times 10^{-3}$	US	Boscardin (1980)	
Brick and masonry/ brick bearing walls/ low-rise structures	Architectural	Horizontal strain	0.6 $\times 10^{-3}$	Germany	Niemcyzk (1949)	0.5 $\times 10^{-3}$
			0.4 $\times 10^{-3}$	UK	Beevers and Wardell (1954)	
			0.5 $\times 10^{-3}$	USSR	Polshin and Tokar (1957)	
			0.8 $\times 10^{-3}$	UK	Priest and Orchard (1957)	
			0.5 $\times 10^{-3}$	Japan	Goto (1968)	
			0.4–0.5 $\times 10^{-3}$	India	Singh and Gupta (1968)	
			0.25 $\times 10^{-3}$	UK	Littlejohn (1975)	
			0.5–1.0 $\times 10^{-3}$	UK	National Coal Board (Anon., 1975a)	
			< 0.75 $\times 10^{-3}$	US	O'Rourke (1976)	
			0.5–1.0 $\times 10^{-3}$	UK	Attewell (1977)	
			1.0–1.5 $\times 10^{-3}$	US	Cording et al. (1976)	
			0.5 $\times 10^{-3}$	US	Yokel (1978)	
			0.5 $\times 10^{-3}$	US	Boscardin (1980)	
Brick and masonry/ brick bearing walls/ low-rise structures	Architectural	Deflection ratio	0.3–0.7 $\times 10^{-3}$	USSR	Polshin and Tokar (1957)	0.3 $\times 10^{-3}$
			1.0 $\times 10^{-3}$	US	Grant (1974)	
			0.4 $\times 10^{-3}$	UK	Burland and Wroth (1975)	
Brick and masonry/ brick bearing walls/ low-rise structures	Functional	Angular distortion	3.5 $\times 10^{-3}$	US	Meyerhoff/Terzaghi (1953)	2.5–3.0 $\times 10^{-3}$
			3.3 $\times 10^{-3}$	US	Skempton and McDonald (1956)	
			4.0–6.0 $\times 10^{-3}$	USSR	VNIMI (Anon., 1958)	
			2.0 $\times 10^{-3}$	US	Bjerrum (1963)	
			3.3 $\times 10^{-3}$	US	Grant (1974)	
			3.3–5.0 $\times 10^{-3}$	Poland	Starzewski (1974)	
			3.0 $\times 10^{-3}$		Ulrich (1974)	
			2.0–3.3 $\times 10^{-3}$	Sweden	Broms and Fredrikson (1976)	
			2.7 $\times 10^{-3}$	UK	Thorburn and Reid (1977)	
			2.5 $\times 10^{-3}$	Poland	Adamek and Jeran (1981)	
			3.0–6.0 $\times 10^{-3}$	Japan	Nishida et al. (1982)	
Brick and masonry/ brick bearing walls/ low-rise structures	Functional	Horizontal strain	2.0–4.0 $\times 10^{-3}$	USSR	VNIMI (Anon., 1958)	1.5–2.0 $\times 10^{-3}$
			1.0 $\times 10^{-3}$		Ulrich (1974)	
			2.5–3.5 $\times 10^{-3}$	US	Cording et al. (1976)	
			1.5 $\times 10^{-3}$	Poland	Adamek and Jeran (1982)	
Brick and masonry/ brick bearing walls/ low-rise structures	Functional	Deflection ratio	0.14–0.22 $\times 10^{-3}$		Rigby and Dekoma (1952)	0.5 $\times 10^{-3}$
			0.25 $\times 10^{-3}$		Wood (1952)	
			0.6 $\times 10^{-3}$	US	Horne and Lambe (1964)	
Brick and masonry/ brick bearing walls/ low-rise structures	Functional	Radius of curvature	1.9–12.4 mi (3–20 km)	USSR	VNIMI (Anon,, 1958)	12 mi (20 km)
			12.4 mi (20 km)		Ulrich (1974)	
			12.4 mi (20 km)	Poland	Adamek and Jeran (1982)	
			8.0 mi (13 km)	Japan	Nishida et al. (1982)	

Table 10.6.11. Damage Criteria for Buildings—cont.

Building Category	Damage Severity Level	Movement Type	Movement Limits	Country	Reference	Suggested Value
Brick and masonry/ brick bearing walls/ low-rise structures	Structural	Angular distortion	7.0–8.0 $\times 10^{-3}$	US	O'Rourke et al. (1977)	7.0 $\times 10^{-3}$
Brick and masonry/ brick bearing walls/ low-rise structures	Structural	Horizontal strain	3.5 $\times 10^{-3}$ 2.75 $\times 10^{-3}$	UK US	National Coal Board (Anon., 1975a) Boscardin (1960)	3.0 $\times 10^{-3}$
Steel and reinforced concrete	Architectural	Angular distortion	1.0–2.0 $\times 10^{-3}$ 2.0 $\times 10^{-3}$ 2.0–2.5 $\times 10^{-3}$ 2.2 $\times 10^{-3}$ 1.3 $\times 10^{-3}$ 2.0 $\times 10^{-3}$	US USSR US US UK	Skempton and McDonald (1956) Polshin and Tokar (1957) Sowers (1962) Breth and Chambrosse (1975) O'Rourke (1976) Attewell (1977)	1.3 $\times 10^{-3}$
Steel and reinforced concrete	Functional	Angular distortion	2.5–3.3 $\times 10^{-3}$ 3.3–6.6 $\times 10^{-3}$ 3.3–5.0 $\times 10^{-3}$	 US Poland	Thomas (1953) Skempton and McDonald (1956) Starzewski (1974)	3.3 $\times 10^{-3}$
Timber frame	Architectural	Angular distortion	2.0 $\times 10^{-3}$	US	Mahar and Marino (1981)	1.5 $\times 10^{-3}$
Timber frame	Architectural	Horizontal strain	1.0 $\times 10^{-3}$	Japan	Goto (1968)	1.0 $\times 10^{-3}$
Timber frame	Functional	Angular distortion	5.0–10.0 $\times 10^{-3}$ 3.3–5.0 $\times 10^{-3}$	Poland Sweden	Starzewski (1974) Broms and Fredriksson (1976)	3.3–5.0 $\times 10^{-3}$

Legend:
Architectural: Small scale cracking of plaster and sticking of doors and windows.
Functional: Instability of some structural elements, jammed doors and windows, broken window panes, building services restricted.
Structural: Impairment of primary structural members, possibility of collapse of members, complete or large-scale rebuilding necessary, may be unsafe for habitation.

No data available on rigid, massive structures/central core design.

Table 10.6.12. Damage Criteria for Highway Bridges

Damage Severity Level	Allowable Movement: Type of Movement	Allowable Movement: Allowable Magnitude	Source	Suggested
Architectural	Angular distortion	1.0 $\times 10^{-3}$	Moulton et al. (1982)	1.0 $\times 10^{-3}$
Functional	Angular distortion	4.0–5.0 $\times 10^{-3}$	Moulton et al. (1982)	3.0 $\times 10^{-3}$
Architectural	Differential settlement	1.0 in. (25 mm) 2.0 in. (50 mm) 1.0 in. (25 mm)	Grover (1978) Bozozuk (1978) DiMillio (1982)	1.0 in. (25 mm)
Functional	Differential settlement	2.0–4.0 in. (25–50 mm) 2.5 in. (65 mm) 4.0 in. (100 mm) 2.0–3.0 in. (50–75 mm)	Moulton et al. (1982) Walkinshaw (1978) Bozozuk (1978) Grover (1978)	2.0 in. (50 mm)
Architectural	Horizontal movement	1.0 in. (25 mm)	Bozozuk (1978)	1.0 in. (25 mm)

Damage Level Legend:

Architectural: Minor cracking, opening and closing of construction joints in abutments, cracking and spalling of concrete decks.
Functional: Superstructure distress, horizontal displacement, bearing damage or damage to abutments, warping or tilt of bridge decks, bumps at compressed and open expansion joints.
Structural: Instability of primary structural members, possibility of collapse.

