Appendix B
Mining Operations and Subsidence

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Introduction

Coal mining involves the extraction of coal seams or beds. Although the thickness of a coal seam will vary, minable seams generally are continuous over large areas. When the deposit is close to the ground surface (less than approximately 200 feet deep), it is generally mined using surface methods. Deeper deposits are generally mined by underground methods.

Geologic strata above and below a coal seam are known as overburden and underburden, respectively. The overburden and underburden strata that are actually in contact with coal in an underground mine are called the “roof” and “floor,” respectively. Blocks of coal left in place to help support the roof of the underground mine are called “pillars.”

Removal of coal by underground methods creates a limited void in the stratigraphic column. As a block of coal is extracted, natural forces act on the stability of the overburden and if large enough, cause the overlying column to subside. Even in the strongest formations, large underground mine openings will eventually be filled by the collapse of the overburden and may result in crushing of adjacent pillars by the transfer of the overburden load previously carried by the mined coal. Underground coal mining methods are generally classified, or distinguished from each other, by the type of support used to prevent the roof from collapsing prematurely, endangering workers and equipment.

Room-and-Pillar Mining Operations

Room-and-pillar mining is a type of underground extraction used where the roof is supported primarily by pillars. Coal is extracted as a group of rectangular shaped parallel rooms, or entries, are driven into the coal seam. Crosscuts are periodically driven between entries. Parts of the coal seam are left between the entries and crosscuts and serve as pillars to support the roof. The pillars are arranged in a regular pattern, or grid, to simplify planning and operation. Pillars can be of any shape but are usually square or rectangular. The dimensions of the rooms and pillars depend on many design factors, including the stability of the immediate roof and floor, the strength of the coal in the pillars, the thickness of the coal seam extracted, and the depth of mining. A series of entries are designed to outline an area called a panel or block of coal that defines a working section of a mine. Panels are typically bordered by barrier pillars in order to permit easier isolation of abandoned panels from active parts of a mine.

Typically, coal seams mined by underground methods in the United States range in thickness from 2.5 to 15 feet. For roof control and safety reasons, the width of the rooms, or entries is generally limited to 20 feet. The spacing, or centers, between entries varies from 40 to 100 feet depending on the stress distributions determined in the design and operation of the mine. Spacing between crosscuts is limited by ventilation required and is subject to federal and/or state safety laws (usually limited to approximately 100 feet). A general representation of room-and-pillar mining is shown in Figure 1, Conceptual Room and Pillar Mining.

In underground coal operations, there are two types of room-and-pillar mining:

- Conventional room-and-pillar mining
- Continuous room-and-pillar mining

Conventional mining involves a cyclical system of extraction, employing mobile equipment to conduct the production cycle of operations as follows:.

- Undercut the coal face
- Load overlying holes in the coal seam with explosives
- Blast
- Load broken coal
- Install roof bolt or other support

In continuous room-and-pillar mining, the first four unit operations of conventional mining are eliminated and performed by a high-performance continuous-mining machine. In the United States, most room-and-pillar mining is conducted using a continuous-miner system which includes:

- A coal extraction machine (continuous miner).
- A coal haulage system (shuttle cars and conveyor belts).
- A ground support system (roof bolts and pillars).

The continuous miner is electric and hydraulic powered and track-propelled. Major components of this machine include a rotating-cutting drum and a gathering system beneath the cutting drum which loads an internal conveyor. The machine operator drives the rotating-cutting drum which is situated at the front (head) of the machine to the unmined coal face, activates the hydraulic pistons that force the rotating-cutting drum into the coal and cuts coal out of the coal face. The gathering arms which are located on an inclined plate beneath the rotating cutting drum shifts the cut coal to the internal conveyor for transfer to the rear (tail) of the machine. A rear, articulating conveyor then transfers the coal to independently-operated shuttle cars or a series of short transfer conveyors.

The shuttle cars (10 to 15 tons per car) or transfer conveyors are used to transport mined coal from the continuous miner to a conveyor belt transfer point within the mine. Shuttle cars are either electric or diesel powered, 2- or 4-wheel drive, and have either a conveyor or push-ram system to discharge the coal to the stationary conveyor belt system which transports coal outside the mine portal, usually to a run-of-mine (ROM) coal stockpile.

Pillars and roof bolts are used to support the roof and overburden. Solid pillars of coal are left in place within each panel during the initial (advance) mining stage to support the overburden above the panel and along the main access corridors (main entries) of the mine. Support of the immediate roof over panel entries and crosscuts is typically provided by the use of roof bolts. Roof bolts are long steel rods or wire-rope cables anchored in holes drilled into the roof rock. Bolt anchorage is provided by either resin glue or mechanical anchors. The bolts create a supporting “beam” of rock by bonding or “bolting” several layers of the immediate roof-rock strata together. The general mining/production sequence allows for the continuous miner to advance about 20 feet before the roof of the mined area must be secured with roof bolts. More than one continuous-miner may be advancing entries and crosscuts in one panel, in order to allow for uninterrupted mining, i.e., while roof bolts are being installed in some entries, mining, loading and haulage can continue in other panel entries.

As a general rule, 15 to 70 percent of the coal within a panel remains in place in the form of pillars after the rooms are mined on the advance (partial extraction). To increase coal recovery, the roof can be temporarily reinforced with props and/or additional bolts so that some portion of those pillars not required to temporarily support and to protect the active entries can be systematically removed on the retreat from a panel (full extraction). In this second stage of mining, pillars are “robbed” (partially removed) as the mining equipment “retreats” from each advance mined room. As pillar-robbing progresses back toward the panel access, the rooms are allowed to cave in, and the mined-out panel is sealed and abandoned. Pillar robbing can be anticipated to reduce the coal left in place in the form of pillars to 10 to 60 percent of the coal in the panel.

Longwall Mining Operations

Longwall mining is an underground extraction method used in generally flat-lying, tabular coal deposits. A “long” face is established across a panel, which is bounded on both sides by entries. These entries are known as the “headgate” entries and the “tailgate” entries. The headgate entries are used for the passage of intake air and the transportation of coal, personnel, and supplies, while the tailgate entry is used for the passage of the return air. A general representation of a longwall mining face area is shown in Figure 2, Conceptual Longwall Mining.

The longwall panel layout is simple and conducive to good ventilation, and crews always work under heavily supported roof. Since the longwall system involves caving across the entire face width, no coal is left as residual pillars within the block of coal, as must be done in room-and-pillar mining. Therefore, coal recovery is higher for longwall mining. Depth of overburden for a longwall operation can vary from 200 to over 2,500 feet, with coal extraction thickness ranging from 4 to 15 feet.

Panel width and panel length are usually determined by experience, based on the size and shape of the coal deposit, geologic conditions, and the capacities of the transportation, ventilation, and power equipment that can be supplied. In the United States, the panel width typically ranges from 700 to 1,200 feet; panel length also varies, ranging from 3,000 to over 15,000 feet.

While the width of the panel face, or wall, is measured in hundreds of feet, the actual working area is narrow, measured in feet out from the face. A longwall system is kept open, by a series of heavy-duty, electric and hydraulic powered, yielding supports that form a cantilever or umbrella of protection over the face. As a cut, or slice, is taken along the panel face, the supports behind the shearer retract, advance and re-engage, allowing the roof to cave in the mined-out area behind the supports. The caved material is known as the “gob.”

A very old method, longwall mining originated in European coal mines in the seventeenth century and has widespread use in coal-producing countries outside the United States. Only since the 1960s, when self-advancing, hydraulic support systems (chocks and shields) were perfected, has longwall mining been accepted in the United States. Other innovations that have led to its growing use in coal fields are the development of mobile, flexible, armored conveyors and high-speed continuous longwall mining machines (shearers).

Longwall mining operations in the United States are predominantly of the “retreating” type. That is, the headgate, tailgate, starter and recovery entries are initially developed completely around the block of coal to be mined. Then the longwall mining system is erected in the starter room and the longwall face "retreats" from the starter room at the back of the panel toward the shield recovery room separated from the main entries by a barrier pillar. See Figure 3, Typical Longwall Panel Layout in the United States. Longwall development is strikingly similar to the development for room-and-pillar mining.

Longwall operations in the United States are conducted with a longwall mining system. As with the continuous miner, the longwall system will include:

- A coal cutting (extraction) machine (shearer).
- A coal haulage system (face conveyor and headgate panel conveyor).
- A roof support system (shields).

Whereas, the continuous-mining system involves several independently operated pieces of equipment to mine coal, the longwall mining system is totally integrated, with all of the necessary equipment interconnected. For example, the longwall mining system, the shearer actually rides on top of the face conveyor and the shields are physically connected to the face conveyor.

