CHAPTER 3:

PRINCIPLE PARAMETERS

OF

SUBSIDENCE

Kewal Kohli
Stefanie Self

DEQ Exhibit 18

3.1 PRINCIPLE PARAMETERS THAT CHARACTERIZE SUBSIDENCE

The following parameters are commonly used to describe the geometry of a subsidence trough. All angles lie in a vertical plane normal to one of the edges of the mine panel (Figures 3.1.1, 3.1.2 and 3.1.3). Ideally, the angles are constant for a particular mine panel for a particular mine site.

- Angle of Advance Influence (α)
  The angle with the vertical made by a straight line extending from the edge of the mined-out area to the nearest point of maximum tensile strain on the subsidence profile.
- Angle of Break (δ)
  The angle with the vertical made by a straight line extending from the edge of the mined-out area to the nearest point of maximum tensile strain on the subsidence profile.
- Angle of Complete Mining (ψ)
  The angle with the vertical made by a straight line extending from the edge of the mined-out area to the nearest point of maximum tensile strain on the subsidence profile.
- Angle of Critical Deformation or Angle of Damage (ζ)
  The angle with the vertical made by a straight line extending from the edge of the mined-out area to the point on the subsidence profile that could potentially damage a surface structure.
- Angle of Draw (β)
  The angle with the vertical made by a straight line extending from the edge of the mined-out area to the nearest point at ground exhibiting no subsidence. The angle delineates the boundary of the subsidence trough, excluding any heave zone. Typically 20°-27°.
- Compressive Strain (ε_c)
  The amount of shortening per unit of length, and usually is represented by a negative value.
- Curvature (k)
  The difference in surface slope between two adjacent line sections divided by the average length of the two line sections on a subsidence profile.
- Dimension B
  The horizontal distance from the inflection point of the subsidence profile to the nearest point of maximum subsidence on the subsidence profile.
- Displacement (U)
  The horizontal component of the surface movement is called displacement.
- Inflection Points
  The points on the subsidence profile where the profile changes from convex to concave. At the inflection point, the subsidence is equal to half of the maximum possible subsidence at the center, the surface slope is maximum and the curvature is zero. The distance from the inflection point to the nearest edge of the opening is the "offset", d of the inflection point. This has been found to located at the point where the Subsidence has reached half of its maximum value ($S_{max}/2$).

- Maximum Subsidence (S_{max})
  When the panel width exceeds a critical value, the maximum subsidence reaches its maximum possible value
- Mining Depth (h)
  Effective height of total overburden above coal seam being mined. Typically, this is the value from the top of the coal seam to the surface.
- Mining Height (m)
  Effective height of void left by mining (this will usually include the entire coal seam, plus some roof and/or floor material).
- Slope (i)
  Also called tilt, it is the difference in surface subsidence between the two end points of a line section divided by the horizontal distance between the two points on a subsidence profile.
- Strain (ε)
  The change in length per unit length in a given direction. Ground strain represents the amount of extension or compression of the ground surface in the immediate vicinity of each ground surface point relative to an original.
- Subsidence (S)
  The vertical component of the surface movement is called subsidence.
- Subsidence Factor (a = S/m)
  The ratio of maximum subsidence to mining height. The subsidence factor is governed by the lithology of the overburden and the dimension of the mined-out area. The harder rocks in the overburden strata, the smaller will be the angle of draw and vice versa. In the US, its range is found to be 0.4 to 0.85.
- Tensile Strain (ε_t)
  The amount of lengthening per unit length, and usually is represented by a positive value.

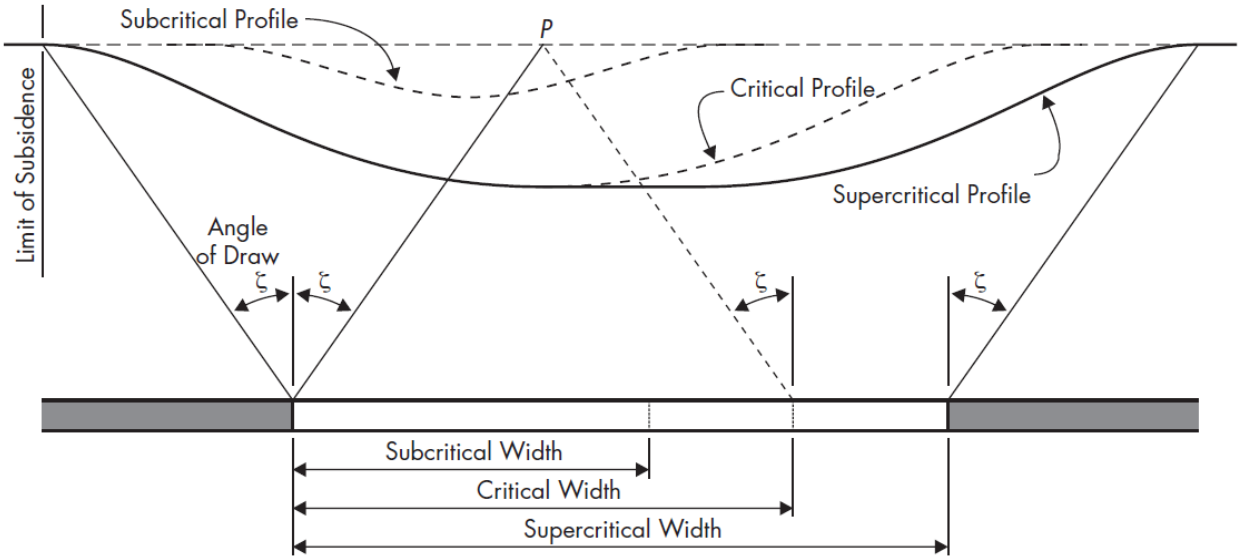

Fig 3.1.1 Continuous Subsidence Profiles above Laterally Extensive Extraction Zones (Darling 2011)