Table 10.6.13. Damage Criteria for Roads

Damage Severity Level	Movement Limits: Type of Movement	Movement Limits: Tolerable Range	Source	Suggested Value
Architectural (Minor pavement cracking)	Horizontal strain	$1.2–3.8 \times 10^{-3}$	Instn. Civil Engrs. (Anon., 1977)	1.0×10^{-3}
Architectural (minor pavement cracking)	Slope	$5.0–10.0 \times 10^{-3}$		5.0×10^{-3}
Functional (undulations and water accumulation)	Slope	5.0×10^{-3}	Kratzsch (1983)	5.0×10^{-3}
Structural (adverse effects on driving dynamics—large-scale cracking affecting base/subgrade; severe local gradients; potholes)	Slope	10×10^{-3} 10×10^{-3} $10.0–20.0 \times 10^{-3}$	Maize et al. (1941) Sowers (1962) Kratzsch (1983)	10×10^{-3}

Table 10.6.14. Damage Criteria for Railroads

Damage Severity Level	Movement Limits: Type of Movement	Movement Limits: Tolerable Range	Source	Suggested Value
Risk of derailment and rider discomfort	Horizontal strain	2.0×10^{-3} 3.0×10^{-3}	Kratzsch (1983) Saxena and Singh (1980)	2.0×10^{-3}
Risk of derailment and rider discomfort	Slope	12.5×10^{-3}* 10.0×10^{-3} *2.5×10^{-3} (for railway stations)	Kratzsch (1983) Saxena and Singh (1980) Kratzsch (1983)	10.0×10^{-3} or maximum permissible track gradient specified by design

ground. If the magnitude of the ground movements are such that either the pipeline or its joints (or couplings) are unable to accommodate the deflection or strain which is developed, they may fracture or fail.

Damage may be caused either by excessive strain along pipe lengths or excessive distortion at the joints or both. Three basic modes of failure may be identified (O'Rourke and Trautmann, 1982):

1. Strain in pipe material leading to rupture or intolerable deformation.
2. Rotation of the joints leading to leakage or loss of connectivity.
3. Axial slip at the joints leading to leakage or disengagement of adjacent pipe lengths.

The first two failure modes may be caused by differential settlement, and the first and third by lateral displacement.

The largest percentage of pipe failures are caused by compressional forces causing excessive telescoping at joints. Tensile failures are the next major mode, whereas failures due to ending or shearing rarely occur (Tilton, 1966). British experience recognizes the following types of fractures: beam, pull, shear, thrust, and leverage (Anon., 1975a).

The extent to which a pipeline can absorb ground deformations is said to be dependent upon the stress/strain behavior of the pipe material, the rotation and pull-out capacity of the couplings, connections to other structural elements, corrosion resistance of pipe and joints, and other general factors such as state of repair and installation technique (O'Rourke and Trautmann, 1980). The location of the joints with respect to the subsidence profile and the degree of rigidity of the pipeline will also significantly affect the nature and extent of damage. At times the joints constitute the weakest link in a pipeline system and are usually affected by ground movements long before the pipe length.

Couplings in water and gas distribution mains increase pipeline flexibility. Flexible couplings are generally equipped with a gasket that is compressed to prevent leakage. These joints are capable of sustaining rotations that vary from 1 to 7º. Mechanical joints can tolerate about 2 in. (50 mm) of horizontal slippage before leakage. When both horizontal strains and differential settlements must be sustained, pipeline joints can be designed to rotate and telescope. Welded pipelines are most susceptible to damage by compression because ground movements cause local wrinkling or buckling of the pipe wall. Once local wrinkling has initiated, all subsequent deformations will tend to concentrate at the location of the wrinkle. Local wrinkling may occur at compressive strains on the order of 0.4 to 0.6% (Bouwkamp and Stephen, 1973). Butt-welded steel pipelines are most capable of sustaining the differential soil movements caused by mining subsidence, but these must be high quality welds, free of significant corrosion.

Damage Criteria—Ground movement limits may be prescribed for two basic damage levels:

1. Interruption of use.
2. Failure or loss of use.

Pipelines are usually laid under fairly stringent grade requirements. A change of ground slope may affect power costs in the form of greater pumping requirements or may cause inconvenience to the users. These constitute impaired use of the application. Ground movement limits for this level are difficult to assign because of its site-specific nature. However, utility companies sometimes provide standards for a given type of application. If these are known, appropriate criteria can be developed for a given area. Gas line leaks pose a special hazard, because of the

Table 10.6.15. Damage Criteria for Pipelines

Type of Pipe	Damage Severity Level	Movement Limits: Type of Movement	Movement Limits: Range	Source	Suggested Value
Cast iron pipe with lead-caulked joints	Failure of pipes or couplings	Angular distortion	4.0×10^{-3}	O'Rourke and Trautman (1982)	4.0×10^{-3}
Cast iron pipe with lead-caulked joints	Failure of pipes or couplings	Horizontal strain	$0.5–2.0 \times 10^{-3}$	Grard (1969)	1.0×10^{-3}

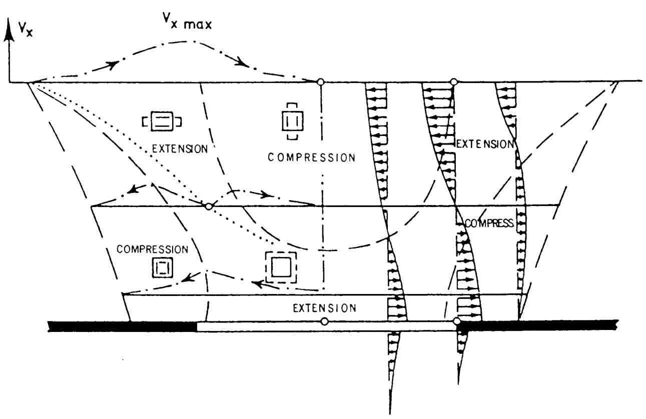

Fig. 10.6.13. Horizontal deformation of a continuum over workings in a bedded deposit (Kratzsch, 1983).

toxic and/or explosive effects of the constituents. Available data for failure are shown in Table 10.6.15.

10.6.4.3 Shafts and Subsurface Structures

Shafts: Mine subsidence damage affects not only surface structures but also those located within the rock mass. With shallow workings, it is possible to leave a protective shaft pillar, which is not mined. However, in deep mines, the size of pillars becomes excessive, and large amounts of ore tend to become sterilized within them. Hence it is impractical not to mine within the safety zone.

