CHAPTER 2:

MECHANICS

OF

SUBSIDENCE

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DEQ Exhibit 17

MECHANICS OF SUBSIDENCE

2.1 SUBSIDENCE TERMS

2.1.1 TYPES 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. Mine subsidence may be defined as the ground movements that occur due to the collapse of the overlying strata into mine voids. Surface subsidence generally entails both vertical and lateral movements (Hartman 1992).

Subsidence can be classified into two types – continuous and discontinuous, or also as planned and unplanned subsidence. Typically, continuous subsidence is planned, while discontinuous subsidence is unplanned. Due to the unpredictability of discontinuous subsidence, typical work on these events is more reactive than proactive, and is covered in more detail in the NTTP AML Workshop on Subsidence. In this course, we will focus mainly on the continuous and predictable types of subsidence associated with current, active coal mines.

Discontinuous vs Continuous Subsidence

- Discontinuous Subsidence
  Difficult to predict, is usually caused by failure of voids in older mines. Can also be caused by pillar, roof or floor failure.
- Continuous Subsidence
  Fairly easy to predict, this type of subsidence occurs almost immediately following mining of a high percentage of the coal seam.

Planned vs Unplanned Subsidence

- Planned Subsidence
  Lowering of the ground surface in a predictable manner - predictable (within limits) as to a real extent, amount of subsidence and amount of ground surface distortion -- as a result of mining.
- Unplanned Subsidence
  Lowering of the ground surface in a manner that cannot be predicted as to a real extent, amount of subsidence or amount of ground distortion, as a result of failure at mine level of the overburden support system (coal pillars/mine roof/mine floor) or as a result of the action of other unanticipated causes, such as the piping of unconsolidated sediments into the mine.

In either case, the geometry of the subsidence trough is governed in varying degrees by the thickness of the overburden, the strength and deformability of the overburden strata, coal pillars and mine roof and floor, and the dimensions and geometry of the mined out area.

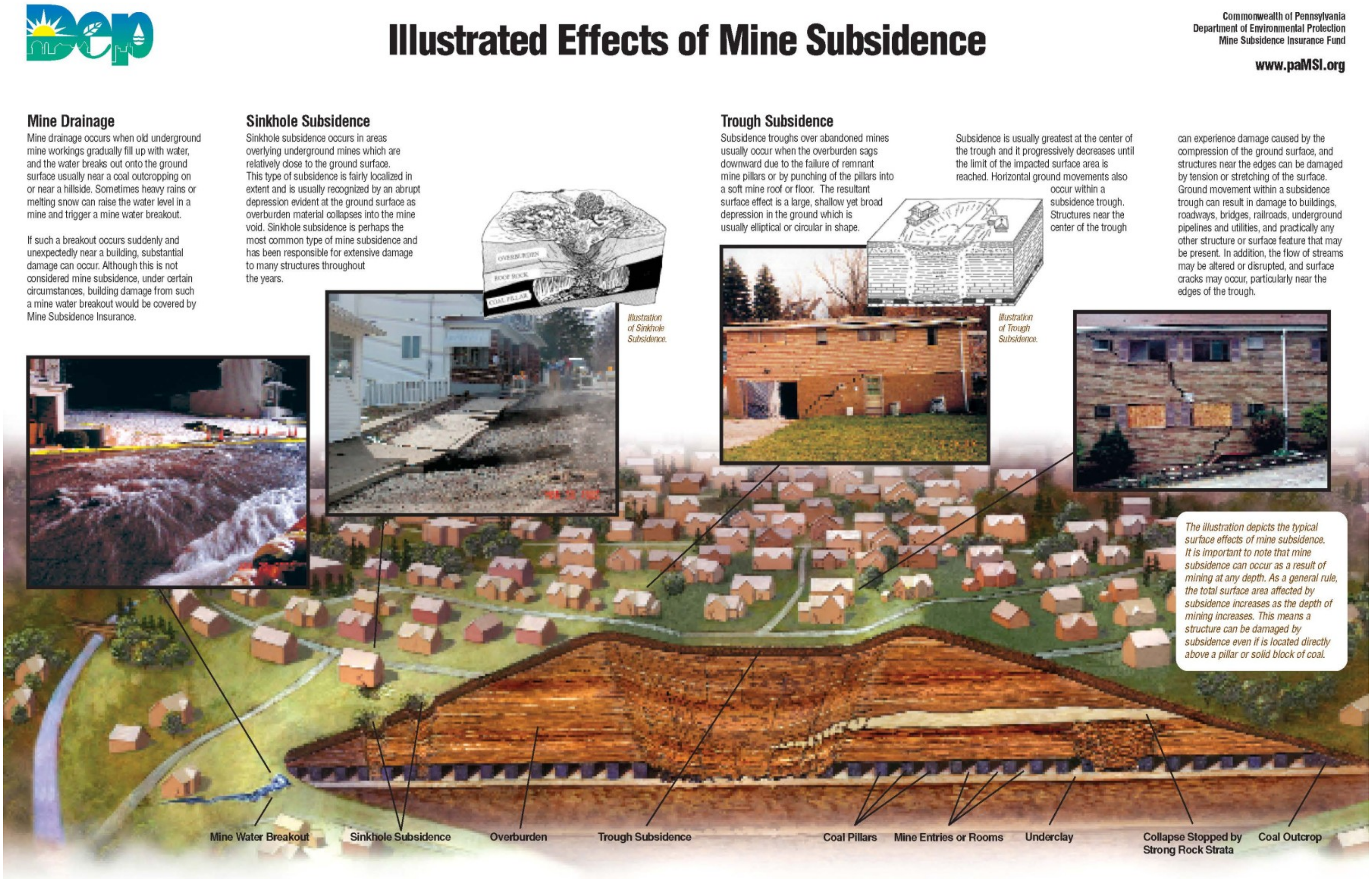

Fig 2.1 Illustrated Effects of Mine Subsidence (PA DEP MSI Website)