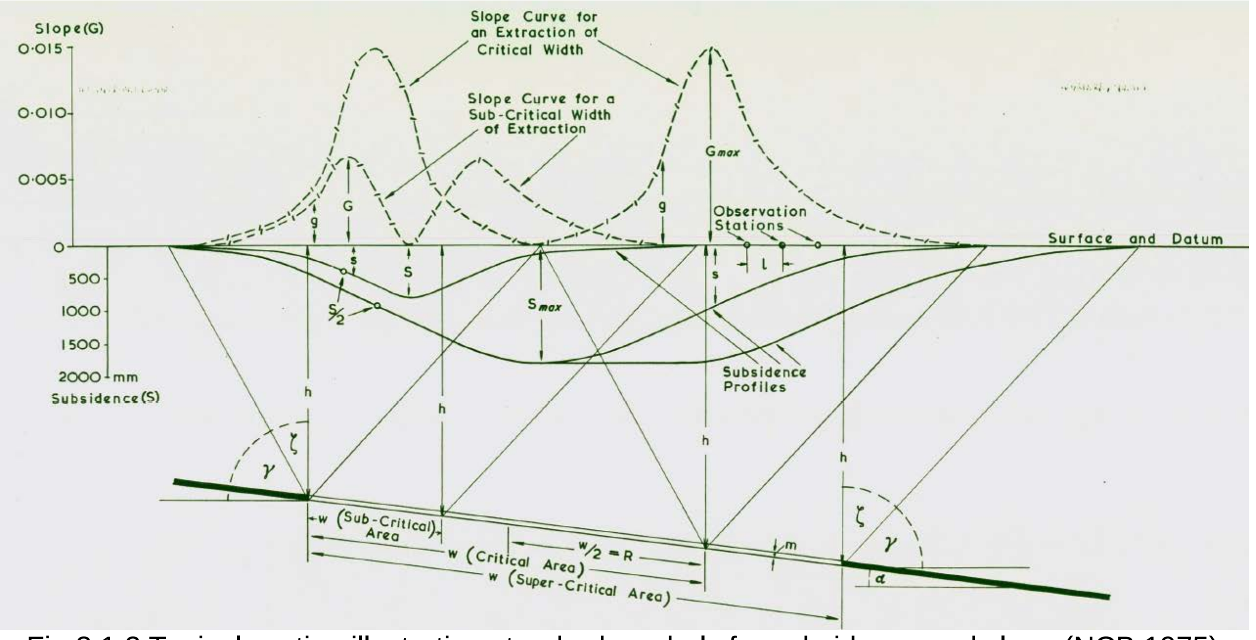

Fig 3.1.2 Typical section illustrating standard symbols for subsidence and slope (NCB 1975)

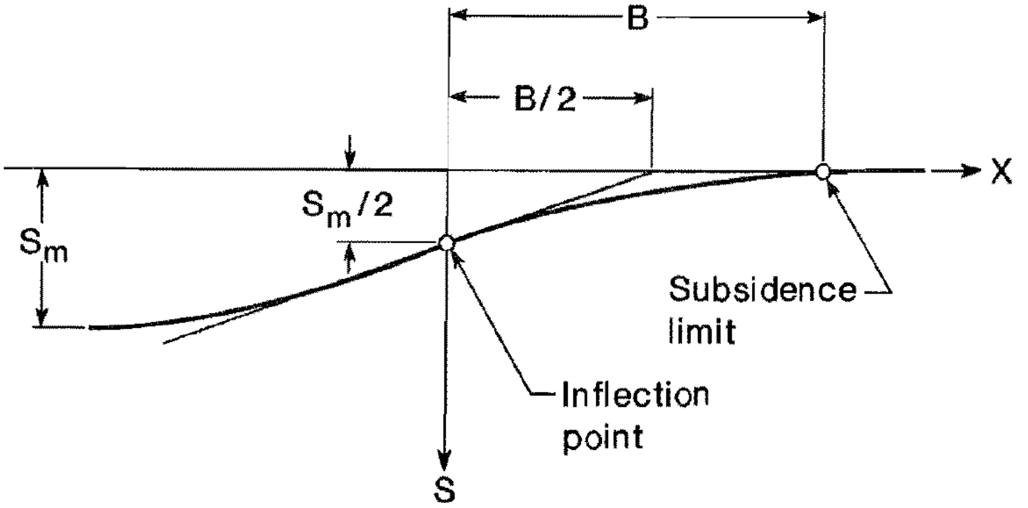

Fig 3.1.3 Maximum Subsidence and Inflection Point (Tandanand and Powell 1991)

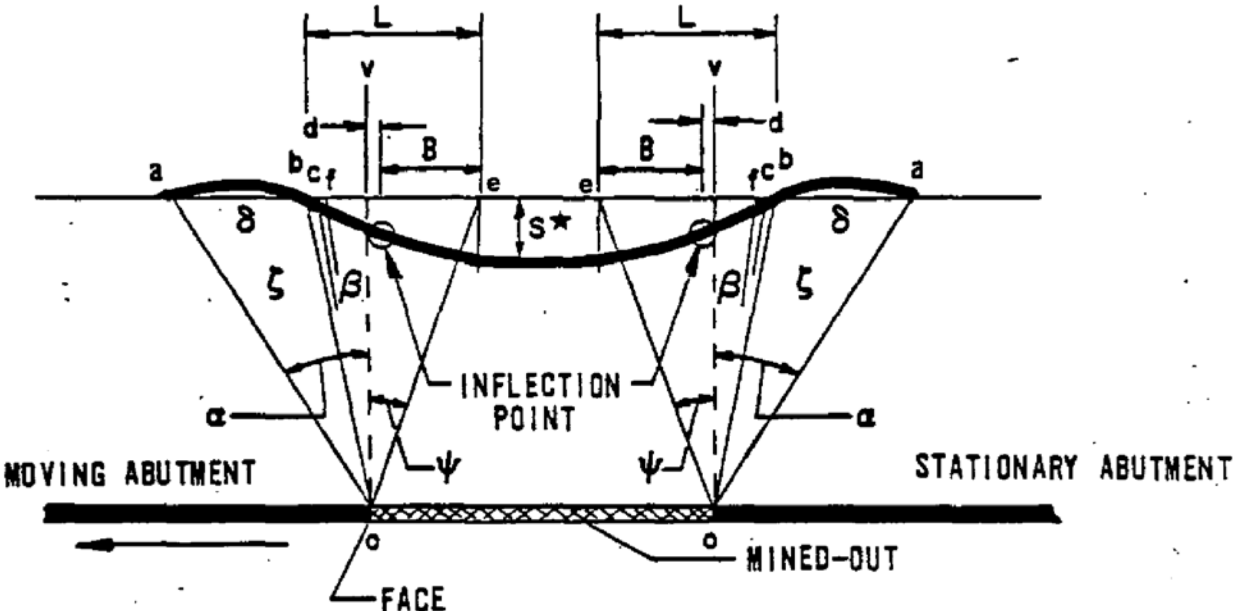

Fig 3.1.4 Principal Parameters that Characterize the Subsidence Trough (OSM 1991)

3.2 TYPES OF SUBSIDENCE TROUGHS

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. There are three types of subsidence troughs:

- Subcritical
  Lowering of the ground surface in a predictable manner -- predictable (within limits) as to areal extent, amount of subsidence and amount of ground surface distortion -- as a result of mining.
- Critical
  Lowering of the ground surface in a manner that cannot be predicted as to areal 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.
- Supercritical
  Lowering of the ground surface in a predictable manner - predictable (within limits) as to areal extent, amount of subsidence and amount of ground surface distortion - as a result of mining.