Fig. 10.6.13 depicts movements of the strata above the mine openings as if it were a continuum and not bedded. If the entire mine pillar were mined, a shaft through these strata would be subjected to compression near the surface and tension near the mine floor. If the pillar were partially retained, the type and magnitude of the ground strains experienced by the shaft would depend upon location of the shaft within the pillar, and would vary along the length of the shaft. Generally, the horizontal movements of the shaft tend to be towards the center of the workings near the surface and away from them near the floor and immediate roof. The net result is that the shaft tends to lean towards the gob as the face approaches the shaft, and then reverses itself as the face goes past. Finally, the shaft may become vertical again with time. During this period, hoisting equipment experiences increased wear in the inclined shaft. Rupture of the shaft, however, does not normally occur, since assuming the shaft experiences a compressive strain of 2×10^{-3}, the walls of a 20-ft (6-m)-diameter shaft close by only ½ in. (12 mm). The horizontal compression is largely absorbed by the pressure arch in the rock and compressible material surrounding the shaft. Although bending of the shaft is not large, bending stresses need to be considered in the design of rigid linings. Fractures in the shaft lining invariably accompany shear movements in severely bent strata.

With appropriate mining techniques, it is possible to use the shaft for hoisting as well as maintain integrity through water-bearing zones. Principles to follow include (Kratzsch, 1983):

1. *Compensating* axial tension and compression stresses along the shaft with the use of two or more faces.
2. *Working symmetrically* around the shaft, minimizing shaft tilt and shear.
3. *Minimizing subsidence* by backfilling or leaving a core pillar.
4. *Designing* the shaft lining to accommodate movements.
5. *Observation* of axial deformation, tilt, and bending regularly during the operation.

Designing flexible shaft linings implies

1. Introducing a *sliding joint,* which reduces friction and seals the shaft through water-bearing zones.
2. Providing an *expansion joint* in the lining at the mining horizon, which absorbs axial compression.
3. Placing *compressible courses,* 100 to 150 ft (30 to 50 m) apart, so that the shaft can yield or bend, but the shaft loses watertightness.
4. Using a *weak mortar,* which serves as a compressible course, and facilitates masonry repair.
5. Furnishing an *annular cushion* of fly ash at the mining horizon; this absorbs lateral expansion of the seam, and vertical compression.
6. Constructing an *outer ring of concrete,* which seals fractured strata and prevents shear movements from intersecting faults.
7. *Monitoring* movements so as to recognize danger in a timely manner.

A cross section of a shaft through water-bearing strata designed to absorb ground movements is shown in Fig. 10.6.14.

Damage Criteria—No specific values for damage can be provided, since this is dependent on the design of the lining, but the horizontal and vertical stresses in the shaft lining can be computed and checked against the strength values of the lining materials.

Subsurface Structures: The degree of damage experienced by subsurface structures depends upon their location with respect to the mine workings. These may be sited at various horizons:

1. *Below mine level:* the extent of damage incurred should be small, even if these are within the zone affected by movements.
2. *At mine level:* adequately designed and supported chambers should remain open, but the passageways leading to these may be difficult to maintain unobstructed, unless they are located in the shaft pillar. Openings sited in the shaft pillar would be subjected to minor movements.

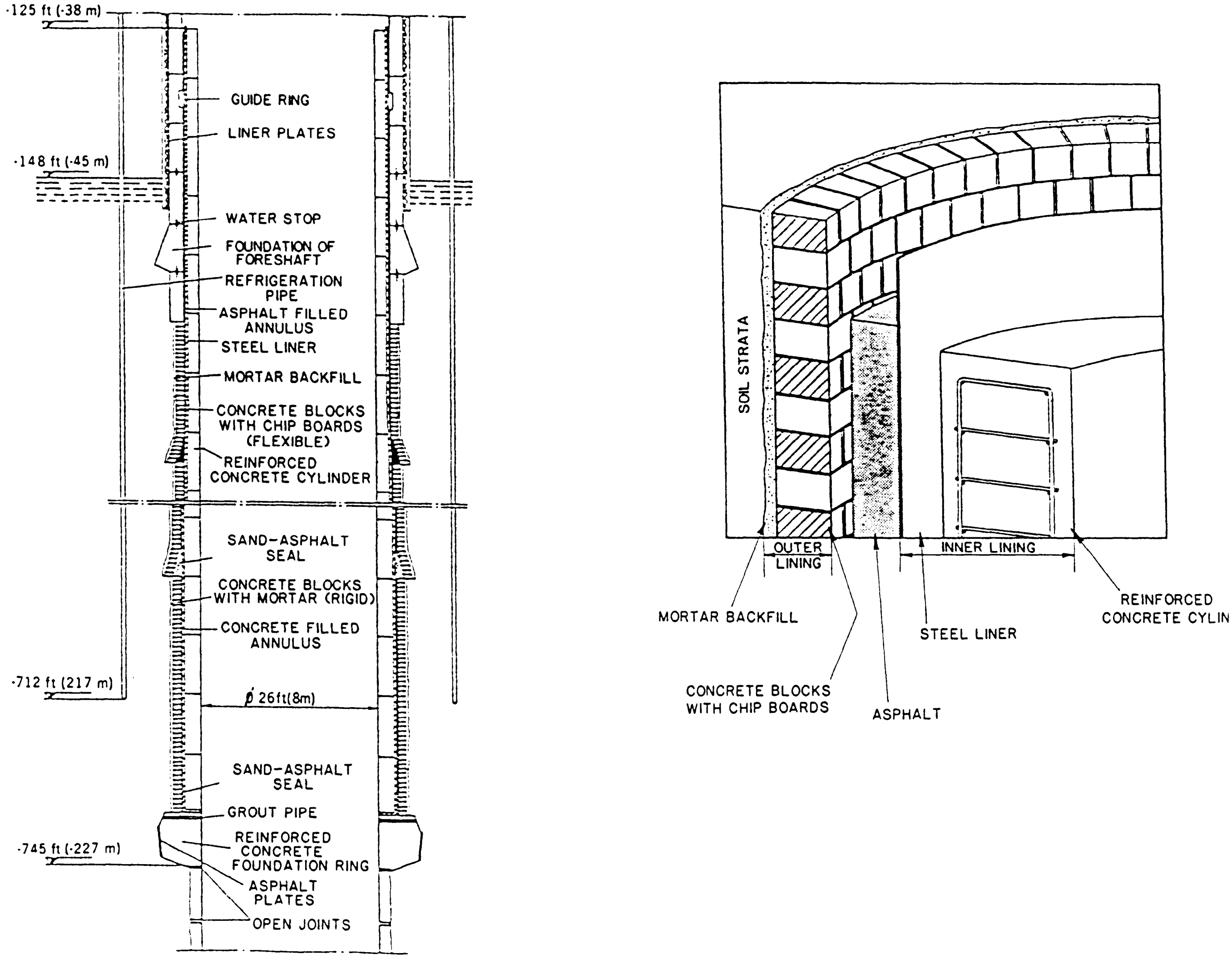

Fig. 10.6.14. Cross section through a shaft lining through water-bearing strata, designed to tolerate subsidence (Stoss and Braun, 1983).

3. *Above mine level, in the rock strata:* openings situated in this region may be subjected to large movements, and occasional shock loads or sudden falls; thus these would be costly to design and keep open. Structures located at a height above 60 times the seam thickness, and surrounded by thick plastic or viscoelastic strata (e.g., shales) may not experience sudden movements and could survive the subsidence effects with slight damage.