2.1.2 FACTORS CONTROLLING HEIGHT OF THE CAVED AND FRACTURED ZONES

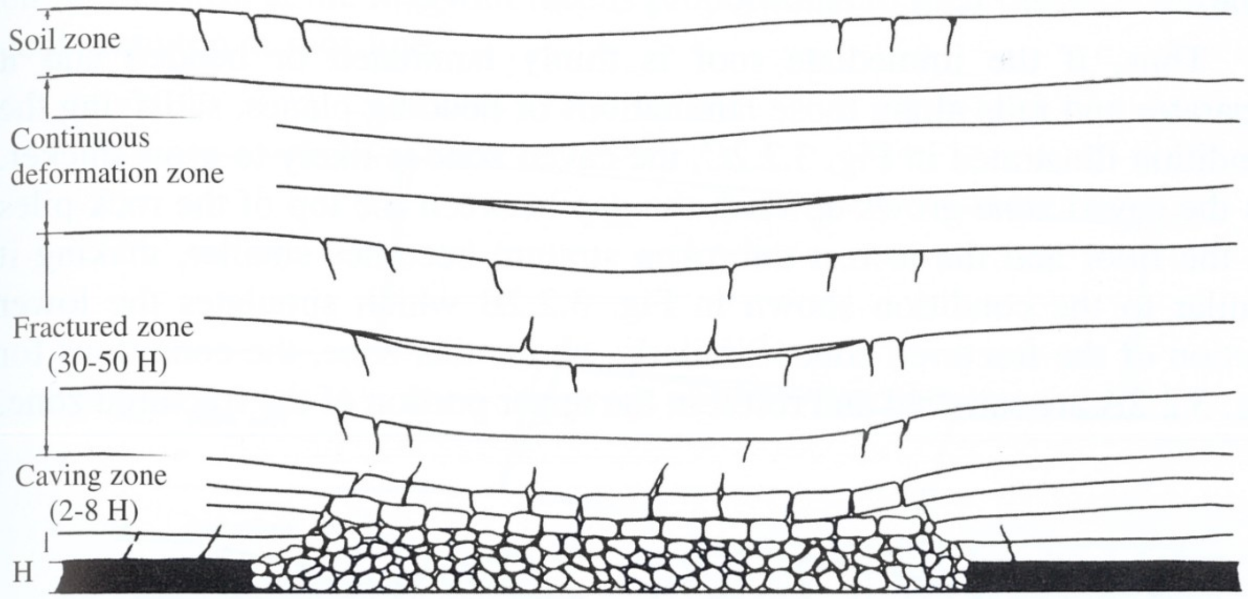

Fig 2.1.1 – Overburden Movement (Peng 2006)

Surface subsidence manifests itself in three major ways:

1) Cracks, fissures or step fractures
2) Pits or sinkholes (also called chimney subsidence)
3) Troughs or sags

Many geological and mining parameters affect the magnitude and extent of subsidence (Darling 2011).

- Extraction Thickness/Mining Height
  The thicker the material extracted, the larger the amount of possible surface subsidence. Note that it is the actual extracted thickness, not the in-situ thickness that must be considered. Where mining takes place in several overlying mining horizons, subsidence is related to both the total extracted thickness and the sequence of horizon extraction.
- Mining Depth/Overburden Depth
  The magnitude and time to onset of subsidence are dependent on depth.
- Inclination of Extraction Horizon (Dip of coal seam)
  Asymmetric subsidence occurs when the zone being mined is inclined. Subsidence becomes skewed and mitigation measures such as pillars become less effective. The subsidence profile is translated in a downdip direction with both the limit angle and the horizontal strains increased downdip and reduced updip.
- Degree of Extraction (Percent Extraction, see below and Figure 2.2)
  Reducing the amount of material extracted will reduce the amount of subsidence. Thus, lower extraction ratios tend to both reduce and delay the onset of subsidence.
- Mined Area

The critical width of a mined void must be exceeded in all directions if maximum subsidence is to develop.