When the mined-out area is small (both width and length), the final (static) subsidence profile has a pointed bottom with the maximum value at the center of the profile. The maximum subsidence at the center increases with increasing size of the mined-out area. This is the subcritical trough. When both the width and length of the mined-out area have increased to a size 1.2h (h being mining depth), subsidence reaches the maximum possible value at the center. This is the critical subsidence trough. Thereafter, though both the width and length of the mined-out area continue to increase, the maximum possible subsidence does not increase, but spreads laterally into an area. The subsidence trough has a flat bottom, and is known as the supercritical subsidence trough.

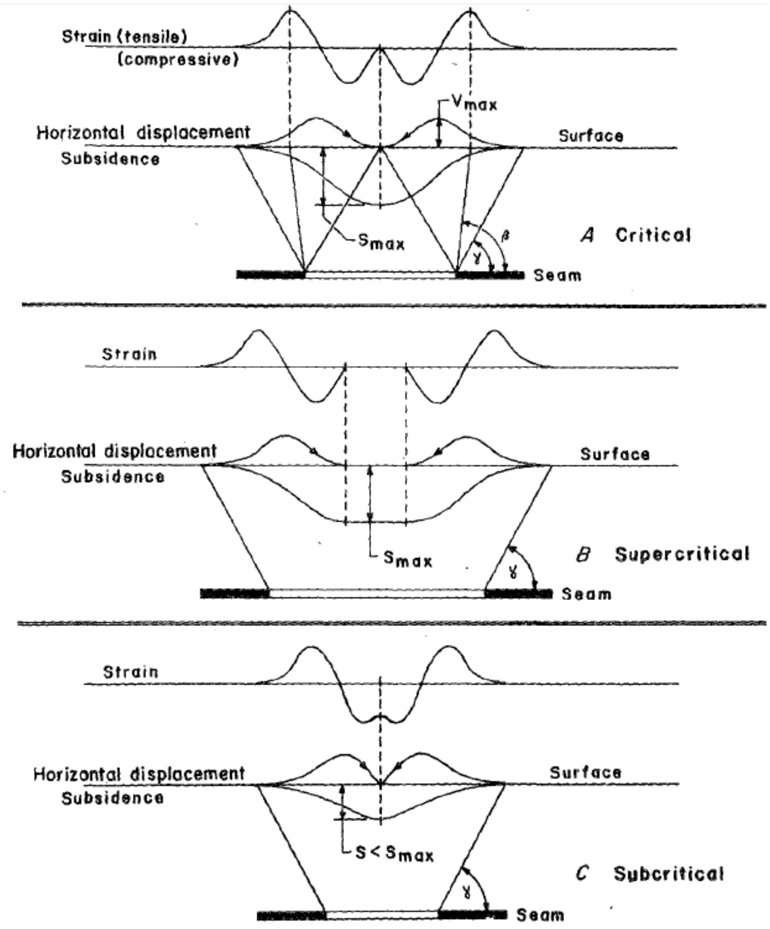

Fig 3.2 Subsidence profiles and strains over various subsidence troughs (Brauner 1973)

3.3 SUBSIDENCE FACTOR AND SUB-CRITICAL, CRITICAL AND SUPERCRITICAL CONDITIONS

There is a point at which the mine panel has reached a width where any further increase results in no increase in the maximum subsidence within that trough. This is called the critical width of that panel, with panels less than that width called sub-critical, and panels wider called super-critical.

There have been attempts to generalize the relationship, but it is not an easy generalization to make, due to the different effects we're discussing.

- Critical — Width = 1.2 X depth
- Sub Critical — Width < 1.2 X depth
- Super Critical — Width > 1.2 X depth

3.4 COMPRESSIVE AND TENSILE STRAINS

Ground strains are related to the unit deformation and distortion at a point on the ground during the subsidence event.

- Compressive Strain (ε_c)

  The amount of shortening per unit of length, represented by a negative value.

- Tensile Strain (ε_t)

  The amount of lengthening per unit length, represented by a positive value.

Both compressive and tensile strains are found along the subsidence profile, as illustrated in Figures 3.1.2, 3.2, 3.3, 3.4.1, 3.4.2 and 3.4.3. Compressive (negative) strains are found near the center of the subsidence profile, with a transition to tensile (positive) strains towards the edge of the panel.

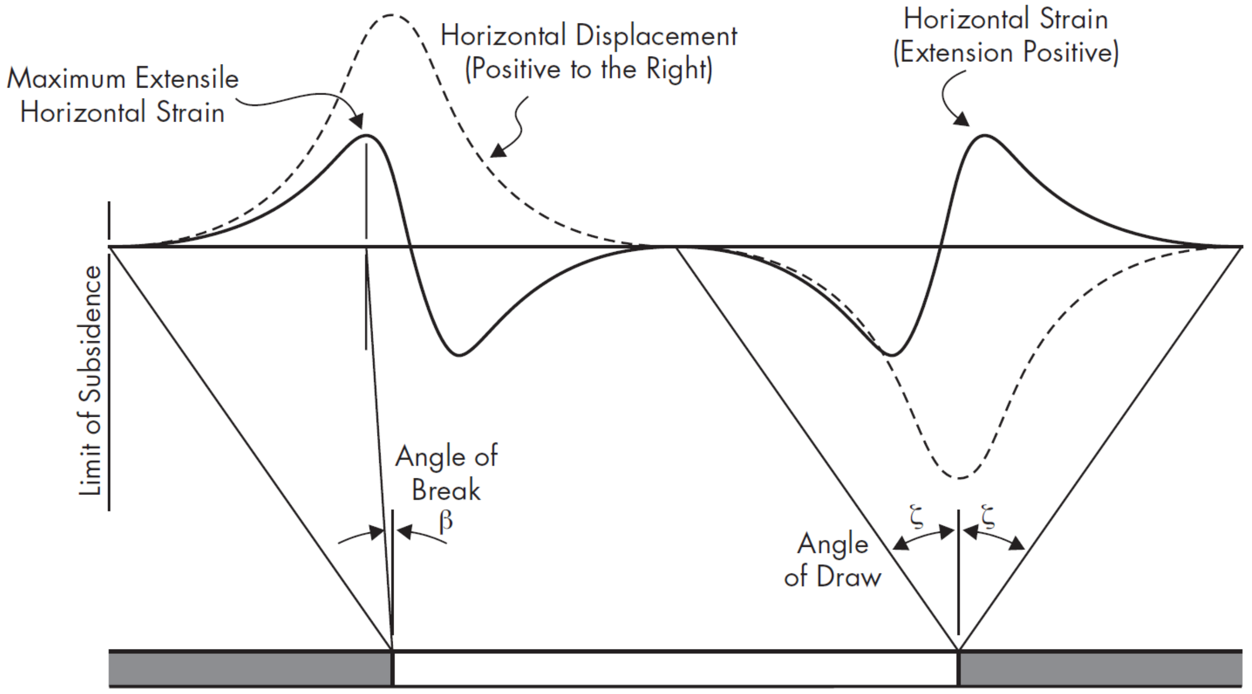

Fig 3.4 Illustration of a Subsidence Profile showing Strains and Angles (Darling 2011)