The shearer, like the continuous miner, is electric and hydraulic powered. The major components of this machine are the rotating-cutting drums and the tram system. The drums, located at each end of the machine, are limited to an up-down movement. The machine operator drives the rotating-cutting drums into the coalbed as the machine trams laterally along the face on the face conveyor, thereby cutting coal from the coal face. Cut coal falls to the floor-supported face chain conveyor for transport to one end of the longwall, the "headgate." There, the coal is transferred to a belt conveyor system that transports the coal outside the mine portal. The opposite end of the chain conveyor from the headgate is across the ‘‘tailgate."

Longwall roof support is provided at the face by the hydraulic roof supports (shields). Major components of the shields include canopy, hydraulic cylinders, hydraulic controls, and the base. The canopy is a thick, reinforced-steel plate that is pushed against the roof by the hydraulic cylinders to support the weight of roof rock from four to more than ten times the shearing height while coal removal operations continue in the shielded area below. Shields are generally 5 feet wide, vary from 4 to 15 feet high, and have a design-load capacity of 500 tons or more per shield. The base length of the shield is relatively short, allowing the face conveyor to sit on the floor in front of the shield bases. Shields are designed to be large enough to safely cover the face conveyor, shearer, and workers. In the longwall system, individual shields are installed next to each other along the entire longwall face, from the face conveyor headgate to its tailgate. See Figure 2, Conceptual Longwall Mining.

The mining/production sequence involves cutting (shearing) a section of coal face, typically 30 to 42 inches deep, from the headgate to the tailgate, using hydraulic rams to move the face conveyor up against the face of the fresh-cut coal seam. Hydraulic rams attached to the face conveyor then move individual shields forward. The unsupported roof behind the shields is allowed to cave to the floor. As slices of the block of coal are systematically removed, the mined area is gradually abandoned.

Mechanisms of Subsidence

Removal of coal deposits by underground mining methods creates voids that are filled when the stress concentrations in the roof of the openings exceed the strength of immediate roof rock allowing the immediate roof to collapse unless supported. The concentration of more and more overburden load onto pillars will eventually crush the pillars when sufficient extraction has occurred. Deterioration of pillars over time has weakened pillars to the point that they fail. These phenomena all lead to potential subsidence of the main roof, the overburden, to deflect downward. The complete removal of large areas of coal by longwall mining allows the almost immediate collapse of the immediate roof and downward deflection of the overburden to the ground surface, known as subsidence. Vertical lowering typical of a flat-lying ground surface over and adjacent to an underlying longwall panel is indicated on Figure 4, Plan View of Surface Subsidence over a Longwall Panel. Subsidence-related deformation of rocks above underground mines can consist of fracturing, fragmentation, caving and chimney collapse, sagging and bedding-plane separation. However, caving of the immediate roof into mined areas does not always translate into surface subsidence. The type of deformation that occurs, and whether the deformation reaches the surface, depends on a number of factors, including rock type, percent swell of overlying rock, rock strength, thickness and competence of overlying beds, mine layout, mine depth, mining height and how far a particular competent horizon lies above the void in the mined area. The magnitude, extent, and duration of subsidence can be minimized by an efficient mine layout, proper barrier and gateroad pillar design, and a rapid and efficient mining system.

Subsidence-Related Deformation

In the overburden above mined areas, three zones of deformation tend to develop in response to subsidence, as shown on Figure 5, Conceptual Representation of Subsidence Deformation Zones. In the caved (fragmented) zone, rocks of the immediate roof are expected to fragment, collapse, and rotate. This zone in coal measure rocks is typically between two and four times thicker than the longwall mining height, but can be as much as ten times thicker than the mining height (the void produced by mining) over adverse four-way entry and crosscut room-and-pillar intersections and similar four-way gateroad intersections. This is shown on Figure 6, Potential Collapse Heights.

Directly above the caved zone, is the fractured zone, where rock strata are expected to fracture into bedding bounded blocks and deflect downward while maintaining bedding continuity. Bedding-plane separations may, however, develop. This zone can be as much as an additional 18 times thicker than the mining height, depending primarily on the competency of the rocks in this section of the overburden. In the third zone, the deformation zone (which some engineers separate into two zones, the continuous deformation zone and the near surface deformation zone) rocks should sag downward without major fracturing, but bedding-plane separations and discontinuous tension cracks can still occur in tensile strain zones at the top and bottom of individual beds. This zone can extend from the top of the fractured zone to the ground surface. After the deformation process, fractures that developed in the softer mudstones, siltstones, shales and softer sandstones tend to close, while fractures that developed in stronger and more brittle rocks may remain open indefinitely.

If deformation reaches the surface, subsidence will typically appear as basins or depressions, pits, and/or open cracks. Subsidence basins can form above room-and-pillar mines with pillars that were initially stable but crushed (failed) after a period of deterioration, or during the robbing of pillars on the retreat or above longwall panels on the retreat. These basins are typically ovaloidal in plan and trough-shaped in section because the panels are large and rectangular, and because coal seams often are nearly horizontal. Subsidence pits (chimneys to the surface) can form above shallow, almost always less than 200-foot deep, intersections of entries and crosscuts, particularly in room-and-pillar mines where the pillars have not been robbed. The overburden directly above the pillars continues to be supported, while the overburden above the mined area collapses into the mined-out rooms and intersections.

Horizontal strain, both tensile and compressive, results from lowering of the surface during subsidence. Tension that can cause cracks occurs as the surface begins to subside and stretch over the outer edges of an undermined panel. Compression develops toward the center of a panel and closes some of the tension cracks in the ground that bend back toward its pre-mining slope. Subsidence induced changes in surface slope are generally minor, having a magnitude commonly less than 3 degrees. Tension cracks are more apparent than compression features because rocks are stronger in compression. Tension cracks are more abundant in solid rock than they are in unconsolidated materials. At the surface, tension cracks can range from small (less than an inch), subtle features that are difficult to recognize to fractures that are several feet wide and several feet deep. Surface fractures may be temporary, with many closing during successive subsidence events, after natural deposition of sediment, or when frost heaving fills them. Surface tension cracks over the edges of individual longwall panels, over gateroad pillars between panels, over the barrier pillars at the ends of individual panels and over barrier pillars adjacent to panel groups, frequently referred to as sections, and along edges of the mined area (the mining boundaries) may remain open indefinitely. This is most evident in areas where brittle sandstones or other rocks crop out. The surface soil cover will have an influence on the cracking that is actually visible at the surface. Unconsolidated deposits of alluvium, colluvium, and soil tend to obscure surface cracks.

Factors Controlling Subsidence

Several factors control the area, amount, rate and duration of subsidence. Mining factors include mining method, mine geometry, extraction ratio, height of the mine workings, and mining rate. Geologic factors include depth of the coal seam, along with the thickness, lithology, strength, structure, fracture and joint set orientation, and bulking or swell factor of the overburden. The subsidence factor and the angle of draw are used to describe the maximum vertical displacement and the areal extent of subsidence, respectively.

The mine geometry (or mine design) determines the size and configuration of the rooms, pillars, and panels, the height of the openings and pillars; and the spatial relation to any abandoned mines that may be located above and/or below the active mine. Generally, mines are designed so that the subsidence process can take advantage of joints in the overburden. This can smooth subsidence by minimizing sagging of the immediate roof before the roof collapses, minimizing the potential of periodic weighting of either pillars or the coal exposed in the longwall face. Although subsidence can be reduced by leaving pillars for support, this procedure may only delay subsidence because pillars and roof rocks generally deteriorate and yield with time and weathering.

The extraction ratio is the ratio of the amount of coal extracted to the total amount of coal in either the panels, entries or the mine area. Longwall mining, because it potentially extracts 100 percent of the coal between the gateroad pillars, generally achieves an overall panel extraction ratio of about 78 percent of the total coal in the panel, including the gateroad pillars on either side of the panel. The extraction ratio typically decreases to about 72 percent when the barrier pillars within a mining section are included. Room-and-pillar mining generally extracts about 64 percent of the total coal within individual panels on the advance. Pillar robbing upon retreat from a panel generally increases the extraction ratio to about 81 percent of the total coal between the panel barrier pillars. When barrier pillars within a mining section are included the recovery drops to about 51 percent of the total coal in an individual panel employing advance mining only, and to about 70 percent when barrier pillars within a mining section are included. Recovery from advance and retreat room-and-pillar mining is generally nearly as much of the coal as does longwall mining. However, longwall mining has proven to be generally safer, more productive and effective at greater depths than room-and-pillar mining.

The mining method also influences the amount of subsidence. Longwall mining usually results in more subsidence than room-and-pillar mining, partially because of its generally greater extraction of coal and partly because the stump pillars left within the panels when robbing do not crush out flat when they fail under the overburden load. Efficient robbing of pillars, however, can result in surface subsidence nearly equal in magnitude to that associated with longwall mining. Subsidence above room-and-pillar mining areas is also less predictable and more variable in surface expression than above longwall panels because the extraction ratios and heights of caving are more variable. Long-term deterioration of coal pillars can delay the resulting surface subsidence decades and the timing of a pillar collapse cannot be accurately predicted.