4. *Above mine level, in unconsolidated materials:* these openings are close to the surface and in deep mines, if properly designed and lined, may endure the ground movements due to the flow of the surrounding soils; some repairs would probably be required.

There are no data on structures within mine overburdens; validation of the above scenarios is needed.

10.6.4.4. Renewable Resource Lands

Renewable resource lands include aquifers and areas for the recharge of aquifers and other underground waters, areas for agricultural and silvicultural production of food and fiber, and grazing lands (Anon., 1979). In addition, significant springs, perennial streams, and other surface waters that support aquatic life or supply water to any public water system may be classed as renewable resources.

Agricultural Lands: Adverse effects of subsidence movements on agricultural lands include

1. *Formation of surface fissures* in the zones subjected to tensile stresses, which form pathways to drain the water away from the topsoil, thus being detrimental to plant growth. Flow of water in the cracks also causes erosion, thereby widening them (Schumann and Poland, 1970).

2. *Alteration in the ground slope.* Steepening increases flow velocity, which in turn enhances surface runoff and erodibility, whereas gradient reduction could lead to waterlogging of the soil. Crop yields may tend to decrease in either case.

3. *Disruption of surface drainage patterns* resulting from changes in ground elevation or slope. Lowering the topographic barriers to flow increases the potential for flooding (Moore and Nawrocki, 1980). In flat terrain, ponding may occur, especially if the water table is shallow and underlain by an impermeable stratum (Wohlrab, 1969). Changes in slope disturb the existing hydraulic regime.

4. *Modification of the subsurface hydrology* due to generally downward migration of the groundwater through cracks, and consequent decrease in soil fertility.

5. *Deterioration of groundwater quality* due to contact with sulfides and other minerals (Temple and Koehler, 1954; Lovell,

Table 10.6.16. Damage Criteria for Prime Farmlands

Damage Severity Level	Movement Limits		Source	Suggested Value
	Type of Movement	Tolerable Range		
Moderately reduced productivity	Horizontal strain	$2.0–3.0 \times 10^{-3}$	Inferred	$2.0–3.0 \times 10^{-3}$
Severely reduced productivity	Horizontal strain	5.0×10^{-3} 5.0×10^{-3} $<10.0 \times 10^{-3}$	Orchard (1969) Voight and Pariseau (1970) Jachens and Holzer (1982)	5.0×10^{-3}
Moderately reduced productivity	Slope	$2.0–3.0 \times 10^{-3}$	Inferred	$2.0–3.0 \times 10^{-3}$
Severely reduced productivity	Slope	6.0×10^{-3} $6.0–8.0 \times 10^{-3}$ $5.0–8.0 \times 10^{-3}$	Pierce et al. (1983) Fehrenbacher et al. (1978) U.S. Dept. Agriculture (Anon., 1951)	6.0×10^{-3}

1973; Kim et al., 1982) or changes in sediment loads (Moore and Nawrocki, 1980).

6. *Occurrence of subsidence pits* (sinkholes), which may result in upsetting the drainage system by either accumulation or loss of water and, in extreme cases, damage to equipment and life.

The effect of mine subsidence on farming depends on the type of crops, soil character, hydrology, topography, and other environmental factors. Essentially, subsidence damage caused to agricultural lands is characterized by the loss of use or reduced productivity. Increasing ground movements generally cause a decline in productivity, but the precise amount of decline is site specific and, thus, difficult to quantify in general terms.

Agricultural lands may be classified in various ways, but one that is commonly used in relation to mine subsidence is dividing such property into prime and nonprime farmlands. Prime farmland has "the best combination of physical and chemical characteristics for producing food, feed, forage, fiber, and oilseed crops. It is the land that gives the highest agricultural yield with minimum input when managed according to modern farming methods" (Guernsey et al., 1979). Generally, soils constituting prime farmland have slopes of less than 8 to 10×10^{-2} (Fehrenbacher et al., 1978; Guernsey et al., 1979). All lands not classed as prime farmland fall into the nonprime category.

Damage Criteria—Essentially, subsidence damage caused to agricultural lands is characterized by the loss of use or reduced productivity. Increasing ground movements generally cause a decline in productivity, but the precise amount is site-specific. In some instances, the extent of damage severely jeopardizes the capability of the land to economically produce crops, labeled "severely reduced productivity." Another level of damage, termed "moderately reduced productivity," accounts for less severe damage, such as decreased crop production potential because of loss of soil fertility. Ranges for these are presented in Table 10.6.16.

Forests and Grazing Lands: The types of damage caused by mine subsidence to forests and grazing lands is similar in nature to that for agricultural lands, but they are generally less susceptible to the damaging effects of subsidence movements than farmlands.

Damage Criteria—Table 10.6.17 depicts the current information. Small changes in slope are not likely to cause appreciable damage to forests and grazing lands.

10.6.4.5 Hydrologic Effects

Surface Water Bodies: The formation of open cracks, fissures, or pits at the bottom of surface bodies of water (streams, lakes, ponds) may lead to partial or complete loss of water by its drainage to lower strata or mine workings. Depletion of such water resources seriously impact public water systems and aquatic life forms. In extreme cases, catastrophic inundations of underground mine workings may occur.

Damage Criteria—Available data are given in Table 10.6.18; further guidance on the minimum depth required to maintain levels below the recommended limits is presented in Table 10.6.19.

Groundwater Aquifers: Mine subsidence affects groundwater aquifers in several ways:

1. *Lowering of groundwater* levels or hydrostatic head due to the formation of breaks and fractures in the strata above underground mine workings may decrease the groundwater supply.
2. *Changes in streamflow rates;* increases may occur due to faster movement through fractured strata, water accumulations in subsidence troughs, or reduced evapotranspiration because of a drop in the water table, whereas decreases are caused by water diversion.
3. *Alteration in water quality* produced by chemical interaction with the minerals or adjoining strata.

The prevailing hydrogeologic environment is significantly affected by subsidence-induced fissuring. Cessation of mining could bring about reconsolidation of the strata, but this may or may not result in the rebound of groundwater to premining levels. Water table depression is generally localized near the mine workings (Anon., 1981; Hill and Price, 1983), but the effects on the hydrologic regime could be highly variable and complex. Local structural features (e.g., faults, synclines, or anticlines) and the nature, continuity, and dip of the beds have a profound influence on subsidence damage. The significant presence of impermeable clay layers in the overburden inhibits groundwater drainage (Singh and Kendorski, 1981). The adverse impacts of water table lowering can be significant, especially in arid regions (Piper, 1933; Ward and Wilmoth, 1968; Subitzky, 1976; Rauch, 1978), and can reduce plant growth (Anon., 1981). Subsidence-induced streamflow rate variations have been noted (Growitz, 1978; Sgambat et al., 1980) as has the deterioration of water quality (Sgambat et al., 1980; Anon., 1981; Stoner, 1983), which is detrimental to water usability.

Damage Criteria—There is significant likelihood of damage to a water-bearing stratum if it is located within the caving or bed separation zones of an underground excavation. The strain limit suggested in Table 10.6.20 may be conservative since these strata are subjected to horizontal constraints, increasing their resistance to fracturing.