3.5 STATIC AND DYNAMIC STRAINS

Subsidence discussed above is the final profile that has developed long after mining has stopped. In a supercritical final subsidence trough, the central portion subsides uniformly. Thus any structure located there is not subjected to any permanent surface deformation (would drop vertically straight down, after subsidence is completed). However, during mining (while the face is moving), a structure is subjected to dynamic deformations associated with the dynamical subsidence trough (Figures 3.5.1, 3.5.2 and 3.5.3).

- Static Strain

  Strain along the surface after final subsidence, after all movement has concluded.
- Dynamic Strain

  Strain at the surface during subsidence development, as mining progresses toward, beneath and past a point on the surface.

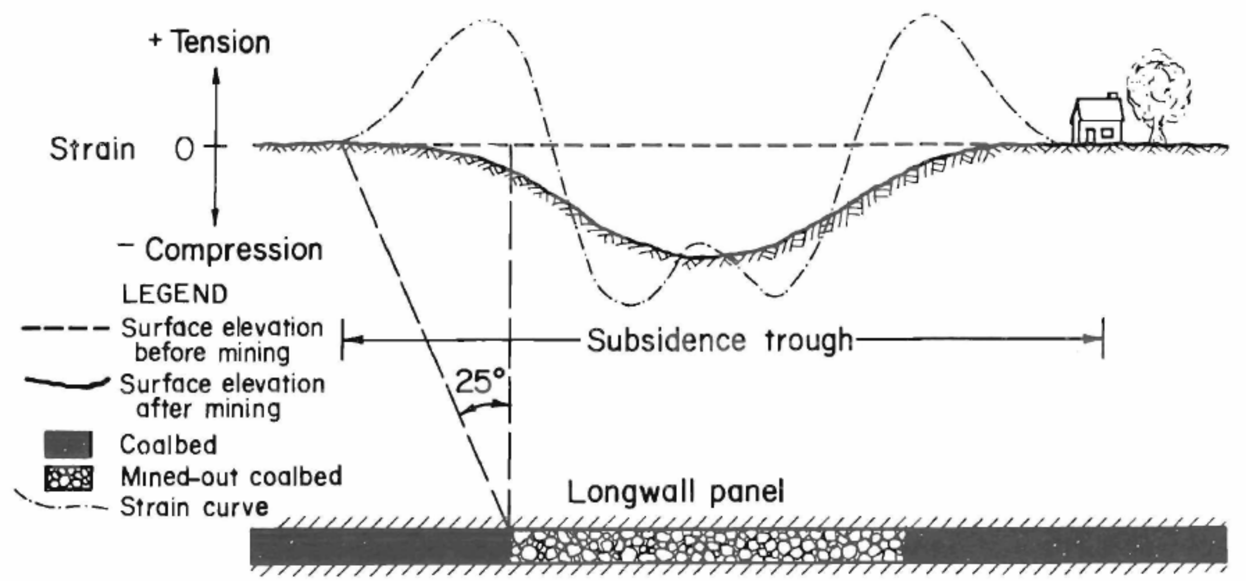

Fig 3.5.1 Subsidence trough and strain distribution (Ingram 1989)

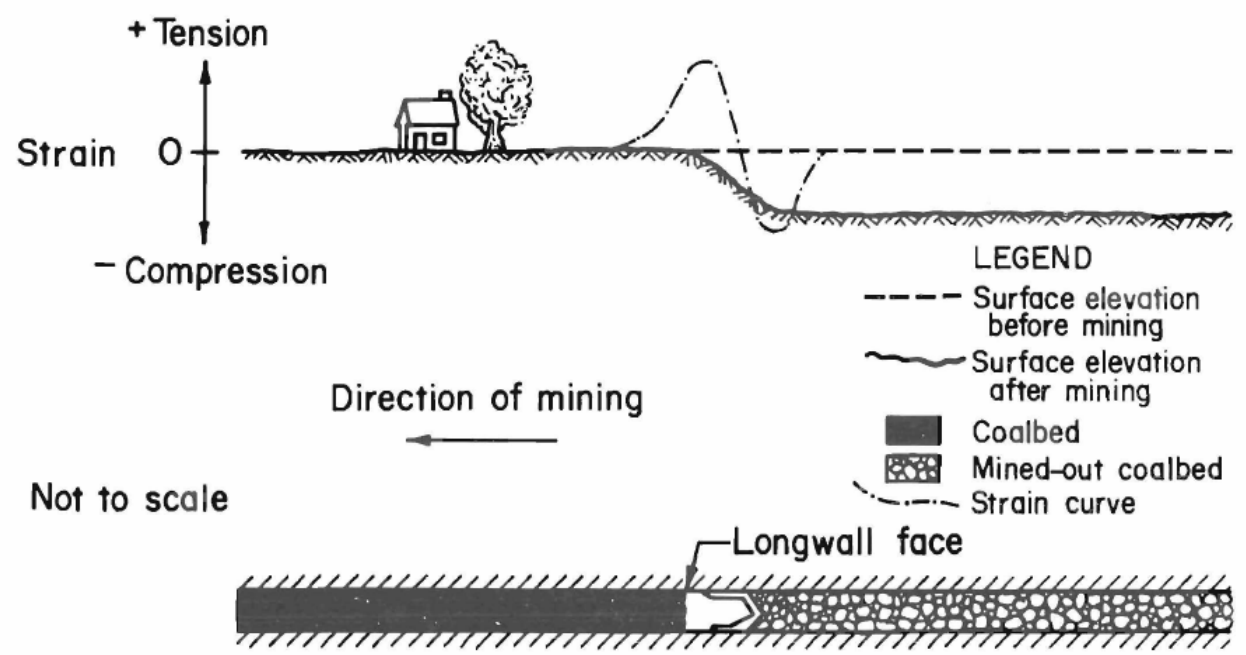

Fig 3.5.2 Strain along wave of subsidence during longwall development (Ingram 1989)