The mining rate also affects subsidence. When the mine face is extracted at an even and rapid rate, smoother subsidence profiles occur with less differential movement.

The extracted mining height, width of the individual panel with respect to the depth of the deposit and thickness of the overburden control maximum subsidence. The subsidence factor is the ratio of maximum surface subsidence to the seam mining height and is often expressed as a percentage. For example, if a maximum 7 feet of subsidence occurred over a mine panel with a 10-foot mining height, then the subsidence factor would be 70 percent. In the Western United States, subsidence factors range from about 45 to 90 percent of the thickness of coal extracted. However, the subsidence factor will increase with increasing panel width, unless both the previous and new panel widths exceed the critical width, which ranges from approximately 1.0 to 1.4 times the depth. Figure 7, Critical Panel Width for Maximum Subsidence, indicates that the maximum surface subsidence (S_{max}) over a longwall panel develops when panel width reaches and exceeds the critical width. The load on the collapsed roof rock, gob, increases as panel width increases up to the limiting critical panel width. The load on the central portion of panels wider than critical is the weight of the overburden, with none of the overburden load transferred to adjacent unmined coal or barrier pillars.

The angle of draw identifies the measurable limits of subsidence beyond the boundaries of the mined area, i.e. the areal extent of subsidence occurring at the ground surface will be larger than the area extracted underground. It is expressed in degrees from vertical above the edge of the mined area. For example, if the angle of draw were 20 degrees and the overburden were 1,000 feet thick, then measurable subsidence would be anticipated as much as 364 feet beyond the edge of the mined area. In the western United States, subsidence angles of draw range from about 5 to 30 degrees. The angle of draw appears to be dependent on the proportion of different rock types present in the overburden. The angle of draw increases with an increasing proportion of lower strength mudstone and shale in the overburden. The angle of draw decreases with an increasing proportion of stronger sandstone and limestone in the overburden.

Sagging, caving, and fragmentation are governed by the strength and structure of the overburden. The composition of the mineral grains and the cements that bind the grains together affect the strength of the rocks. The dip of faults and fractures in the overburden may present low shear strength sliding surfaces that can influence, or even locally control, the angle of draw. The strength and structure of the overburden rocks are considered when determining room, pillar, and panel orientation.

The percent swell, or the volumetric percent increase of fragmented rocks relative to their undisturbed in-place volume, is a factor influencing subsidence. The bulking factor is determined by the size and shape of the broken rocks, the contact stresses among rock fragments within the fragmented zone, and the relative strengths of the affected rocks. The percent swell is generally lowest where the overburden is composed of soft claystones and thinly bedded shales, and highest where hard, thickly bedded to massive sandstones and limestones predominate. If rock fragments randomly fall to the floor of the mined area, and if strong, massive rocks occur in the collapsed, fractured and deformation zones, then the percent swell is higher. Higher percent swell of the overburden results in filling the mined volume with less collapsed rock and, therefore, in less subsidence of the overlying rocks and reduced tension and compression at the surface.

Prediction of Subsidence

Subsidence associated with underground mining is anticipated, and its magnitude and extent can be predicted. Often, predictions of maximum surface subsidence and horizontal tensile and compressive strains are used to help assess the secondary impacts to other resources (both human and natural). Data collected during actual subsidence are used to verify that measured subsidence does not exceed predicted values.

A method of calculation developed by the British National Coal Board (NCB) on the basis of surface and underground measurements at 177 named and 10 unnamed longwall panels offers one of the most comprehensive, conservative, and accurate techniques for predicting subsidence, surface strains and slope (tilt) associated with longwall mining. Other researchers have modified it for the generally greater proportion of stronger sandstone strata in the overburden overlying coal mines in the western United States. Inputs to the longwall subsidence prediction model are depth, mining height, frequently less than seam thickness, and panel and gateroad geometry. Inputs to room-and-pillar subsidence prediction are the same except percent extraction and final panel pillar, entry and crosscut geometry replaces longwall geometry.

Subsidence profiles can be used to illustrate subsidence and strain predictions above and across longwall or room-and-pillar retreat mined panels. In this example, the longwall panels are in a virgin area (not previously subsided), 800 feet (244 m) wide including the 20-foot width of the gateroad entries on both side of the longwall block, overburden is about 1,000 feet (305 m) thick and mining height is 11 feet. The panel width to panel depth based maximum subsidence prediction can be conservatively made using Figure 8, NCB Panel Width/Depth Maximum

Subsidence (S_{max}) Prediction, predicts 0.76 times the 11-foot mining height, or 8.4 feet. Applying the virgin ground correction of 0.9 for the previously subsided NCB model reduces the predicted maximum subsidence factor to 0.68 and the predicted maximum subsidence (S_{max}) to 7.5 feet. Maximum subsidence would occur over the middle of each panel with the same Sub-critical width/depth ratio.

Figure 9, NCB Subsidence Profile Graph, permits the conservative estimation of subsidence for any distance from the center of a panel for any point along a cross section perpendicular to the long axis of any panel whose location is at least 0.7 times its depth from either end of the panel, i.e. the center of the panel is not affected by the barrier pillars at the panel ends.

Final subsidence over the gateroad pillars between two adjacent panels is dependent on whether the gateroad pillars are designed to be rigid or to yield when the first panel is retreated past or if at least one of the gateroad pillars is designed to function as a rigid pillar or to crush when the face of the second panel has retreated well past. If the two gateroad pillars in the example above are 40-foot wide and separated by a 20-foot wide entry and considered rigid, the distance from the panel centerline to the center of the gateroad is 450 feet (800/2 + 40 + 20/2). Enter the Y-axis of Figure 9, NCB Subsidence Profile Graph, for the panel width/depth ratio of 0.8 (800/1000). The X-axis entry point is 0.45. These two lines converge at approximately 0.173 times S_{max}, 7.5 feet, or 1.3 feet of subsidence when the first panel has been mined and subsidence has stabilized and twice that, 2.6 feet after the second panel has passed. Additional subsidence will take place if the gateroad pillars crush. An available method of estimating the additional subsidence resulting from gateroad pillar crushing assumes that the gateroad pillars are part of a room-and-pillar panel. The method requires the pillar dimensions and extraction percentage.

Tensile stretching and compressing of the ground surface has been the greatest adverse subsidence impact, particularly in urban areas. Tensile strain develops at the ground surface above, outside and inside the boundaries of a mined and subsided panel and compressive strain develops inside the area inside a mined panel. Figure 10, Critical Panel Width for Maximum Tensile (+E) and Compressive (-E) Strains, graphically demonstrates that sub-critical width panels will develop lower maximum tensile strain (+E) values than critical or super-critical width panels, but that the maximum compressive strain (-E) can be greater for sub-critical panels because the compressive strains from both sides of the sub-critical panel become additive toward the center of narrow sub-critical panels.

Tensile strains are the cause of tensile cracking of the ground surface around the perimeter of an underlying longwall panel and compressive strains can cause pressure ridges to be forced up at the ground surface. Tensile and compressive strains exceeding the individual tolerances of all kinds of surface structures can cause severe damage. Strains on the order of 1,000 to 1,500 $\mu\varepsilon$ (micro-strain which is 0.001 in/in) may result in the cracking of gypsum plaster; gas mains may be at risk at 2,000 $\mu\varepsilon$; cracks become obvious in monolithic reinforced concrete buildings, river beds and reservoirs may experience leakage and main railways damaged when subject to 4,000 $\mu\varepsilon$ and 6,000 $\mu\varepsilon$ may damage and distort 60-foot long residential buildings, main roads, structures steel, brick and even wood buildings will be distorted.