Example 10.6.2. Mine S is planning to develop several longwall panels and needs to obtain a permit, and hence to predict

Table 10.6.17. Damage Criteria for Forests and Grazing Lands

Surface Features	Damage Severity Level	Movement Limits: Type of Movement	Movement Limits: Tolerable Range	Source	Suggested Value
Pasture, woodland, range, or wildlife food and cover	Severe	Horizontal strain	$5.0–10.0 \times 10^{-3}$		5.0×10^{-3}
Wetlands	Severe	Horizontal strain	5.0×10^{-3}	Inferred	5.0×10^{-3}
Pasture, woodland, range, or wildlife food and cover	Severe	Slope	$450–660 \times 10^{-3}$ $250–350 \times 10^{-3}$	U.S. Dept. Agriculture (Anon., 1951; 1973) (Griffin, 1977)	300×10^{-3}
Wetlands	Severe	Slope	$30–80 \times 10^{-3}$	Griffin (1977)	30×10^{-3}

Table 10.6.18. Damage Criteria for Surface Water Bodies

Surface Features	Damage Severity Level	Movement Limits: Type of Movement	Movement Limits: Range	Source	Suggested Value
Natural: Sea or tidal waters, lakes, ponds, marshes, rivers, streams	Severe (implies partial or complete loss of water)	Horizontal strain	$5.0–10.0 \times 10^{-3}$	Wardell (1976)	5.0×10^{-3}
Artificial: Canals, impounded waters					

Suggested Vertical Distance Between Mine and Water Body = > 60 × (Mining Height)

Table 10.6.19. Minimum Cover For Total Extraction Under Water Bodies (with potential for causing catastrophic damage)

Seam Thickness (t): Feet	Seam Thickness (t): Meters	Minimum Cover Thickness (D): In terms of t	Minimum Cover Thickness (D): Feet	Minimum Cover Thickness (D): Meters
3	0.9	117 t	351	107.0
4	1.2	95 t	380	115.8
5	1.5	80 t	400	121.9
6	1.8	71 t	426	129.8
7	2.1	63 t	441	134.4
7.5	2.3	60 t	450	137.2
>7.5	>2.3	60 t	450	137.2

the surface damage expected due to subsidence. The mining height is 7.6 ft (2.3 m) and the depth of cover varies between 478 and 1022 ft (146 and 312 m). The mining company assumes that the angle of draw is 15º (probably low). Panel widths are expected to range between 500 and 700 ft (152 and 213 m).

Surface structures present in the permit area include buildings (e.g., a school), roads, and pipelines. Surface land use within the plan area is primarily pasture and woodland. There are no major aquifers or streams that serve as a significant water source for public water supply. There is one perennial spring fed by a perched aquifer, which is presently used for watering stock. This spring can be expected to have low flow rates during times of low precipitation or go completely dry during times of drought. The only persistent regional aquifer in the plan area is a sandstone, approximately 50 ft (15 m) below the valley level.

Solution: The extent of subsidence $S(x)$, slope $G(x)$, and horizontal strain $e(x)$ at the locations of the structures, and the expected worst-case sites for the renewable resource lands, may be determined by any of the methods discussed in Example 10.6.1 or by using one of the prevalent computer programs (see Table 10.6.7). These values are then compared with the ranges of slope and strains for various damage levels given in Tables 10.6.11 through 10.6.18 and 10.6.20. The expected damage levels can thus be obtained, as shown in Table 10.6.21. This information may be then provided in the permit application.

10.6.4.6 Nonmining Damage

When the time span for surface damage is prolonged, accounting for subsidence generated by nonmining causes is important and needs attention. In mining areas, local inhabitants have a tendency to blame mining activity for any damage that may be observed in local structures or lands. Such claims may not be justified in many instances. Types of nonmining damage that have been noted include the following.

Soil Settlement: Differential settlement of buildings can occur on fill material, especially when the fill is improperly compacted or part of the structure is on the fill and the rest on virgin ground. Such effects are also noted if some of the foundations are old and have already settled, whereas the rest of the foundation is relatively new. Inadequate bearing capacity of foundation soil and consolidation of soft clayey soil could also result in uneven settlement. The extent of damage caused depends upon the amount of settlement that develops and the orientation of the structure with respect to the settlement pattern.

Shrinking/Swelling of Soils: When soils shrink or swell due to the influence of water, damage may occur in surface structures that appears to be similar to subsidence damage. The change in moisture content could occur because of seasonal precipitation or drying, from leaks in water lines or sewers, or by trees and other vegetation in the vicinity. Roots tend to drain the clay; this is especially noticeable under paved areas since these areas are otherwise protected from precipitation and drying effects.

Table 10.6.20. Damage Criteria for Groundwater Aquifers

Features	Damage Severity Level	Movement Limits: Type of Movement	Movement Limits: Tolerable Range	Source	Suggested Value
Aquifers	Severe (implies partial or complete loss of water)	Horizontal strain	5.0×10^{-3}	Inferred	5.0×10^{-3}

Suggested Vertical Distance Between Mine and Aquifer = > 60 $\times$ (Mining Height)

Table 10.6.21. Damage Level Assessment for Ex. 10.6.2

Structure/ Resource	Overburden Depth m (ft)	Expected Strains ($\times 10^{-3}$) (Knothe)	Expected Strains ($\times 10^{-3}$) (NCB)	Expected Slopes ($\times 10^{-3}$) (NCB)	Strain Limit ($\times 10^{-3}$)	Slope Limit ($\times 10^{-3}$)	Expected Damage Level
Buildings	152–174 (500–570)	16.5–18.8	5.5–6.3	20.5–23.1	3.0	NA	Major structural damage
Roads	152–174 (500–570)	16.5–18.8	5.5–6.3	20.2–23.1	1.0	5.0–10.0	Surface cracking and considerable grade changes
Pipeline	152–274 (500–900)	10.4–18.8	3.5–6.3	12.9–20.2	1.0	NA	Widespread failure of pipe or couplings
Surface water	152–174 (500–570)	16.5–18.8	5.5–6.3	20.2–23.1	5.0	NA	Fissuring beneath stream bed, significant water loss
Aquifer	137 (450)	21.0	7.0	25.7	5.0	NA	Partial or complete dewatering
Forests/ grazing lands	146–311 (480–1,020)	9.2–19.6	3.0–6.6	11.3–24.0	5.0	300.0	Localized surface fissuring, little drainage effects

NA = Not available

Soil shrinkage generally induces vertical strains in the structure rather than the horizontal strains that commonly damage buildings due to subsidence. The building itself tends to shelter the inner portions so the outer walls are generally affected. These walls depict a tendency to pivot outward about the foundation. Swelling of the soil reverses the movement partially, but the cracks remain.

In cold areas, freezing and thawing effects may also cause expansion and contraction of poorly drained fine-grained soils in a manner similar to moisture-sensitive soils (DuMontelle et al., 1981).

Groundwater and Precipitation: Deviations in groundwater flows or significant changes in precipitation could cause damage to structures. Such changes may be a result of mining or due to other reasons. The effects of water drainage into mined excavations, leading to surface subsidence, must be recognized as mining-related and treated accordingly. However, alterations in groundwater flow may also be caused by building activity in the area, installation of wells for farm irrigation, or major excavations some distance away which affect an aquifer. These are entirely unrelated to the mining activities.