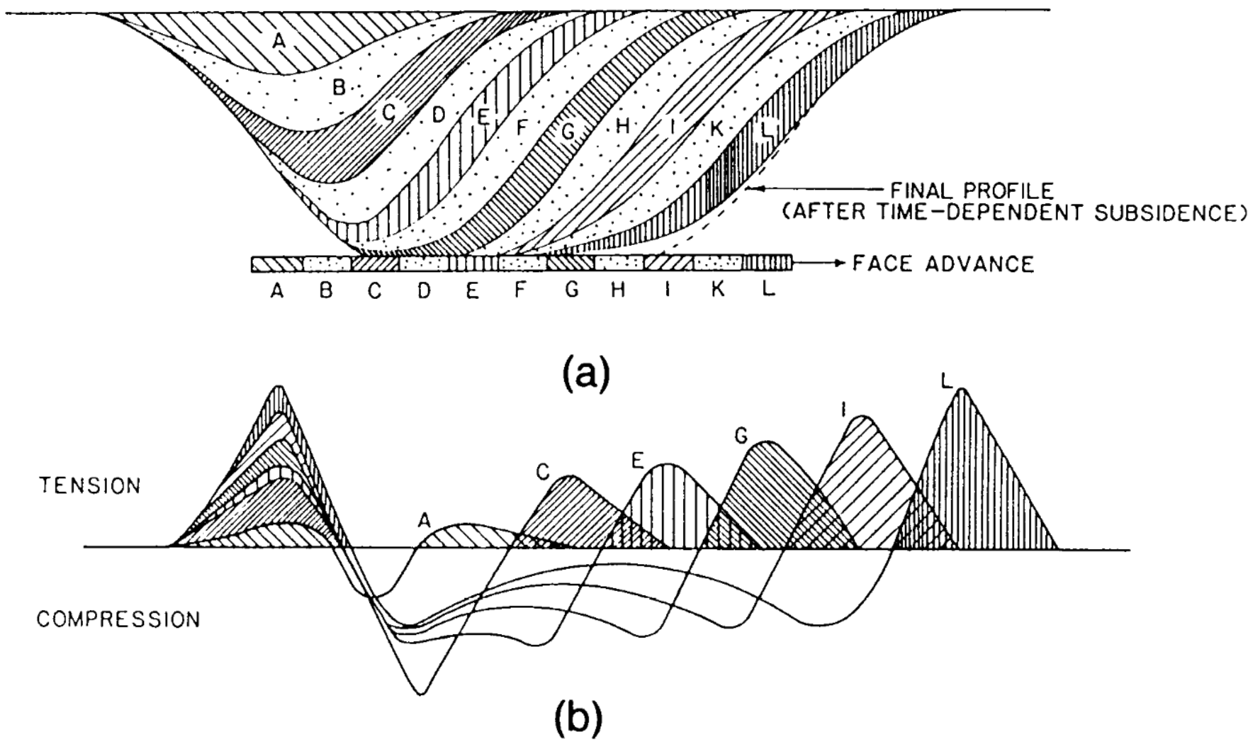

Fig 3.5.3 Development of Subsidence (Hartman 1992)

Consider a point on the ground surface. When the face has approached to within a given distance A of the point, the point begins to rise, or heave. The point continues to rise as the face draws nearer and reaches maximum of an inch or two when the face has approached to within a second given distance B. As the face draws closer, the point commences to move downward and achieves its pre-mining elevation once again when the face lies at a third distance C from the point. The point has moved below its initial elevation by the time the face is directly beneath the point and continues to move downward in the almost direct proportion to the distance the abutment has traveled beyond the point. The subsidence is nearly complete by the time the face has reached distance D from the point. Further movement is residual- time-dependent creep deformations that take place after mining is finished. Residual movements can be influenced by changing conditions, such as flooding of the mine, which may alter the properties of the rock materials years after the completion of mining.

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.

Vertical ground movements along a transverse section often take place (but may not always be noticed) when the face is as far distant as 0.5 times the thickness of the overburden 'h' from the section line. These initial, relatively subtle movements are generally associated with the passage of the heave zone at the lead edge of the traveling wave. More commonly ground movements are not recognized until the face has approached to within 0.25h of the section line, at which point the ground surface begins subsiding below the original ground surface elevation. Movements then continue systematically downward as the face passes beneath and then beyond the section line (Figure 2.8). The movements are generally complete when the face has passed 1.5h to 2h beyond the section line.

3.6 LONGITUDINAL AND TRANSVERSE PROFILE

A subsidence trough is generally characterized by stationary surface profiles in the longitudinal and transverse directions.

- Longitudinal Profile (Figure 3.3)
  Drawn along the panel centerline where the ground movements in the direction of mining are most pronounced.
- Transverse Profile (Figure 3.3)
  Drawn across the short dimension of the panel, perpendicular to the longitudinal axis, and is often drawn along the panel bisector.

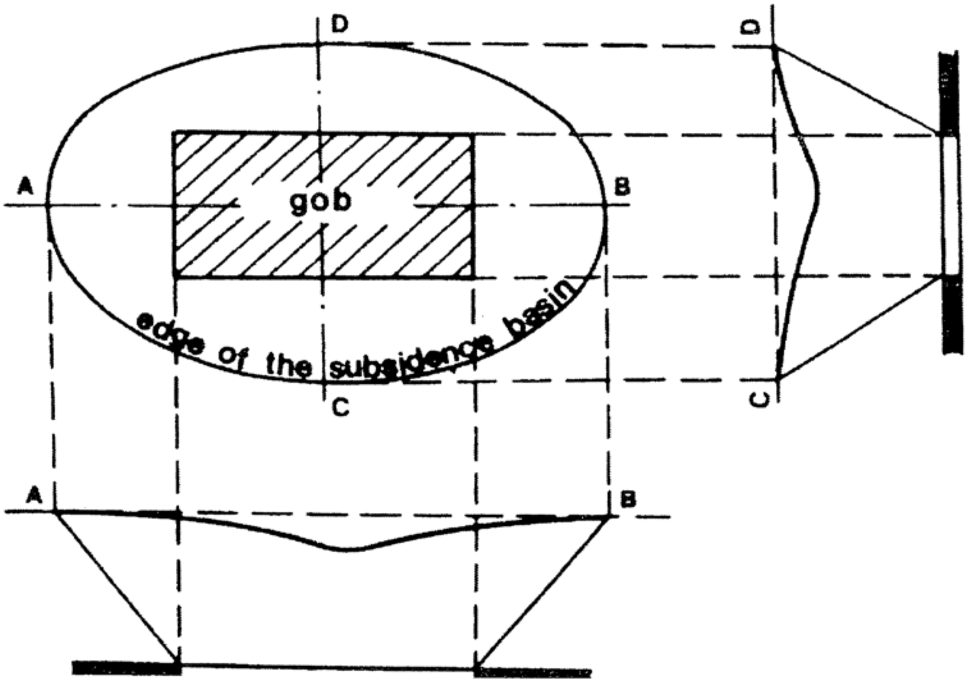

Fig 3.6 Longitudinal (A-B) and Transverse (C-D) Profiles of Subsidence Trough (Peng 2006)

3.7 SUBSIDENCE FACTOR AND PERCENT HARDROCK

Subsidence factor has been found to increase with the decrease in the percent of hardrock in the overburden.