The NCB subsidence study developed the graphical method of predicting maximum tensile (+E) and compressive (-E) strains based on maximum subsidence (S_{max}) and mining depth, as shown on Figure 11, NCB Maximum Strain and Slope Prediction Graph. The longwall example produced a maximum subsidence (S_{max}) of 7.5 feet, assumed an 800-foot panel width, a

1000-foot panel depth, for an 0.8 width/depth ratio. Enter the X-axis with the 0.8 panel width/depth ratio, which crosses the EXTENSION (+E) line at a MULTIPLIER value of 0.64 and the COMPRESSION (-E) line at a MULTIPLIER value of 0.68. The predicted maximum tensile strain is:

$$+E = 0.64(7.5/1000) = 0.004800 \text{ in/in } (4800\ \mu\varepsilon)$$

and the predicted maximum compressive strain is:

$$-E = 0.68(7.5/1000) = 0.005100 \text{ in/in } (5100\ \mu\varepsilon)$$

Similarly, the tangent of the maximum slope angle (G) is:

$$\text{Tan } G = 2.82(7.5/1000) = 0.02115\ (G = 1.21°)$$

The British NCB also produced a graphical method of predicting the location of maximum tensile and compressive strains across the subsidence trough. See Figure 12, NCB Horizontal Strain Profile Graph. In the longwall example case, with a panel width to depth ratio of 0.8, the maximum tensile strain (+E) is located on the overlying ground surface approximately 0.42 times the 1,000-foot panel depth on both sides of the panel centerline, or 420 feet. Subtracting one-half the 800-foot panel width means that predicted maximum tensile strain (+E) is located approximately 20 feet outside both panel ribsides. The predicted location of the maximum compressive strain (-E) is 0.11 times the 1,000-foot depth from the panel centerline, or on the overlying ground surface approximately 110 feet on both sides of the centerline. The maximum compressive strain (-E) is predicted to be 290 feet inside the gateroad coal pillars that define the panel ribside.

A monitoring program is generally implemented at underground mines to collect subsidence data. The measurements are typically periodic 3-dimensional horizontal and vertical monument locations. These data are used to verify that the predicted subsidence effects are not exceeded by the actual ground conditions and to detect mining induced impacts to surface resources, both predicted and not predicted. In addition, site specific angle of draw, subsidence factor, and tensile and compressive strains can be calculated from the measurements.

A number of techniques and types of equipment can be used in subsidence monitoring programs: conventional ground surveying of monuments located over panels and extending out over unmined areas to measure monument locations and elevations at periodic intervals and calculate the average horizontal and vertical strain between monuments, vector movement and slope (tilt) between monuments; installation of extensometers to measure displacement between monuments and calculate strain; serial photographic surveying; analytical aerial triangulation; digital terrain modeling; surface observations; as well as surface water and spring monitoring. Global Positioning System Monitoring may not have the accuracy needed, but could potentially speed the process and decrease the cost. To be effective, monuments must be constructed so they are unaffected by movements unrelated to subsidence, such as soil heave due to freezing and thawing as well as shrinking and swelling of clay minerals in surface alluvium during dry and wet periods.

The Subsidence Event

Subsidence occurs when either the load of the overburden exceeds the ability of the roof rock to transfer the overburden load to adjacent unmined coal or barrier pillars, or the strength of the gateroad and/or barrier pillars is insufficient to the support the total overlying and arched load transferred from above the adjacent panels. The detailed scenario follows:

Coal is removed to open up the mine void, and the roof support system is withdrawn or is advanced and removed. The immediate roof collapses and "bulks" into the mined volume. The main roof deflects downward onto the collapsed rock. As the main roof deflects, the ground surface follows. The maximum surface downward deflection is a percentage of the mining height, i.e. the subsidence factor. The surface sags downward behind the retreating longwall face or when room-and-pillar pillars are robbed, the pillars fail and the immediate roof collapses during retreat. The subsidence trough formed at the surface is wider than the mined areas, limited in extent outside the panel boundaries by the angle of draw.

The retreat of the longwall face or when panel pillars are robbed and the immediate roof collapses during retreat in room-and-pillar mining, also extends the deformation in the overburden ahead of the moving retreat line. As coal is mined and the retreat progresses, the overburden rocks bend into the subsidence trough, new ground is placed in tension, and new surface fractures open up. When the mining face passes under and progresses away from a particular point on the surface, the area of tensile stress moves away as well. Settling, accompanied by compression, takes over behind the temporary area of tensile stress, and the tension fractures partially close. As the retreat line progresses and successive areas are undermined, this activity takes the form of a smooth subsidence wave on the ground surface. Longwall gateroad pillars and individual room-and-pillar panel pillars can be designed to yield or crush under the overlying and/or arched overburden load transferred. When panels or rooms are progressively mined alongside gateroad pillars, first on one side and later on the other side, gateroad pillar failure will increase subsidence of the overlying ground surface. Gateroad pillar failure can help smooth out surface irregularities and close some of the remaining surface cracks. Massive sandstones in the overburden can also assist in smoothing out irregularities when they act as "beams" and produce a more complete and uniform collapse of different size, shape and strength pillars.

Subsidence movement over longwall mines and over room-and-pillar mines where pillars have been robbed tends to be relatively short-lived. Ninety to 95 percent of the subsidence is expected to occur once coal extraction in an area is complete. The remaining residual subsidence should be completed within 2 to 5 years after mining an individual panel has ceased. Some delayed subsidence may occur over isolated larger and stronger pillars that can deteriorate more slowly.

Sudden subsidence events may occur over room-and-pillar mines where large pillars are deliberately left behind, i.e. not robbed on the retreat, to support the overburden. The pillar, room and crosscut dimensions are designed to support the overburden weight tributary to each pillar. Eventually, one pillar will deteriorate and yield to shed the unsupportable part of its tributary load, onto adjacent stronger pillars. The area of yielded pillars will grow until a group of several pillars will fail. Even the strongest pillar will eventually deteriorate and collapse.

Where a room-and-pillar mined area is fairly shallow and thick and competent beds are present in the roof the overburden load can temporarily be transferred from overloaded pillars that yield to larger and/or stronger nearby rigid pillars. In such a situation, a large area of pillars may fail suddenly as a unit. Subsidence can occur abruptly when a competent overlying bed breaks and the overburden load suddenly tries to shift back onto yielded pillars. Here, the surface expression may not be as smooth as that previously described, and larger cracks can result.

Additionally, a series of such sudden pillar failures can take place progressively, one group of pillars bordering a previously collapsed area will temporarily support the transferred load. However, those pillars will deteriorate more rapidly under the heavier load and after an unpredictable additional time another group of pillars may fail.