Inadequate Drainage or Waterway Regulation: Waterlogging occurs near buildings if proper drainage is not provided. This can induce seepage into building basements and general deterioration of structures, especially if these are made of wood or other materials susceptible to damage by water. Sometimes this type of damage is blamed on mining subsidence.

Faulty Construction, Inferior Materials, or Inferior Subsoil: Poor quality building materials and construction may increase the likelihood of damage to structures. Buildings on poor soil or improperly compacted fill may also suffer disastrous effects. Roof spread is a common form of damage that may occur due to an inadequate number of cross-ties or due to timber decay in older buildings. This permits the external walls to push outward at the top and induce cracking in them. This type of damage may be distinguished from subsidence damage when observed movements are in a direction opposite to that anticipated from mining.

Chemical Attack: Masonry or stone structures show cracking when embedded iron or steel members (such as dowels, hooks, or frames) begin to rust and corrode. Glass panes in metal frames may crack because of the pressure exerted on them by rust. This probably is the case when the window can still be opened, but the glass is cracked.

Dissolved sodium, calcium, or magnesium sulfates in surface water tend to react with Portland cement or lime causing the mortar to expand and deteriorate into a powder. The moisture initially affects the shrinkage cracks, but later induces further splitting. Chimneys with sulfurous gases make easy targets for such damage. If sulfur-containing shales (which are common in coal mining areas) are used for fill or as a foundation for buildings, the concrete floor is liable to show signs of distress from sulfate attack (Anon., 1975a).

Thermal Effects: The differential thermal expansion characteristics between tiles and the concrete surface to which they are bonded may cause them to separate or become loose (such as on the floor). Joints between different materials may also be affected (e.g., plaster board joints, wood and concrete or brick interfaces, concrete/brick and steel contacts). Pavements may crack or buckle because of thermal effects. Pipelines and railroad tracks show marked effects.

Natural Wear and Tear: All structures undergo wear and tear during normal usage, and sometimes it is difficult to isolate damage due to these causes, especially if the maintenance is not regular.

Vibrations: Industrial plants in the vicinity or heavy traffic on nearby roads may generate vibrations, which could induce cracking or cause settling of structures. This may be especially true if blasting is done for construction or seismic investigations.

Minor Earthquakes: Major earthquakes are readily noted and any damage resulting therefrom is clearly evident. In earthquake-prone areas where numerous minor earthquakes occur, however, this may not be the case. The cumulative effect of these can be seen as cracks in walls or other impairment to structures, which may be confused with subsidence damage.

Minor Landslides or Creep: As with earthquakes, the effects of major landslides are noticed. However, a number of small slides or gradual creep, especially on slopes, may induce deterioration that may not be readily visible for some time.

Tectonic Movements: Structural damage can result from long-term movements of the earth's crust. Such gradual motion has lifted pipelines in California and caused measurable vertical and horizontal displacements in Upper Silesia, Poland (Brauner, 1973).

Fluid Withdrawal: As mentioned in 10.6.1, this is considered a nonmining source of subsidence in this chapter. Notable instances include the withdrawal of water for industrial and public use in the Houston-Galveston area in Texas, for agricultural purposes in the San Joaquin Valley in California, land reclamation around New Orleans in Louisiana, production of oil from the Wilmington field near Long Beach, California, and geothermal fluid extraction near the geysers in California.

Nonmining Cavities: In situ coal gasification near Rawlins, WY, tunneling for infrastructure in several urban areas (e.g., Washington, DC; San Francisco, CA; Chicago, IL; Milwaukee, WI), and natural cavity formation in the karst areas of Florida and Tennessee have also resulted in subsidence.

These are, of course, well-publicized examples, but smaller amounts of subsidence continue to occur throughout the country as a result of these mechanisms. Coal mine operators and regulators need to be particularly aware of water and oil/natural gas withdrawal in the vicinity of their mines so that the correct cause of subsidence can be identified.

10.6.5 CONTROL AND PREVENTION OF DAMAGE

There are four types of measures that may be adopted to control subsidence damage (Singh, 1985):

1. Alteration in mining techniques.
2. Postmining stabilization.
3. Architectural and structural design.
4. Comprehensive planning.

Each of these encompasses several methods.

10.6.5.1 Alteration in Mining Techniques

Partial Mining: This may be accomplished in a number of ways:

1. Leaving *protective zones,* which is the most commonly used procedure (Fig. 10.6.15). The zone may entail:

a. Leaving the *entire pillar unmined* beneath structures, such as factories, railroads, major highways, and bodies of water.

b. *Partially extracting the pillar* and backfilling

c. *Room and pillar mining,* with up to 50% extraction; a practice recommended in some states (e.g., Pennsylvania) by regulation. This method does not account for pillars deteriorating with time, especially if the mine is flooded.

It should be borne in mind that any structure supported by a protective zone is liable to become perched at a higher level than the surrounding ground, after it subsides. This may not affect the railroad or highway being protected, but could disturb the utilities to a building. An island may form if the water table is high.

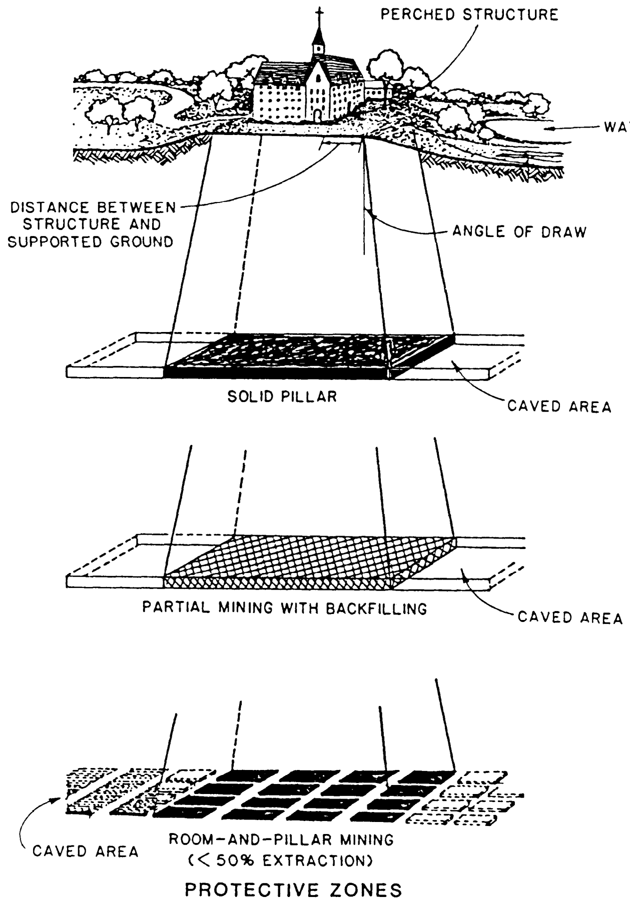

Fig. 10.6.15. Protective zones for surface structures (Singh, 1985).

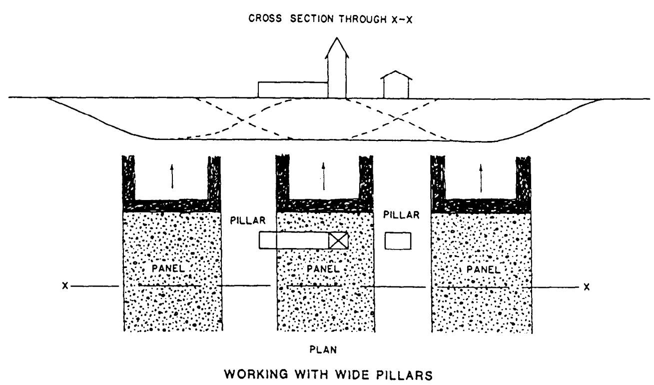

Fig. 10.6.16. Use of sized pillars for protecting surface structures (Singh, 1985).