3.8 SUBSIDENCE FACTOR AND WIDTH/DEPTH RATIO

The subsidence factor increases as the width and length of the panel increase relative to the mine depth. When the mine panel achieves or exceeds certain minimum (or critical) dimensions, a limiting maximum of a is attained. The subsidence factor under such conditions is governed primarily by the composition and properties of the overburden strata.

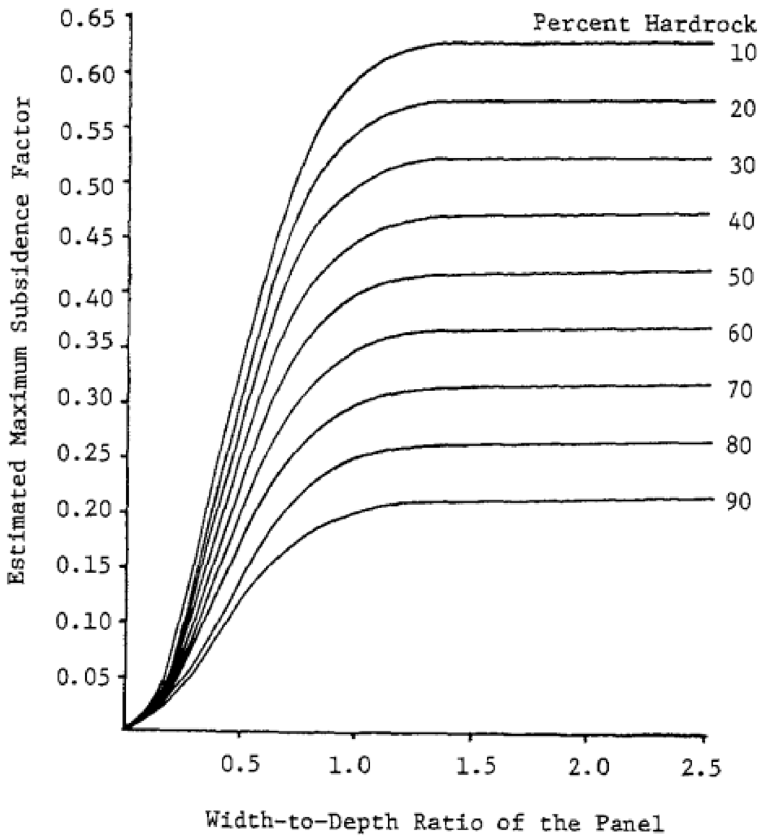

Fig 3.8 Relationship between Subsidence Factor, Width-to-Depth Ratio and Percent Hard Rock (Karmis et al 1983)

3.9 MULTIPLE PANEL EFFECTS

Longwall mining is always conducted on more than one panel running parallel to each other but separated by chain pillars. Surface subsidence caused by one panel tends to overlap those induced by the adjacent panels, depending on the angle of draw, seam depth, and chain pillar size.

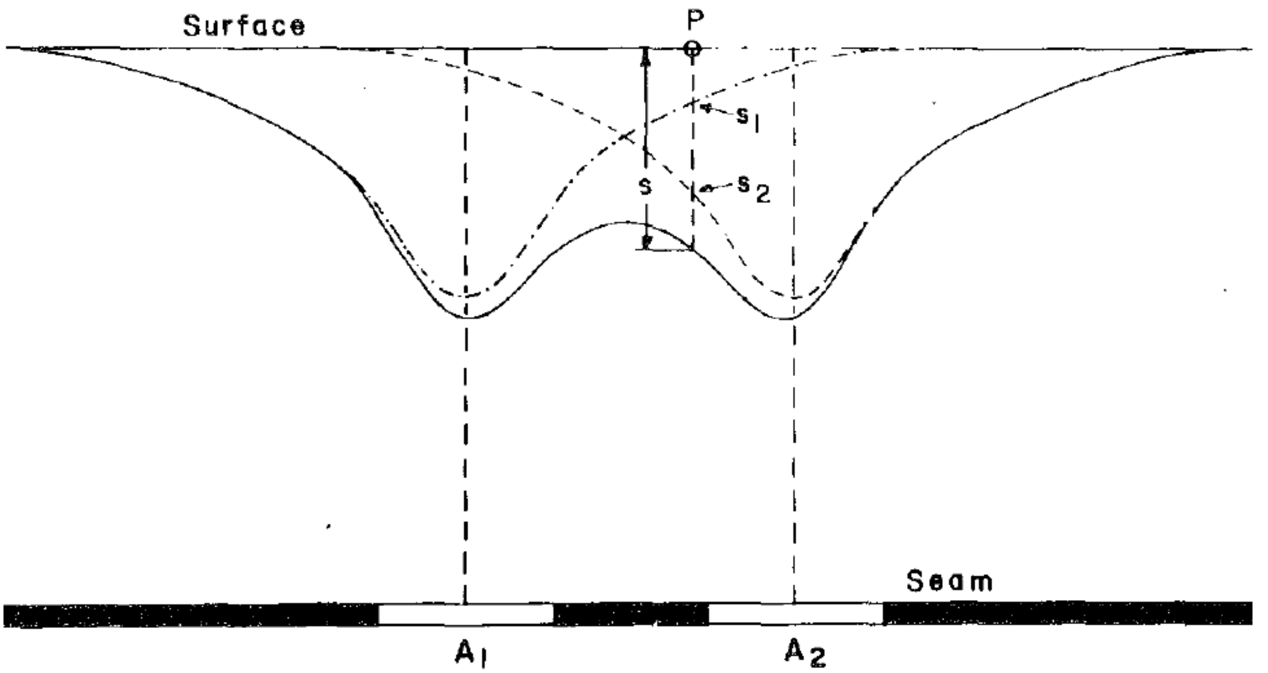

Fig 3.9 Superposition of Surface Subsidence Profiles (Brauner 1973)

3.10 SURFACE TOPOGRAPHY

3.10.1 Sloping Terrain over a horizontal coal seam

Mining subsidence effects on sloping ground surfaces can result in extensive zones of tensile strain developing on the up-slope side of the mined-out areas, in addition to localized steepening of the ground slope. There is an accompanying down-slope movement trend which can be of special significance where slopes exhibit natural creep. The increased zone of tensile strain can be of importance in encouraging the opening of natural and induced fissures, cracks and other weakness features which can lead to aggravation of stability by entry of water.