Figure 1. Conceptual Room-and-Pillar Mining

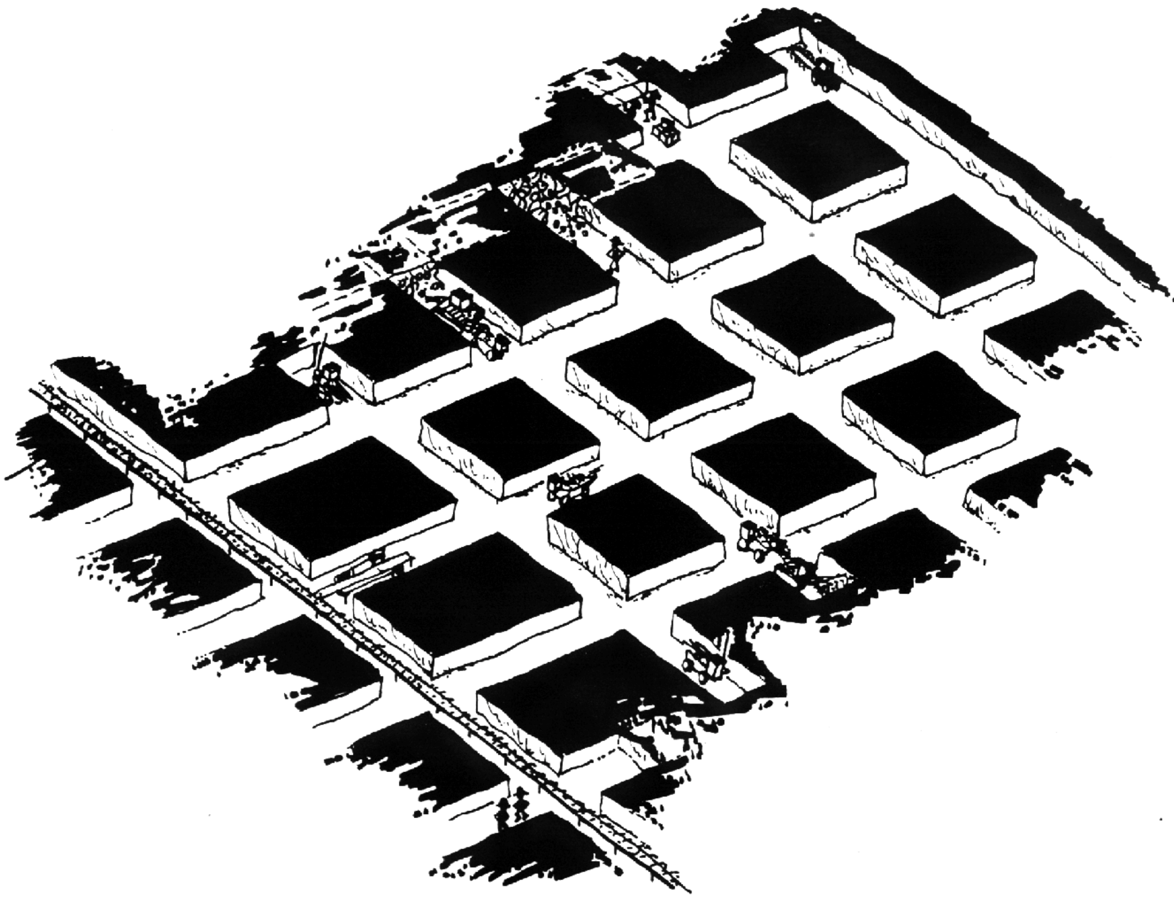


Figure 2. Conceptual Longwall Mining

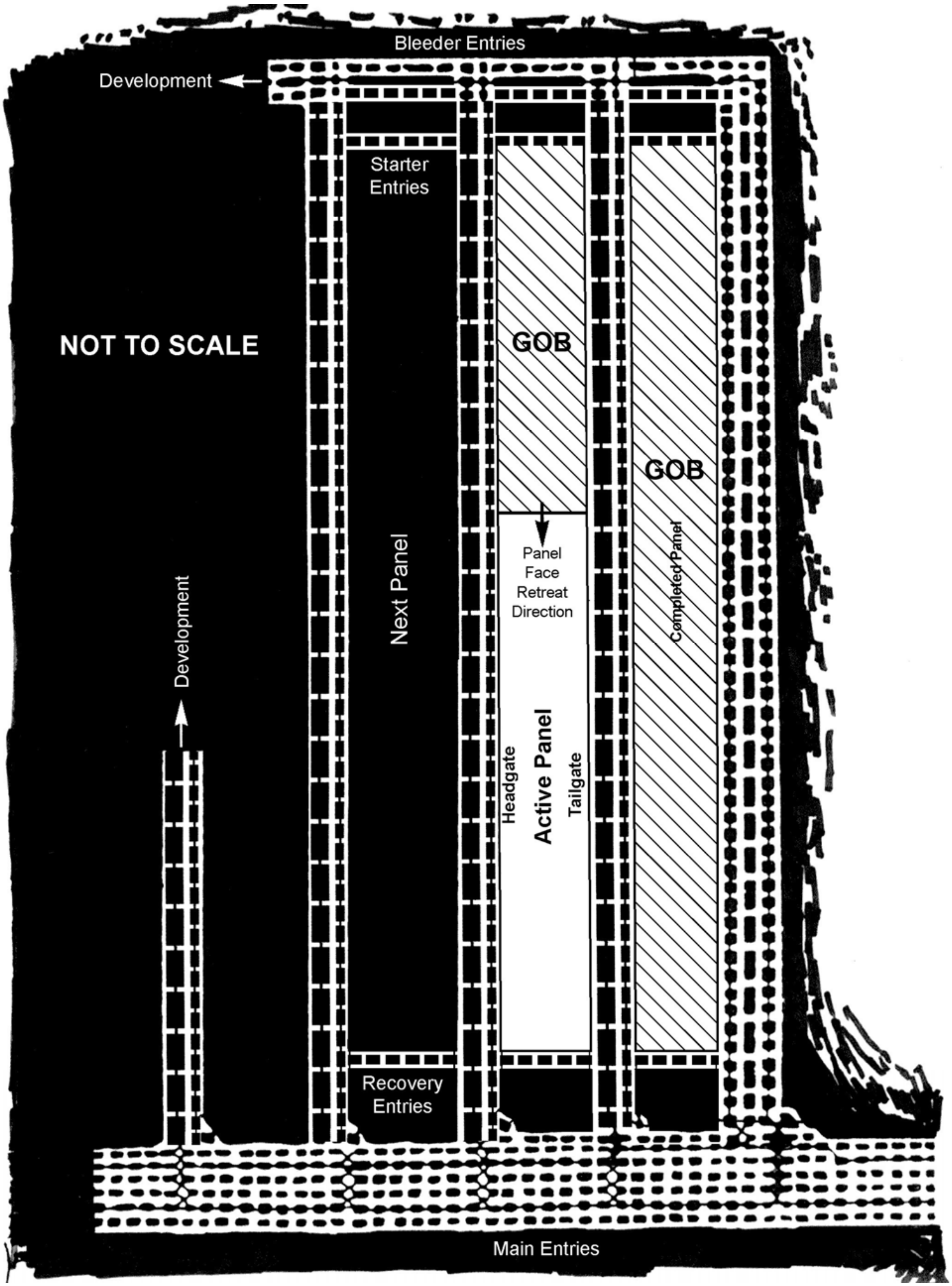


Figure 3. Typical Longwall Panel Layout in the United States

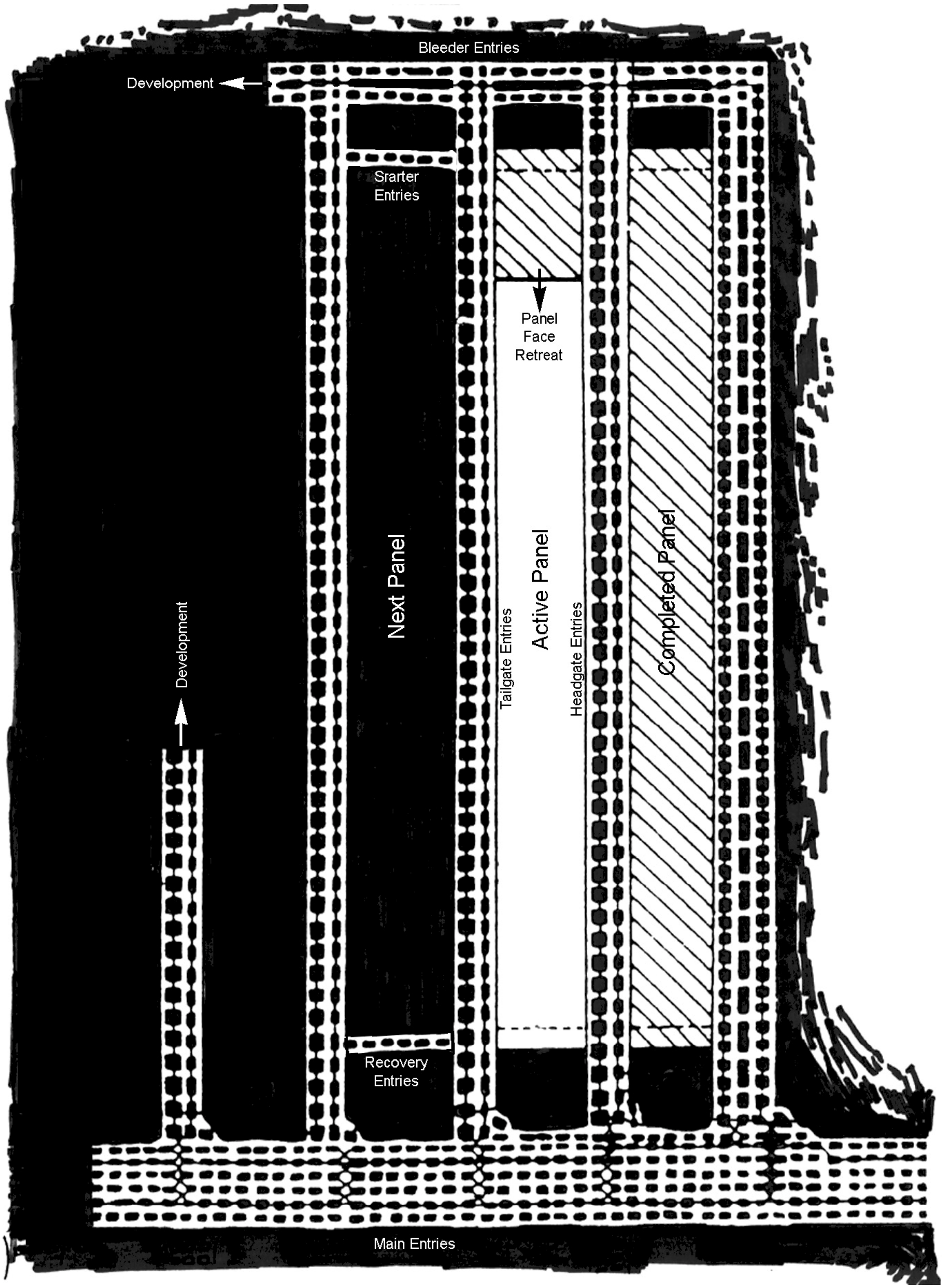