2. Use of *sized pillars,* that is, the pillar width between panels is adjusted so as to uniformly lower the ground surface (Fig. 10.6.16)

3. *Mining subcritical widths,* so that the maximum subsidence is reduced.

Backfilling: This may be done using hydraulic or pneumatic techniques, which reduce the amount of subsidence, but do not eliminate it entirely. It is a very effective method of mitigating subsidence effects, since it not only minimizes the ground-defor-

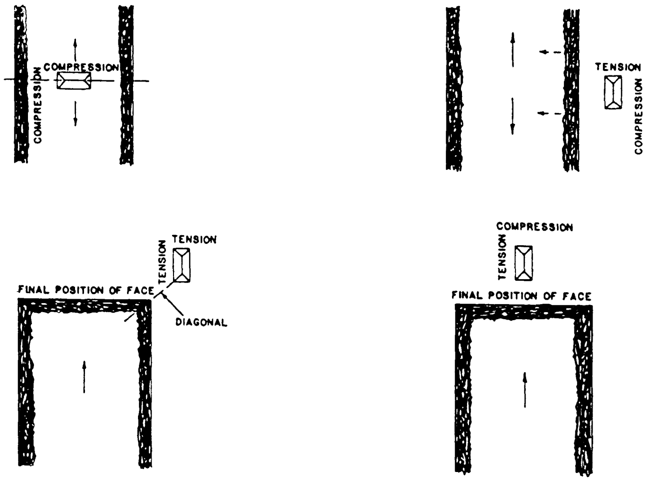

Fig. 10.6.17. Structural strains produced by basic face layouts (Kratzsch, 1983).

mation forces but also conserves the hydrologic regime. Cost effectiveness studies should consider the beneficial effect on the environment such as reduced acid-water drainage, savings in waste disposal and reforestation, prevention of refuse fires, reduced ground fissuring and escape of mine gases, as well as the advantages of long-term strata stability and decreased roof support. Railroads, canals, sewers, and streams experience smaller gradient changes. Hydraulic flushing may also cool the mine air, which is desirable in deep mines. Backfilling may become essential in flat regions with a high water table to prevent flooding, and in areas reclaimed from water bodies (e.g., in The Netherlands).

Harmonious Mining: The technique entails superimposing compressive surface strains on the tensile strains induced by another longwall face in a manner that they move along together. This may be accomplished by staggering two simultaneously worked faces that advance at the same rate, with (1) multiple seams, in which one face is superjacent over another, and (2) single seams, where the panels adjoin.

It is evident, of course, that total cancellation of the traveling strains can only occur if the displacement curves are congruent and symmetrical (i.e., the seam thickness, influence factors, width of compressive and tensile zones, and stowage density, if backfilling is adopted, are identical). Time factors for the mining sequence must also be available from prior experience.

Mine Layout or Configuration: Layout controls the strains experienced by the structure. It may be possible to locate the panel with respect to the building in such a manner as to expose it to deformations that it can withstand (Fig.10.6.17). In some cases, it may be best to stop short of taking all the coal; the loss may not be excessive if the seam is shallow.

Extraction Rate: Face advance cannot be readily altered in mining, and its range is generally limited with the available equipment. A faster rate is desirable in unfractured, viscoelastic strata because it lowers the tensile peak and moves it closer toward the working face. However, in fractured, clastic rocks (such as over previously mined beds), rapid face advance may accentuate displacements and strains and thus induce greater damage.

10.6.5.2 Postmining Stabilization

These techniques have been used in the United States and may extend over large areas (tens of acres or hectares) or be restricted to support a specific structure.

Areal: The four main methods used include:

1. *Backfilling,* which may be conducted
   a. Hydraulically.
   b. Pneumatically.

In either case the procedure may be (1) controlled, when the mine is accessible and barricades can be manually built, or (2) remote (blind), through boreholes when the openings cannot be entered, such as in abandoned mines.

With hydraulic stowing, the water level may rise temporarily in dry mines, acid water may be flushed out into the hydrologic system, and surface drainage may be affected by siltation, pollution, or flooding (especially in shallow mines). The technique is even usable in water-filled mines.

The Dowel1 process (Gray et al., 1974) is a special hydraulic blind-flushing technique, in which the slurry is pumped at a high velocity. The mixture deposits its load when the velocity drops on entering the mine cavity, forming a doughnut-shaped pile. As the pile height nears the mine roof the slurry velocity in the gap increases, keeping the solids in suspension longer, so that the pile grows outward.

Pneumatic stowing causes considerable sparking and may pose a hazard because of the potential for gas ignition.

A commonly used material for backfilling, both hydraulic and pneumatic, is fly ash because of its abundance at coal-fired power plants.

2. *Grouting* entails using a cementitious mixture and thus provides a stronger support. Additives used include Portland cement, pozzolanic mixtures, or organic compounds.

a. *Gravity grouting* is used to simply fill the mine void to whatever extent possible. There is little control, although a perimeter wall may first be built with a thick grout, which is then filled with an expansive grout to achieve good roof contact.

b. *Pressure grouting* is needed if a number of joints need to be filled or roof caving has occurred.

c. *Bag grouting* is a new development (Singh, 1985), and entails lowering a bag through a 6-in. (150-mm)-diameter borehole and filling that with grout until roof contact is obtained.

Grouting under important buildings requires special care (Scott, 1957).

3. *Excavation and fill placement* is only feasible in shallow abandoned mines, with no surface obstructions to excavation. The entire overburden and coal are removed and replaced with compacted fill. Flooded mines may yield large quantities of acid water.

4. *Blasting* of the roof and floor to fill the cavity is a patented technique (Patent No. 1 004 419), which has not been used recently (Gray et al., 1974). Over time, the broken rock compresses, but the movements may be expected to be gradual and evenly distributed.

Site Specific: These techniques are mostly used to support isolated structures.

1. *Grout columns* may be built remotely, but floor and column strengths are variable. Water may impede construction.

2. *Piers and cribs* may be constructed in mine openings that are accessible, if the mine floor and roof are competent.

3. *Deep foundations* may be used with shallow workings. They are, however, liable to damage by lateral shear forces that may be experienced.

4. *Groutcase supports* entail placing casing between the mine roof and floor and filling it with grout. These supplement existing coal pillars.

10.6.5.3 Architectural and Structural Design

Orientation: It is preferable to have the long axis of the building parallel to the subsidence contours. If a fault exists nearby, the shorter axis should be oriented perpendicular to the fault.

Location: Faults tend to concentrate ground strains, hence structures should be located at least 50 ft (15 m) away.

A single building should not be constructed on dissimilar soils, owing to the possibility of differential deformations or settlements.

Subsidence-Resistant Construction: This technique has received considerable attention in the literature. It may be discussed under four major construction categories:

1. *Rigid* in which both the foundation and superstructure are rigid in design. Often the foundations are highly reinforced concrete rafts or beams, capable of withstanding ground displacements and curvature. The structures generally span or cantilever over a subsidence wave. Foundations are of small plan area. Elevator shafts and the like are designed with extra clearances.