- Method of Working (Mining Method)
  The amount of subsidence is largely controlled by the degree of caving induced by the mining method, together with the amount of support offered by any backfilling. Nearly immediate, but predictable, subsidence occurs with longwall mining, whereas with Room-and-Pillar operations both the magnitude and onset of subsidence are largely unpredictable.
- Extraction Rate
  Surface subsidence follows the face as it progresses, and so to minimize the effect of strain and tilt on surface structures, a fairly rapid, constant face advance rate should be adopted
- Competence of Surrounding Materials (Rock Properties)
  Since subsidence propagates from the mine level, the mechanical behavior of the rock adjacent to the mined void directly affects the initiation of subsidence. Weak roofs and floors accentuate subsidence, whereas strong materials can delay or even prevent collapse and hence subsidence. Strong, massive materials above the mine level are able to withstand the effects of extraction for a prolonged period and hence defer the occurrence of subsidence.
- In-Situ Stress State
  High horizontal stresses may foster formation of an arch in the material overlying a mined void, thereby attenuating subsidence. However, arch formation is a complex phenomenon, depending on many geomechanical parameters: It cannot be guaranteed, and arches may fail suddenly and catastrophically.
- Geological Discontinuities
  The existence of faults, folds, and the like may increase and localize subsidence potential so strongly that in areas of adverse geological conditions the effects of the other parameters can be discounted.
- Near-Surface Geology and Surface Topography
  The nature of any near-surface soils and unconsolidated rocks affects subsidence development, with both the thickness and mechanical characteristics of these materials being important. For example, cracks and fissures may form in stiff clays, whereas soft clays may deform plastically and cohesionless sands may flow down into fractures in the underlying rocks.
- Hydrogeology
  Deformation of the strata around mined areas may alter hydraulic gradients, resulting in either the flooding or draining of surface areas and the formation or draining (in aquifers) of underground reservoirs.
- Elapsed Time
  Subsidence does not occur instantaneously but over a period of time. In Room-and-Pillar operations, subsidence may only develop a long time (possibly centuries) after the mining is complete, when pillar degradation leads to roof collapse. In caving operations, surface displacements may occur almost immediately after the face passes below an area. However, as noted, the presence of strong, competent layers overlying an opening can delay this.

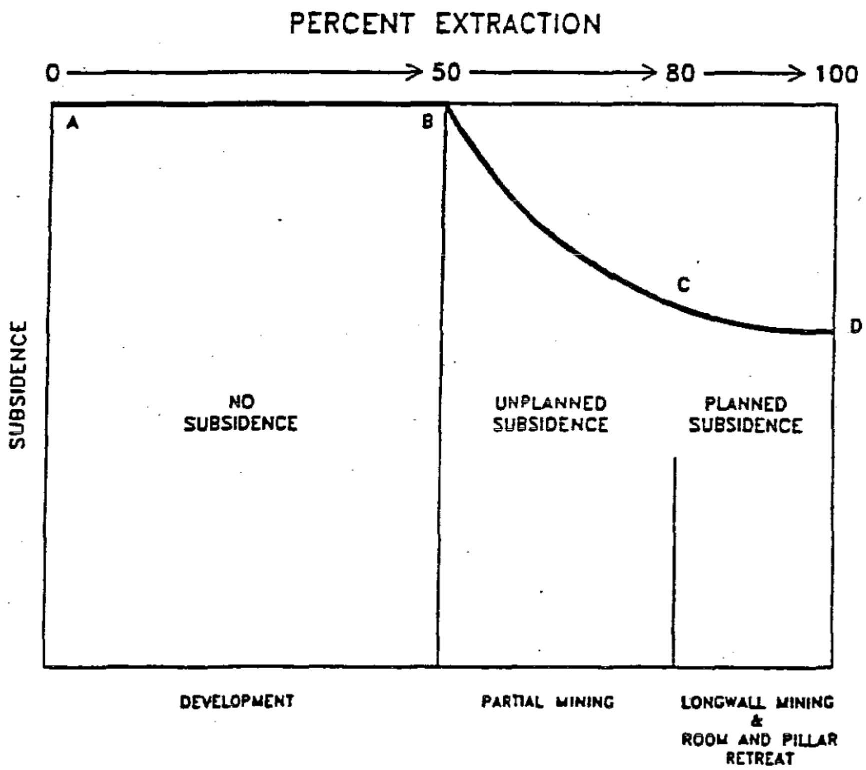

Fig 2.1.2 Schematic of relationship between subsidence and percent equation (OSM 1988)

Relationship Between Subsidence and Percent Extraction

The relationship between surface subsidence and percent extraction is shown in Figure 2.2. Permanent ground support (no subsidence) is denoted by the range A-B; impermanent ground support (some subsidence given a sufficient period of time) by the range B-C; and essentially total withdrawal of support (maximum subsidence), by the range C-D. Curve ABCD serves as a basis for the discussion that follows and is to be recognized as but one of a family of curves governed by panel geometry, overburden lithology, mine depth and mining pattern.

When the percent of extraction of coal from a mine panel is low to moderate (A-B), as is usual during developmental mining, the loads imposed upon the pillars by the overburden are generally small in relation to the size of the pillars. In this situation, subsidence of the ground surface is virtually nil and will remain so over the long term. Subsidence (such as it is) results primarily from the elastic compression of the coal pillars. In contrast, when the percent extraction is high, approaching 100 percent, as is the case during longwall or room-and-pillar retreat mining (C-D), subsidence above the panel approaches the maximum possible for the particular panel geometry and overburden lithology and results primarily from the overburden sagging down into the mined-out area, coming to rest on and compressing the rubble from the now broken mine roof.