Figure 4. Plan View of Surface Subsidence Over a Longwall Panel

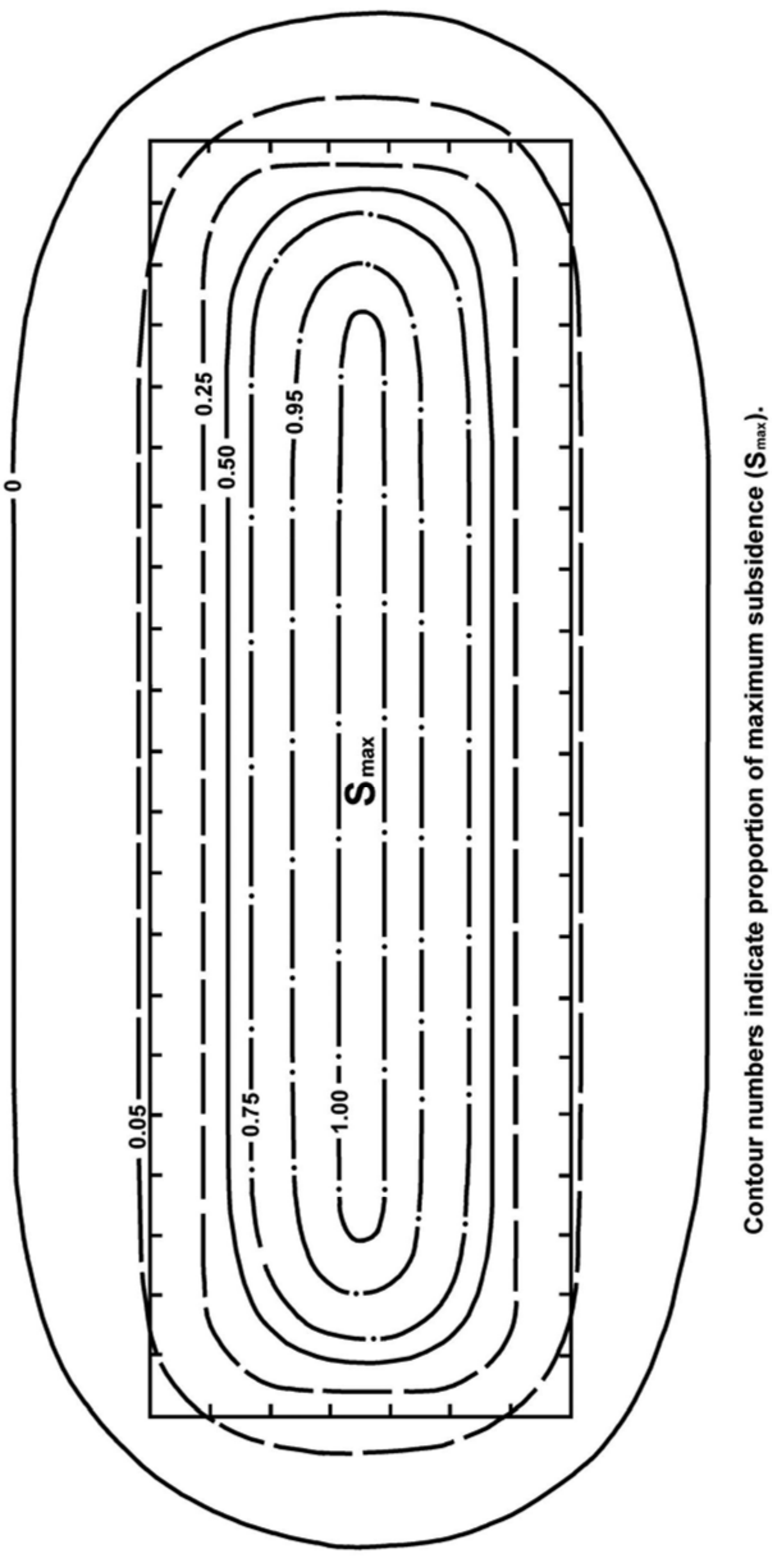


Figure 5. Conceptual Representation of Subsidence Deformation Zones

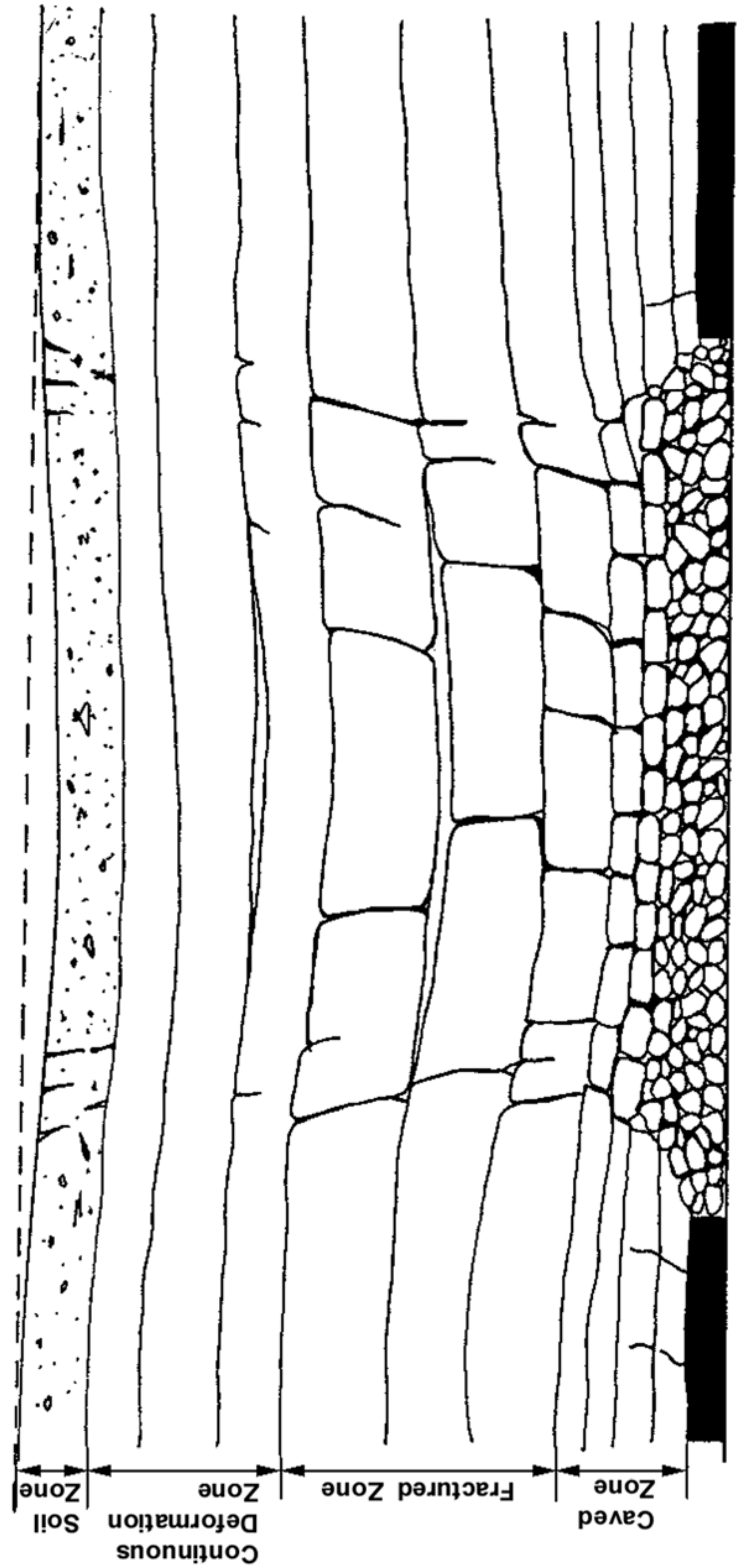


Fig. 1.6. Four zones of strata movement above a longwall panel (Peng and Chiang, 1984) [from Peng, 1992. p5]