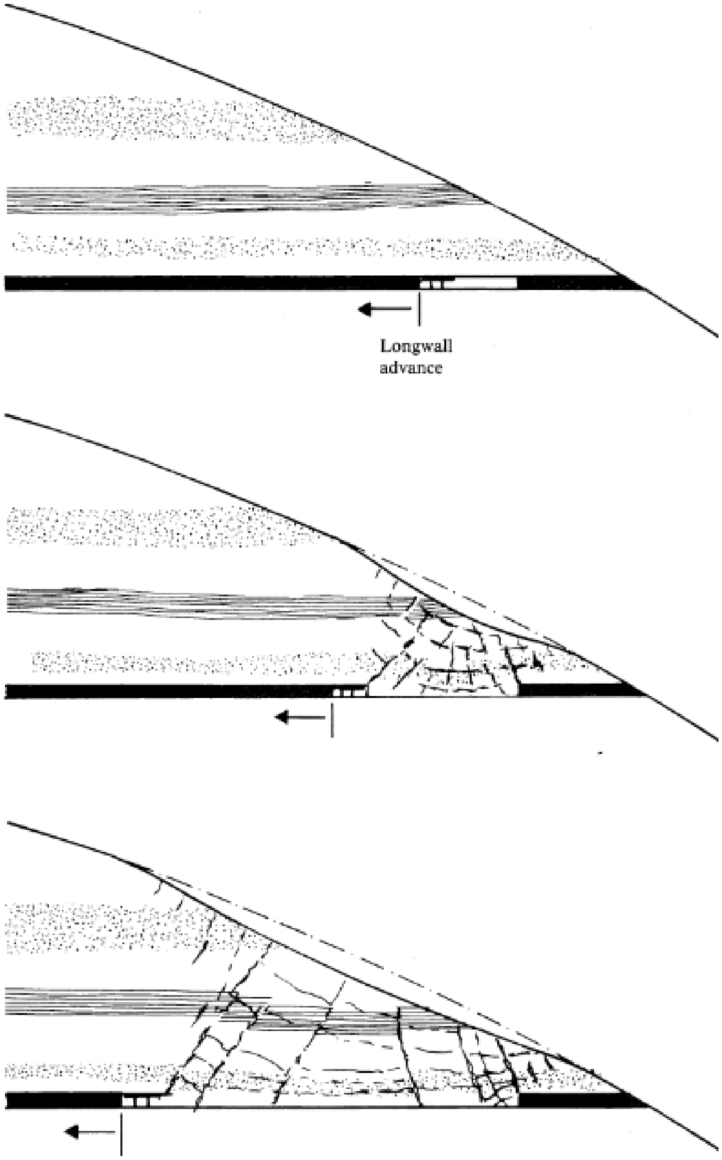

Fig 3.10.1 Initiation and trough development as longwall depth of cover increases (Whittaker and Reddish 1989)

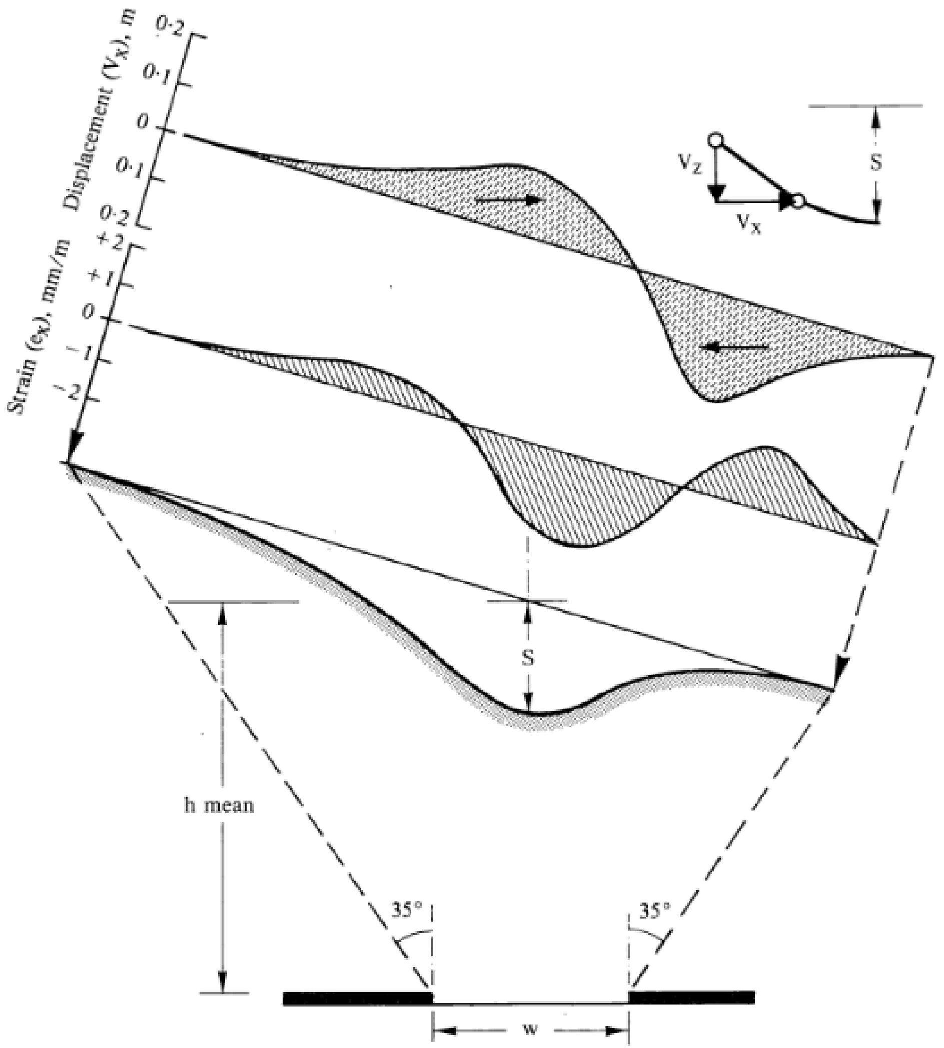

Fig 3.10.2 Subsidence, Strain and Displacement Over a Surface Ground Slope of 15˚
(Whittaker and Reddish 1989)

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.