Where partial extraction room-and-pillar mining is practiced, an intermediate condition may exist (B-C). Here, the recovery of coal by such methods as slabbing or splitting pillars, although not attaining total extraction, may increase extraction to relatively high levels. If the panel has not yet been designed for permanent support, delayed subsidence of variable magnitude may eventually occur as a result of crushing of the coal pillars, failure of the mine roof or punching of the pillars into the mine floor. The result could be unexpected damage to structures at ground surface or, in areas of flat terrain, the pending of water above the panel.

The implication of these data is that ground movements associated with unplanned subsidence can be as significant as those associated with planned subsidence. The difference is, with unplanned subsidence, one cannot be certain as to when or where the subsidence will occur. Thus, in order to meet the requirements of subsidence control, the intermediate range of extractions must generally be avoided in modem mining. One should design either for no subsidence (Zone A-B) by providing permanent pillar support or for the maximum subsidence attainable relative to panel geometry and overburden lithology (Zone C-D), by extracting virtually all of the coal and causing subsidence to take place concurrently with mining.

2.1.3 DURATION OF SUBSIDENCE

Active vs Residual

The duration of subsidence resulting from mining is composed of two distinct phases: active and residual (Darling 2011).

- Active (or Dynamic) Subsidence
  Consists of those movements occurring contemporaneously with mining operations.
- Residual (or Static) Subsidence
  Consists of those movements that occur either following the cessation of mining or the passing of a zone of influence.

2.2 Discontinuous Subsidence

Within the coal mining industry, discontinuous subsidence is usually expressed as chimney or sinkhole subsidence features. These are usually caused by the progressive migration of an unsupported mining cavity through the overlying material to the surface. Pillar collapse in old, shallow workings may lead to similar surface disturbances, but may lead to progressive failure and a wider affected area.

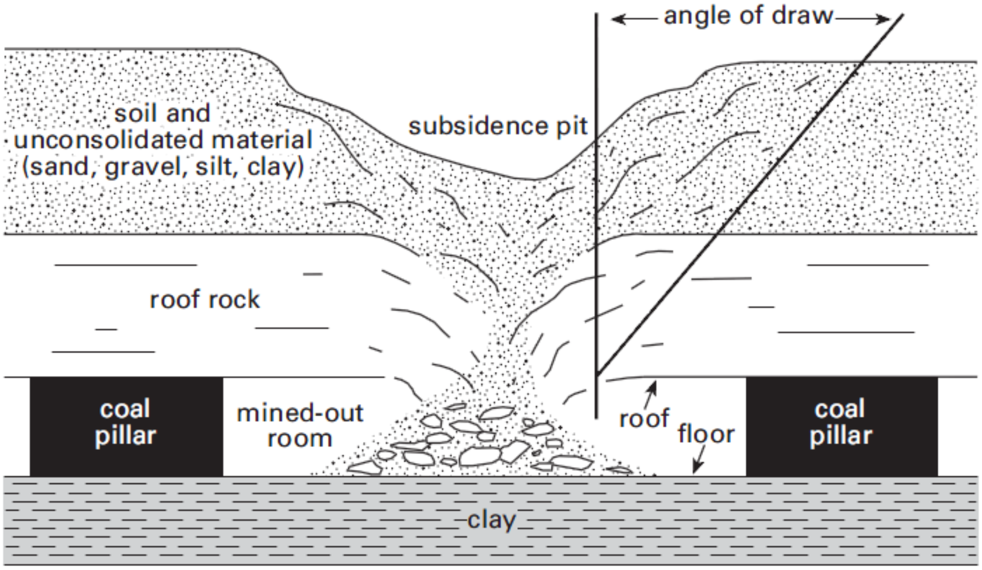

Fig 2.2.1 Diagram of typical subsidence from a mine roof collapse (Crowell 2010)


Fig 2.2.2 Subsidence hole (Crowell 2010)

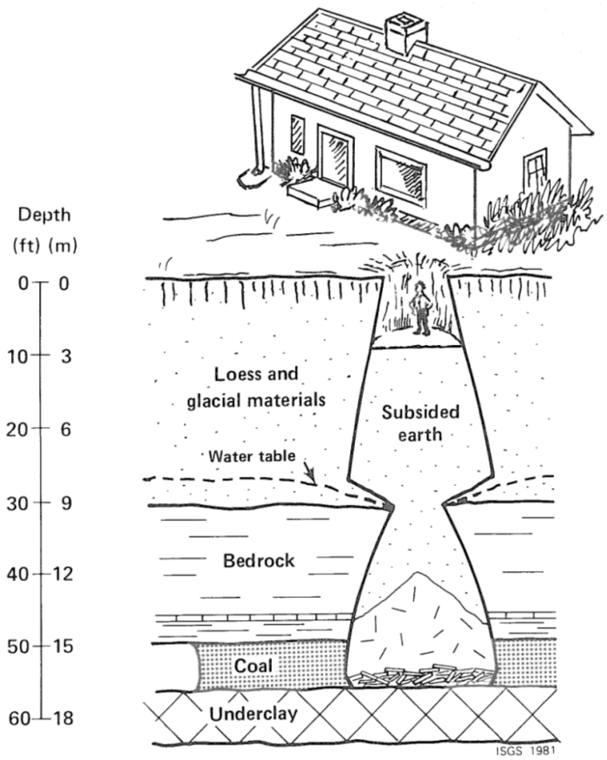

Fig 2.2.3 Cross Section of Typical Pit Subsidence (Bauer & Hunt 1981)

2.3 Continuous Subsidence

After the extraction of a longwall panel or room and pillar section with retreat mining (greater than 80 percent recovery) of sufficient width, the strata in the overburden are subjected to various degrees of movement from the bottom to the top. According to the movement characteristics, the damaged overburden can be divided into four zones (Figure 2.3.1).