Figure 6. Potential Collapse Heights

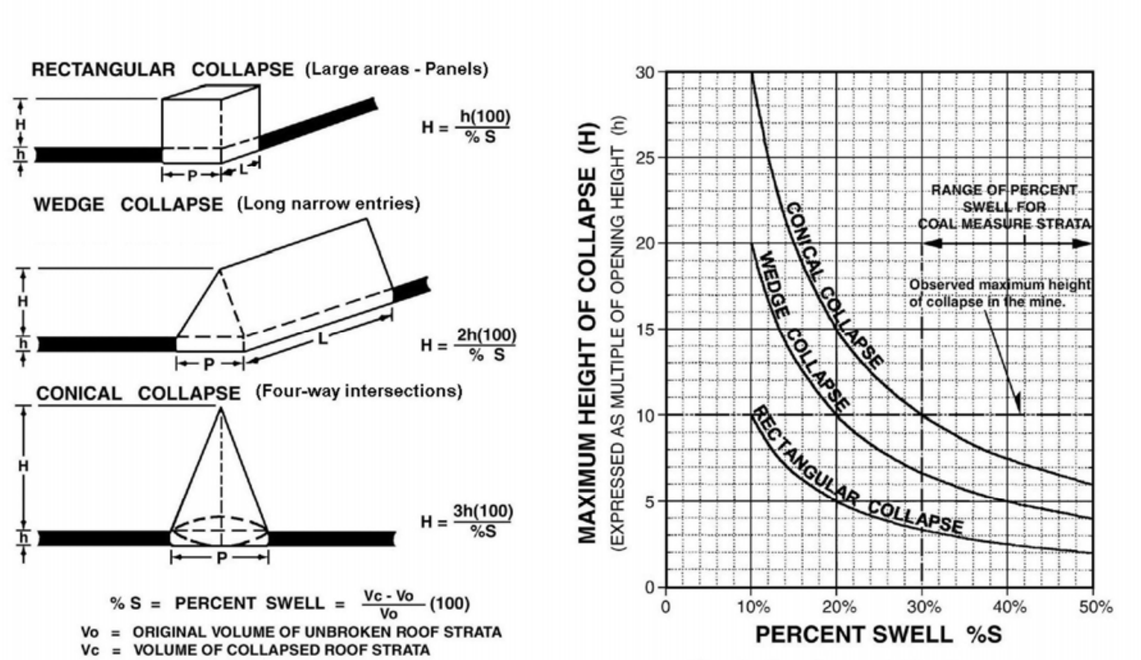


Diagram showing notation for calculating maximum height of collapse (H) in relation to geometry of collapse.

Graph showing variation in maximum height of collapse for different modes of failure and percent swell of rock.

(modified from Piggott & Eynon, 1977)

