Subsidence Mechanisms about Longwall Panels

K. Mills

Strata Control Technology
PO Box 824, Wollongong East, NSW 2520, Australia

Abstract: This paper presents a summary of the components of subsidence about longwall panels that have been observed and inferred from subsidence and other monitoring.

The essentially independent components that make up the total subsidence observed on the surface are isolated and discussed. The combination of these components are shown to generate the range of profiles observed at surface level as subsidence.

Monitoring of displacements within the overburden section provide another dimension to the understanding of subsidence behaviour. The concept of an arch shaped zone of large downward movement over individual longwall goafs is developed in the context of observations of subsidence movements. This concept provides a framework within which to better understand sag subsidence and elastic compression of chain pillars in multiple longwall panels at depth.

Key Words: subsidence, longwall, components, monitoring, New South Wales

Introduction

This paper presents a summary of the various subsidence components that go to make up subsidence behaviour about longwall panels. The concepts developed are primarily based on experience of subsidence and subsurface monitoring about longwall panels in New South Wales. These concepts, while most easily understood in the context of longwall geometries, are by no means limited to longwall geometries. The same basic components of subsidence behaviour are also observed in a wide range of other mining geometries, both within New South Wales and elsewhere around the world.

Experience in New South Wales suggests that vertical subsidence can be divided into four essentially independent components:

- Sag subsidence.
- Elastic compression of the chain pillars and surrounding strata.
- Failure of the chain pillar system (including the immediate roof and floor strata).
- Various topographic effects.

These components are each functions of overburden depth, panel width, chain pillar geometry and surface topography. However, they are essentially independent each other.

In most presentations of generalised subsidence data there is no separation of the various components. The differences between sites are typically ascribed to geological variations rather than to differences in the fundamental subsidence mechanics that may exist.

The aim of this paper is to tease apart the various subsidence components that combine to give what we see on the surface as subsidence.

Sag Subsidence

The term sag subsidence is used here to describe the subsidence associated with sagging or draping of the overburden strata over a single extracted void (or in deeper mines over a series of extracted voids). Sag subsidence forms a major component of generalised subsidence behaviour that is widely recognised and well documented (Holla 1985b, 1987a, 1991c).

Figure 1 shows the general form of sag subsidence behaviour observed for a range of different panel geometries. Surface subsidence is normalised with respect to seam thickness. Horizontal distances are normalised with respect to overburden depth to allow comparison of results from different sites.

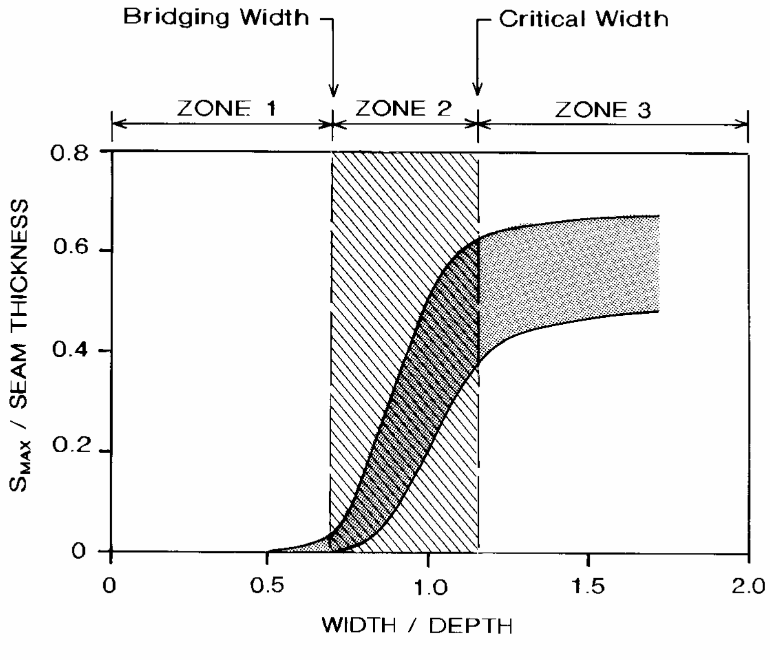


Fig. 1 – Generalised subsidence behaviour

The generalised sag behaviour divides into three zones:

1. Very low subsidence over narrow panels at depth.
2. A transition zone where maximum subsidence is sensitive to panel width and depth.
3. Maximum subsidence where increasing panel width causes no change in subsidence.

The division between the first two zones represents the point at which bridging of the overburden strata is no longer possible. The division between the second and third zones is commonly referred to as “critical width”.

Bridging of the overburden ceases when the panel width to depth ratio (W/D) reaches somewhere in the range 0.6-0.9 depending on the nature of the overburden strata and the horizontal stresses within this strata. At lesser W/D ratios, there may be some subsidence, but the magnitudes are so low as to be more consistent with elastic deflection of the bridging overburden strata.

The transition zone between bridging width and critical width represents a phase when the overburden strata is marginally stable. The amount of subsidence in the centre of the panel is sensitive to variations in panel width, overburden depth and the composition of the overburden strata. The mechanics of overburden behaviour in the transition zone are more easily understood in the context of subsurface monitoring discussed in a separate section below.

For “supercritical width” panel geometries, maximum subsidence is no longer dependent on changes in panel width. The overburden strata in the centre of the panel does not rely on the abutments for support. Instead, it is fully supported on the goaf (and chain pillars in multi-panel geometries at depth).

Elastic Compression

Elastic compression occurs in most materials when they become loaded. The strata above and below longwall chain pillars are no exception. At shallow depth, the magnitude of elastic compression is typically small relative to sag subsidence because the loads concentrated in and around the chain pillars are relatively low. However, as depth increases so does the component of subsidence due to elastic strata compression. At 500m deep, elastic compression may account for upward of 1.0m of surface subsidence.