- Caved Zone

  After the extraction of coal, the immediate roof caves irregularly and fills up the void. The strata in this zone not only lose their continuity; they also lose their stratified bedding. The caved zone is normally 2 to 8 times the mining height depending on the properties of the immediate roof and the overburden.
- Fractured Zone

  This zone is located immediately above the caved zone. The basis characteristics are strata breakage, and loss of continuity, but the stratified bedding remains. The severity of the strata breakage reduces from the bottom to the top. The porosity and permeability of the strata will increase greatly. The combined height of the fractured zone and caved zone is in general 20 to 30 times the mining height. The height of the fractured zone for hard and strong strata is larger than that for soft and weak ones.
- Continuance Deformation Zone

  Here the strata between the fractured zone and the surface bend downward without breaking. Their continuity and thus the original features remain. There may be some open fissures in the tension zone of the surface subsidence profile that do not destroy the strata continuity.

- Soil Zone

  This zone consists of soil and weathered rocks·. Depending upon the physical properties of the soil, cracks may appear when the face is nearby and close back when the face has passed. However, some cracks and especially those along the edges of the panel may remain open after mining.

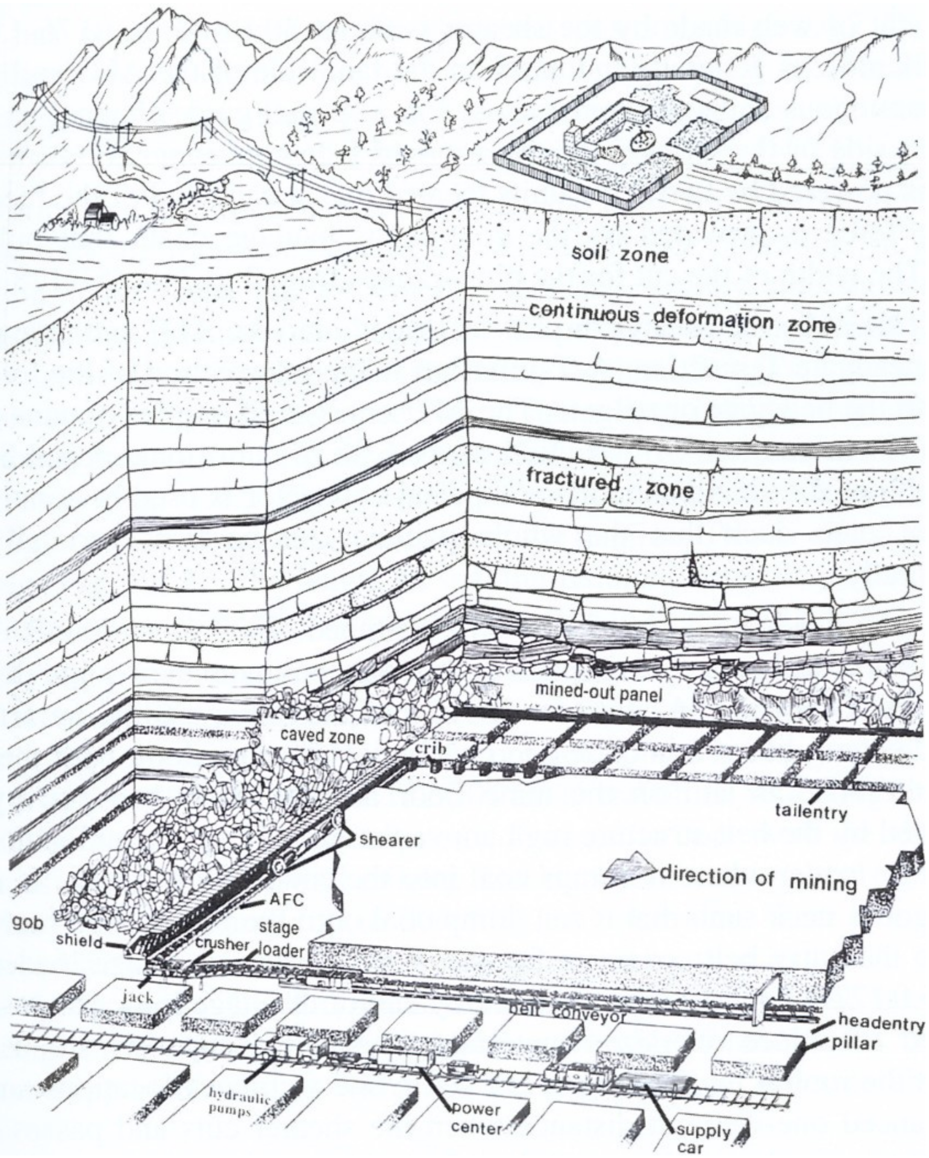

Fig 2.3.1 – Cut-away of Longwall Panel with equipment and overburden movement (Peng 2006)

2.3.1 DEVELOPMENT OF THE SUBSIDENCE TROUGH DURING MINING

A subsidence trough is a dish-shaped depression that develops above the mined-out area and progressively enlarges horizontally and vertically as coal support is systematically removed from beneath. A trough is generally characterized by stationary surface profiles in the longitudinal and transverse directions and by non-stationary "dynamic" ground surface profile ("traveling wave") that accompanies the mine face in its passage from one end of the mine panel to the other (Figures 2.3 and 2.4).