Figure 7. Critical Panel Width for Maximum Subsidence

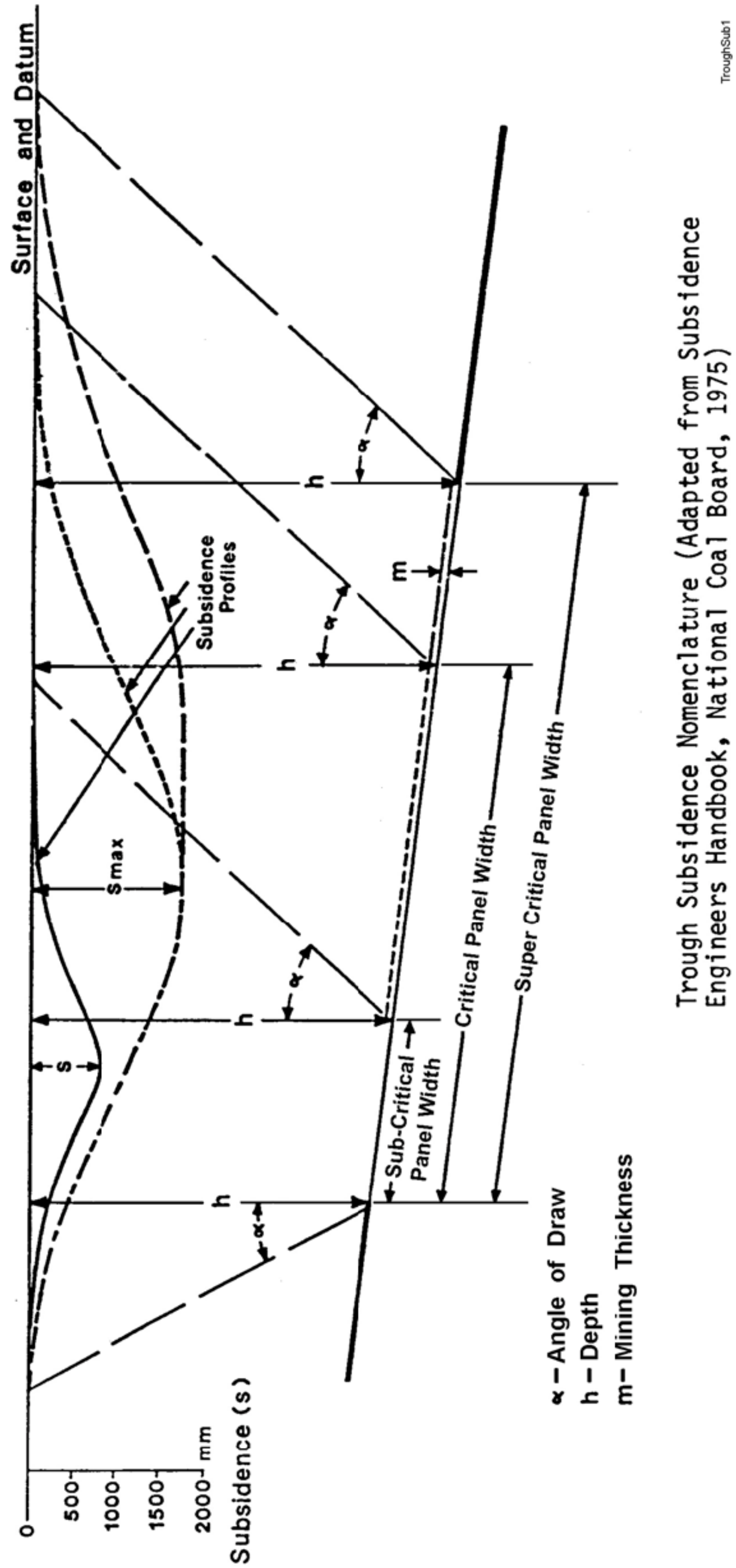


Figure 8. NCB Panel Width/Depth *Maximum Subsidence (Smax)* Prediction

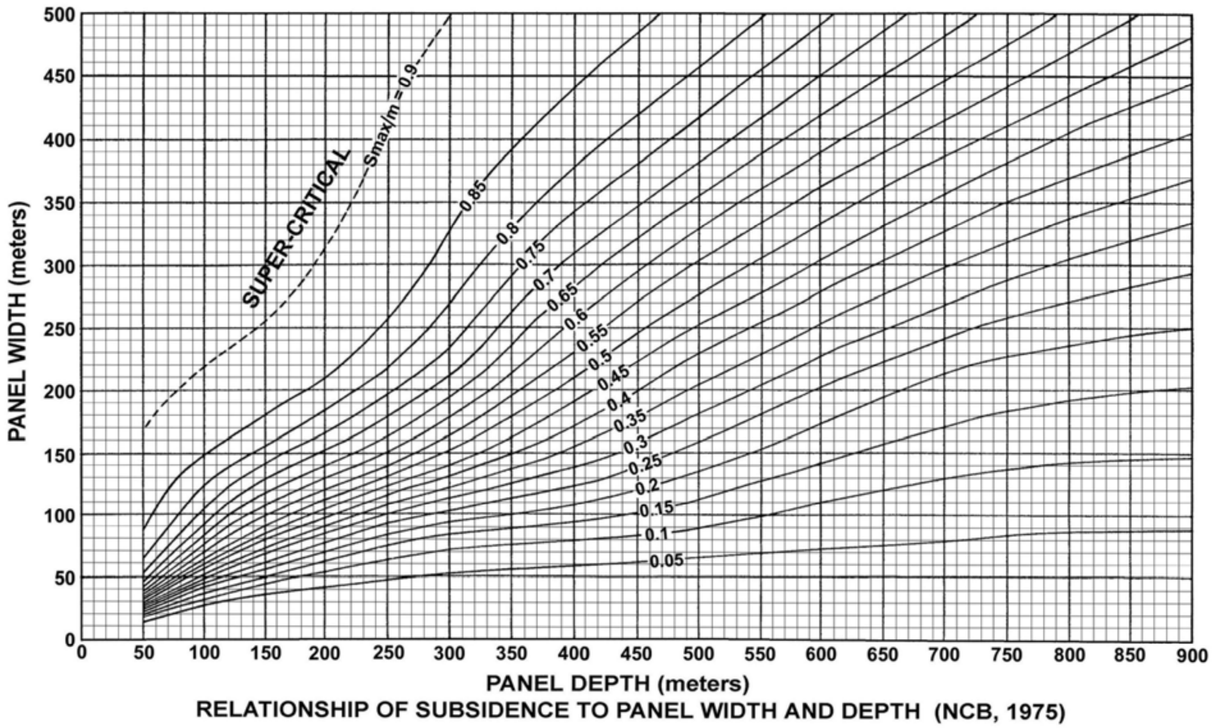


Figure 9. NCB Subsidence Profile Graph

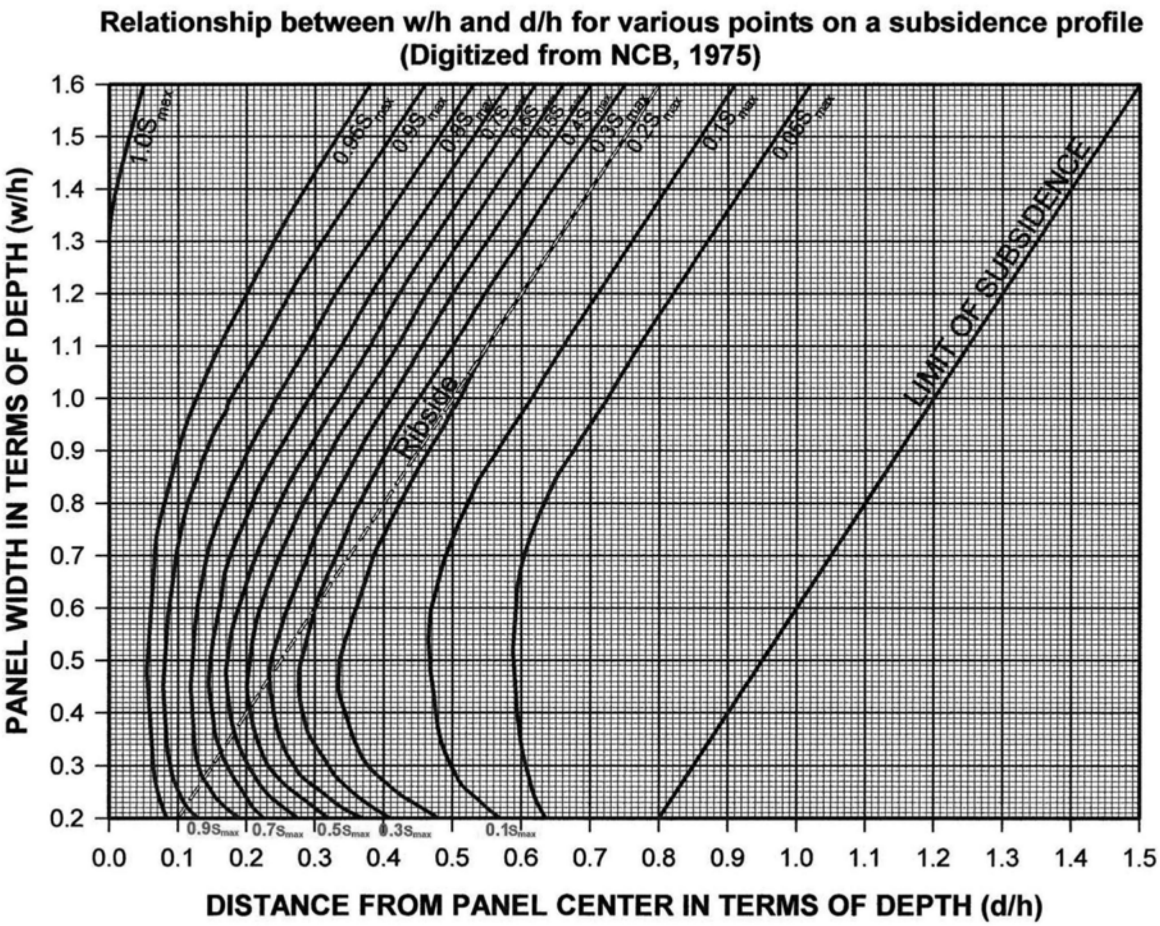


Figure 10. Critical Panel Width for Maximum Tensile (+E) and Compressive (-E) Strains

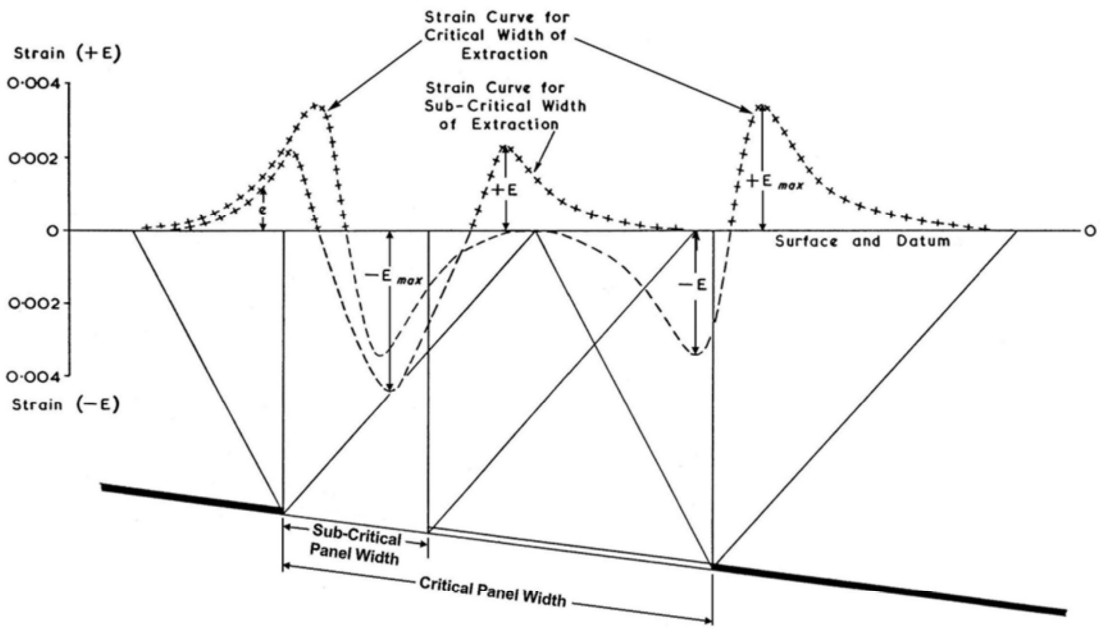
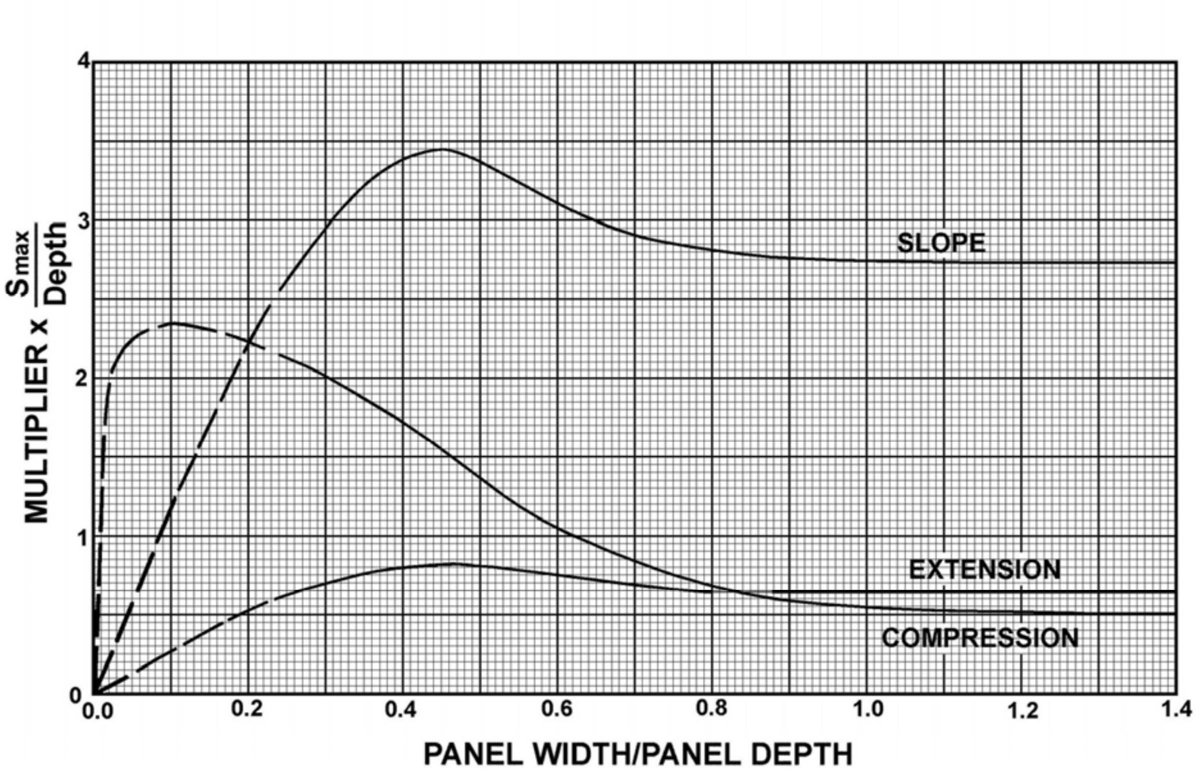


Figure 11. NCB Maximum Strain and Slope Prediction Graph



GRAPH FOR PREDICTING MAXIMUM SLOPE AND STRAIN (NCB, 1975)

Figure 12. NCB Horizontal Strain Profile Graph