Summary of potential ground slope instability arising from mining subsidence (Whittaker and Reddish, 1989)

When considering potential ground slope instability arising from the effects of mining subsidence, there are a number of factors which should be examined:

1) The significantly broadened zone on the up-slope side encourages the opening of existing weakness planes favourably oriented relative to the direction of longwall extraction. The opening of existing weakness planes such as fissures, joints and fault planes can lead to decreasing the structural integrity of the slope.
2) A slope weakened by tensile strain effects in the form of crack development, becomes vulnerable to the access of water and possibly resulting decrease in

natural stability.

3) Steep faces and exposed rock scars can be subjected to increased toppling effects. Small changes in tilt can have an appreciable influence on the natural stability of cliffs and overhangs.
4) There is a resultant movement down the slope which can accentuate any natural creep taking place.
5) In mountainous terrain, major rock structures can experience stability changes. Narrow canyons and scree areas may prove to be vulnerable to changes in tilt.

3.10.2 Level Terrain over an inclined coal 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. See Figures 3.10.3 and 3.10.4.

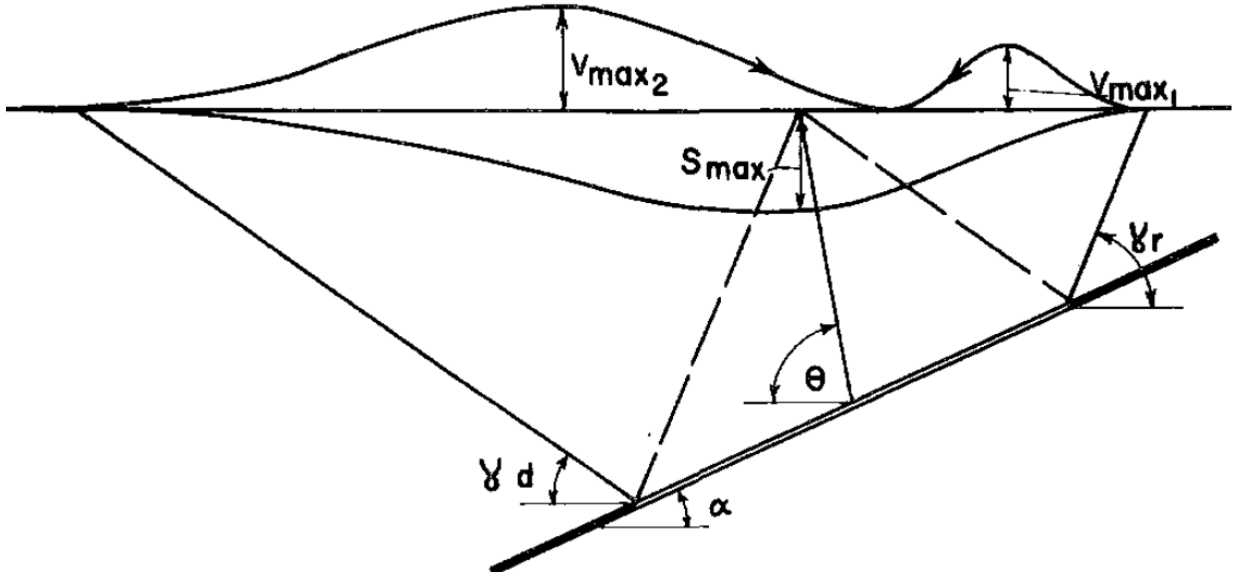

Fig 3.10.3 Subsidence Displacements Over an Inclined Seam (Brauner 1973)

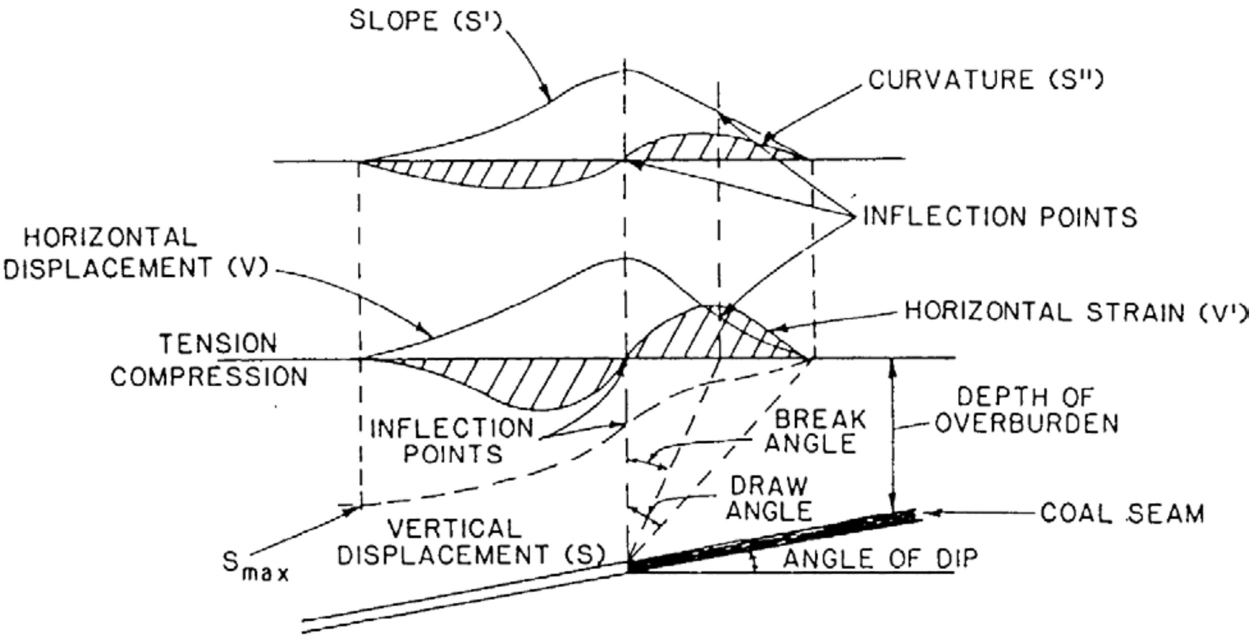

Fig 3.10.4 Schematic of ground movements caused by subsidence (Hartman 1992)

3.11 TIME EFFECTS

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 starts 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.

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

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