- Longitudinal Profile.

  The longitudinal profile is drawn along the panel centerline where the ground movements in the direction of mining are most pronounced (greatest subsidence, slope, strain, curvature). The segment of the longitudinal profile draping over the forward abutment -- that is, draping over the coal pillars beyond the face in the direction of mining- is termed the subsidence development curve and describes the vertical movement experienced by each point at ground surface as it is undermined. The subsidence development curve characteristically consists of three distinct segments (Figures 2.5, 2.6 and 2.7)

  - Heave zone (A-B)
  - Subsidence zone (B-C)
  - Residual Subsidence zone (C-D)

- Transverse Profile

  The transverse profile is drawn across the short dimension of the panel, perpendicular to the longitudinal axis, and is often located along the panel bisector. It can be positioned nearer to the end of the panel, but no nearer than twice the overburden thickness if the profile is to be representative of the maximum ground surface deformation in the transverse direction.

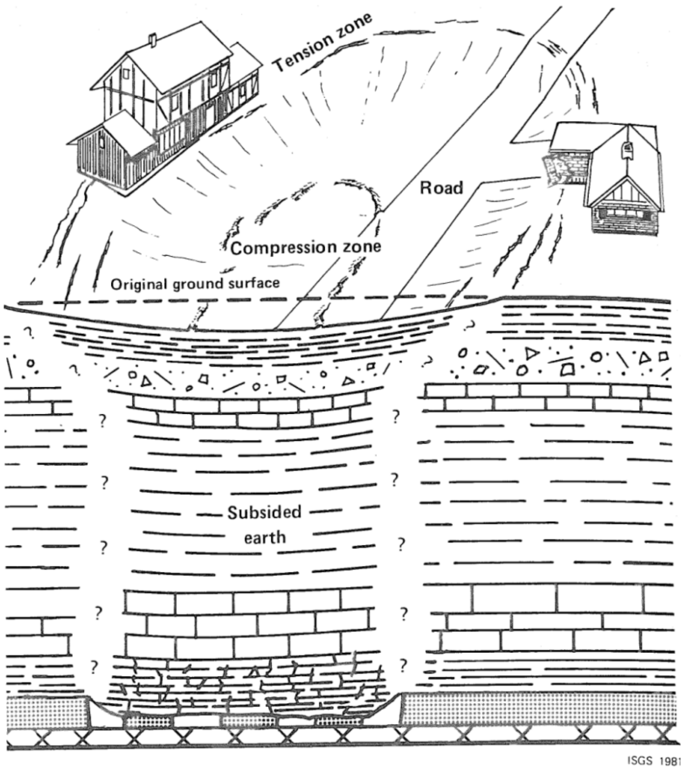

Fig 2.3.2 View of Typical Features of Trough Subsidence (Bauer & Hunt 1981)