2. *Flexible design* permits slab foundations for small buildings such as houses. The slab should preferably be less than 60 ft (18 m) along the side, poured in a single operation, without joints, and finished close to ground level. It is generally underlain by granular material. Reinforcement should be near both the top and bottom so as to accommodate tensile and compressive strains.

If the building has a basement, there should be an open gap around it or filled with a compressible or granular material. Larger buildings may have rollers or slip-joints between the superstructure and foundation. Trenches around structures absorb some of the strains.

Flexible structures are designed to track the traveling subsidence wave without cantilevering, permit free ground movement below the foundation, provide sufficient superstructure support in spite of the ground flexing, and accommodate subsidence deformations that are larger than anticipated without jeopardizing structural stability.

3. *Semi-flexible designs* are used in instances where the structures can tolerate minor damage, such as some warehouses. These do not strictly adhere to the rigid or flexible criteria outlined above. It may be more cost effective to perform minor repairs as required than employ these more expensive designs.

4. *Use of releveling devices,* such as jacks, to prevent tilting. Excessive tilt may cause the gap between adjacent buildings to be reduced to the extent that they touch.

Gaps need to be provided between all buildings to allow for both compression and tilt. Other precautions that are helpful, depending on design philosophy, are (Chen et al., 1974; Anon., 1977)

a. Provide expansion joints to accommodate ground movements and thermal expansion.

b. Minimize the number of door and window openings and use flexible frames; their location should not significantly weaken the structure; do not position front and back doors opposite each other.

c. Avoid weak skin materials within rooms; partitions between building segments should be strong; instead of plaster on ceilings and walls, use plaster board.

d. Floors and roof should be secured to the walls.

e. Allow for tensile strains at all structural connections; movements should be possible for staircases.

f. Exclude masonry arches.

g. Do not have comer or bay windows or porches.

h. Detach outbuildings from the main building

i. Provide excessive falls for gutters.

j. Do not pave immediately adjoining buildings; use bituminous type materials for paving where necessary (e.g., driveways).

k. Employ flexible damp-proof courses (e.g., bitumen).

l. Use light fences around properties rather than walls.

m. Replace rigid retaining walls with earth banks.

Modification of Existing Structures: Total repair expenses may sometimes be reduced if a building is suitably modified prior to its experiencing ground movements. Possible alterations include (Chen et al., 1974; Kratzsch, 1983)

1. Cutting out a part of a house or removing an entire house from a row of buildings; unit lengths should be about 60 ft (18 m), with cuts extending into trenches, and gaps bridged with flexible materials; preferably locate cuts in connection corridors or unit divisions.

2. Digging trenches around a building (and filling with compressive material weaker than the surrounding soil) to below foundation level, without disturbing the foundation; trenches may be covered, if desired, with concrete slabs that do not butt.

3. Slotting rigid pavements or floors, and even superstructures (generally wood, brick, or stone do not present difficulties; concrete may).

4. Introducing slip planes, especially in new buildings.

5. Providing temporary supports and/or strengthening to parts susceptible to damage; support screens, partitions, and ornaments independently of the walls and floor.

6. Using tie rods, if it is anticipated that the roof trusses will be pulled out from their seats; however, indiscriminate use of tie rods may needlessly disfigure the building; stress concentrations at tie-rod bearing plates may pull these through the walls; often temporary corbels provide adequate support for trusses.

7. Installing pretensioned steel mesh around the exterior walls (this could be dismantled and reused later).

8. Taping windows, (especially with metal frames), to avoid flying glass.

9. Removing and storing stained glass windows, until subsidence is complete.

Remedial and Restorative Measures: Increasingly, structures are being constructed so as to be easily repaired after subsidence damage. Since a tension wave is usually followed by a compression wave, cracks should not be patched until all movements have stopped. Debris in the fractures should, however, be removed prior to the compression cycle.

In low-lying areas, the water table may create difficulties, necessitating the installation of drains and pumps.

10.6.5.4 Comprehensive Planning

It is desirable to plan both the surface land use and the mine with full knowledge of the requirements of each. Deep cuts for highways, railroads, or other structures, or excavations for utility tunnels or basements, may reduce the competent overburden thickness above the old workings to induce subsidence. This type of situation can be prevented with planning.

For planning or any other measure to be successfully implemented, it is paramount that everyone affected by subsidence fully comprehend what is being done and why. Therefore, an intensive effort of public education about the subject is in order. This should not only be directed towards the general populace, but also the mine operating personnel, builders and developers, government officials at all levels, and civic groups.

Four situations (Anon., 1977) may be identified, each of which requires a slightly different approach to planning:

1. Existing subsidence potential, existing development.
2. Existing subsidence potential, future development.

3. Future mining area, existing development.
4. Future mining area, future development.

Essentially all these approaches entail either coordination or control of both the surface and subsurface development.

Coordination of Surface/Underground Development: Although not a comprehensive list, typical of the principles that may be followed are

1. Avoid construction near outcrops or faults.
2. Build only specially designed structures over shallow workings; surface effects are magnified as the depth decreases.
3. Locate buildings above steeply dipping seams since the strains induced are reduced.
4. Erect communications or other significant structures in unmined or completely subsided areas.
5. Alter routes of highways, railroads, canals, and other structures to suit coal conditions (e.g., over want areas or near fault planes); subsequent costs for lowering may be thereby reduced.
6. Site linear structures (e.g., canals, railroads) so that they can be uniformly lowered along their entire length; locks may be located over unminable zones, although massive lock structures can be dropped without significant damage.
7. Avoid building important structures near mine boundaries since coordination with several mine operators and surface land owners is onerous; also boundary pillars may introduce higher stresses.

Collaboration between the mining companies and surface owners and developers is essential in regional or zonal planning, otherwise problems will arise.

Land Use/Development Control: Development of land areas overlying mines must be economically justifiable as well as socially and culturally acceptable. This implies that often regional plans should not only be discussed with mine and surface owners, but also be open to public comment prior to adoption. Changes in these plans also deserve an equally protracted treatment.

Federal, state, regional, county, and local government authorities exert considerable control over development of land that is potentially liable to damage due to subsidence through these means:

1. Surface Mining Reclamation and Control Act (SMRCA) of 1977 (Public Law 95-87).
2. Environmental impact requirements.
3. Zoning and subdivision regulations.
4. Building provisions (issuance of permits).
5. Mining regulations.
6. Safety requirements.
7. Insurance needs.
8. Investigative requirements for public buildings (e.g., Pennsylvania's Act 17 of 1972).
9. Special local ordinances.
10. Interagency coordination.

Perhaps in the future, it will be mandated that mine operators prepare plans that depict predicted subsidence locations, extent, trough centers, maximum subsidence, values and direction of tilt, compression and extension zones, and other pertinent data. These could then be circulated to building authorities, highway commissions, railroads, water supply and other utility agencies, pipeline operators, and others who may be affected for comments and suggestions (within strict time limitations). On the other hand, these groups as well as builders/developers should be required to incorporate proper precautions in the design of their respective structures. In extreme cases, construction may be barred from particularly risky areas, and these lands used for parks, forest preserves, and open spaces.

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