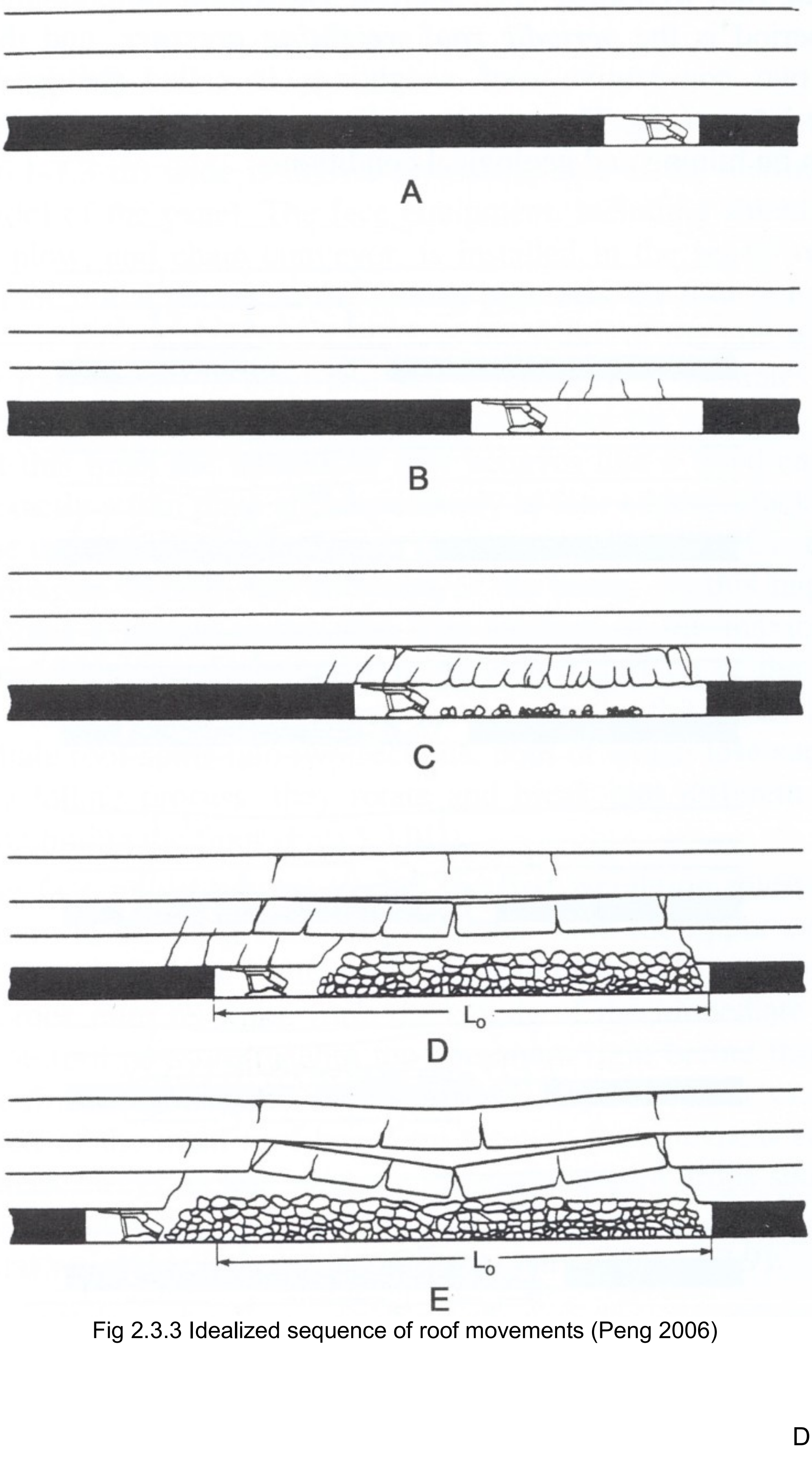

Fig 2.3.3 Idealized sequence of roof movements (Peng 2006)

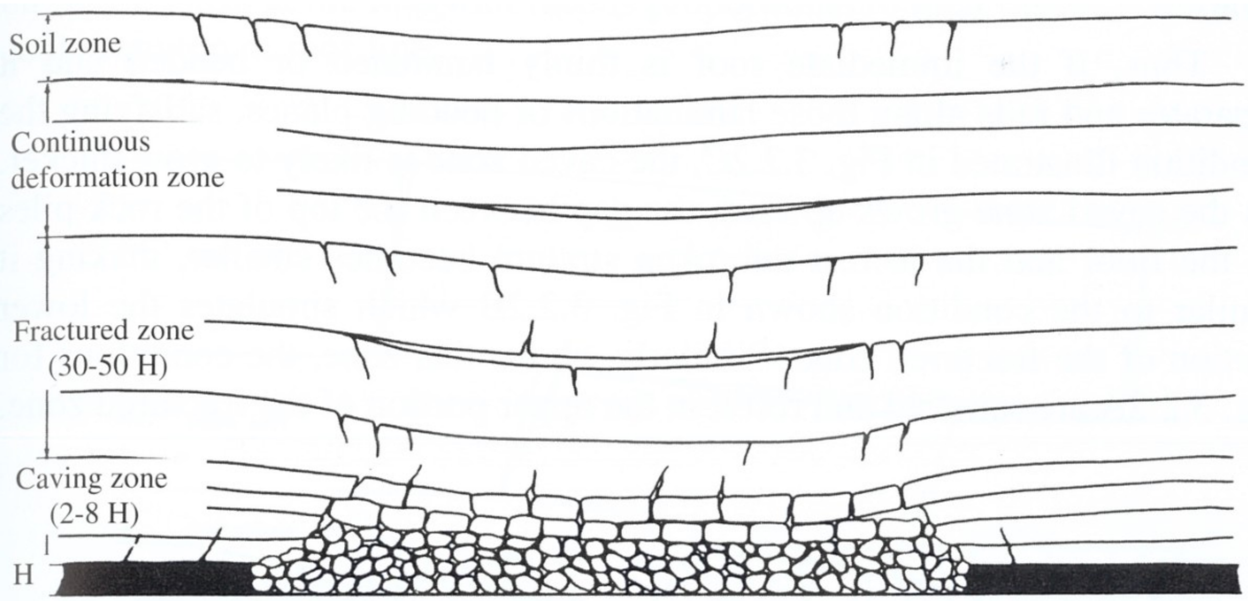

Fig 2.3.4 Immediate and main roofs (Peng 2006)

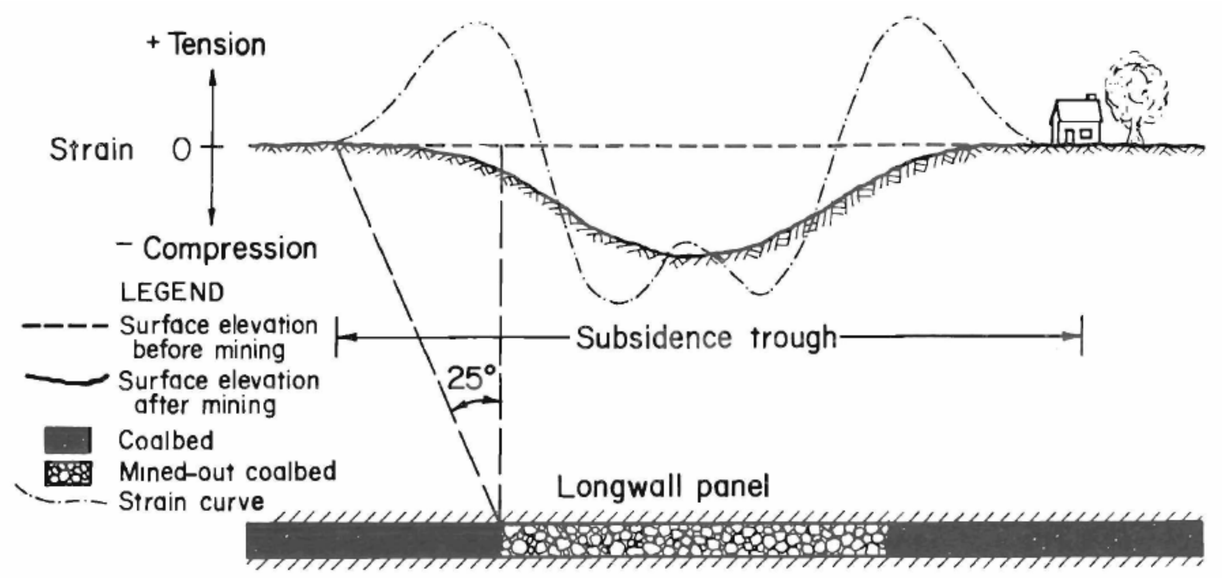

Fig 2.3.5 Subsidence trough and strain distribution (Ingram 1989)

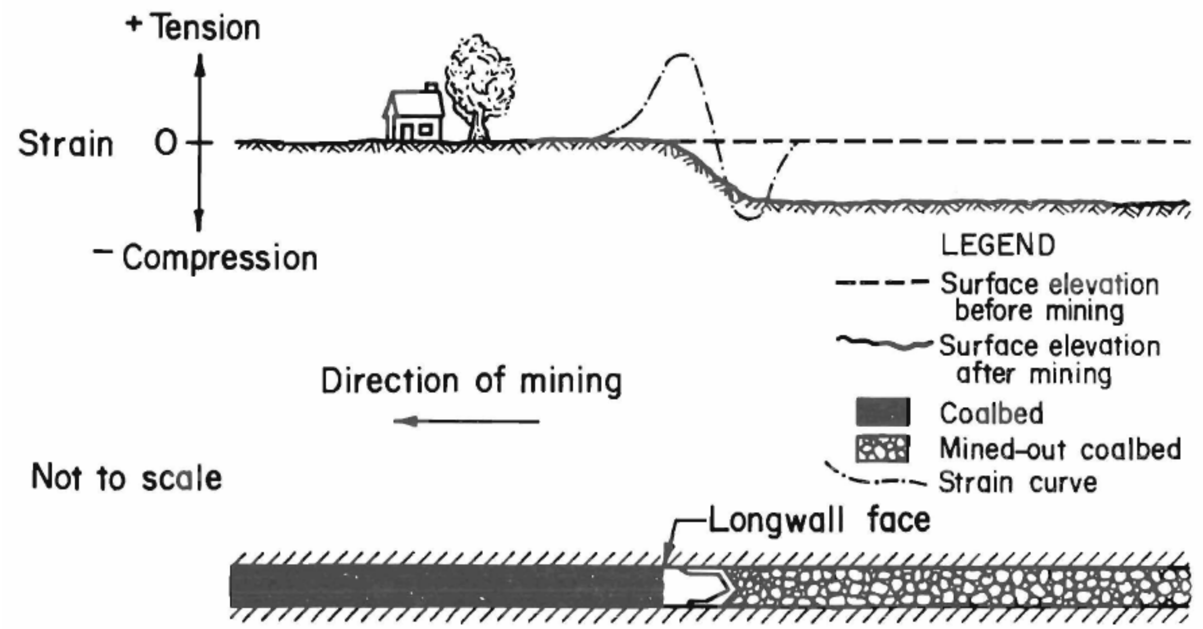

Fig 2.3.6 Strain along wave of subsidence during longwall development (Ingram 1989)

The shape of the subsidence development curve at any site is governed by the mechanical properties of the overburden and by the stiffness of the coal support at mine level.

The ground surface movements above the rear abutment, under ideal circumstances, are identical to those above the forward abutment. The ground surface heaves locally, if not generally. Long term creep and settlement may reduce the heave or eliminate it altogether.

References, Chapter 2

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Pennsylvania Department of Environmental Protection Mine Subsidence Insurance Website http://www.dep.state.pa.us/msihomeowners/

You Tube videos from various sources, listed by subject:

Gob/Goaf animation: http://youtu.be/AR2e77Rqlew

Longwall Mining: http://youtu.be/NsiGV7lmNXE

Subsidence

BHP Billiton – Longwall Mining Subsidence Animation: http://youtu.be/zvvyqJ2qfdw

Fallen Futures part 1: http://youtu.be/tqG_M73Zgv0

Fallen Futures part 2: http://youtu.be/4Q5WjJQj97M

Introduction to Longwall Mining in Illinois: http://youtu.be/9P9h1VrOs8I