When longwall chain pillars are formed, the vertical stress carried by the coal, the roof material above and the floor material below is approximately equal to the weight of overburden strata (concentrated slightly by the formation of the pillar itself). By the time that the chain pillars become isolated in the goaf between two adjacent longwall panels, the vertical stress in the chain pillars is concentrated by an amount that depends on depth.

An increase in vertical stress in the coal of the chain pillars causes the coal to be compressed. Any compression at seam level causes a corresponding lowering of the surface and is seen on the surface as subsidence. Compression of the coal pillar itself typically amounts to only a few centimetres, even at depth. The compression that occurs in the strata above and below the coal seam is much more significant.

Figure 2 shows the vertical stress distribution above and below a loaded chain pillar. The region of vertical stress increase extends into the roof and floor to a distance many times the width of the chain pillar. The vertical stress increase is greatest immediately above and below the chain pillar and gradually diminishes with vertical distance. As each unit of overburden strata experiences increased load, it compresses slightly. The accumulation of compression over a large volume of material can cause a significant downward movement on the surface.

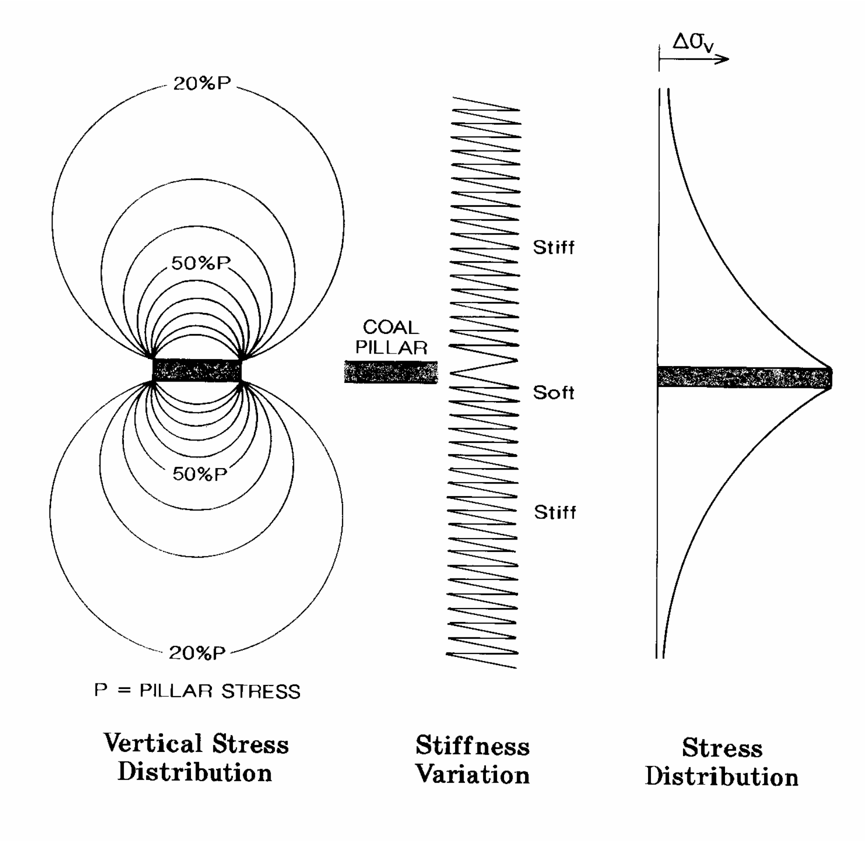


Fig. 2 – Illustration of elastic pillar compression.

In effect the chain pillars act to concentrate vertical stress. This concentration causes a slight amount of compression in the chain pillars themselves but more importantly a large amount of compression in the strata above and below the chain pillars. The total elastic compression of all the strata is seen on the surface as subsidence.

Table 1 summarises the subsidence that occurs due to elastic compression of the chain pillars and surrounding strata for 30m wide chain pillars and 210m wide longwall goafs at overburden depths ranging from 50m to 500m. In all cases, the chain pillars remain stable even when isolated in the goaf. Stress change monitoring of chain pillar loading indicates that large chain pillars are capable of accepting very high loads when isolated in the goaf. The range indicates the range of elastic compression subsidence for typical overburden stiffnesses of 8-16 GPa.

Table 1: Subsidence Due to Elastic Compression

Depth (m)	Elastic Compression (mm)
50	15-30
100	50-100
150	150-250
200	250-400
300	400-750
400	600-1000
500	750-1400

The range of subsidence indicated in Table 1 is typical of the subsidence measured over chain pillars in the field. At depth, when the overburden strata is able to bridge over individual panels, the subsidence observed is controlled by elastic compression of the chain pillars. The overburden strata sags over the multiple panels as if they were one large superpanel. The maximum subsidence is, however, controlled not by the recompression characteristics of the goaf as by the elastic compression characteristics of the chain pillars and the surrounding strata.

Pillar Failure

In the event that chain pillars become overloaded, the pillars (or more likely the pillar system including roof and floor strata) can fail resulting in lowering of the overburden strata and surface subsidence. In large areas of small pillars, pillar failure can occur suddenly and the resulting subsidence can be quite spectacular. As pillar sizes increase, pillar failure tends to become more gradual and the ultimate subsidence is less. This phenomenon is illustrated in Figure 3 for a range of pillar sizes in weak claystone floor strata of the southern Lake Macquarie area of the Newcastle Coalfield (Mills & Edwards 1997). The mining geometries are typically partial extraction geometries. The claystone floor geology allows the pillars to become overloaded more easily.

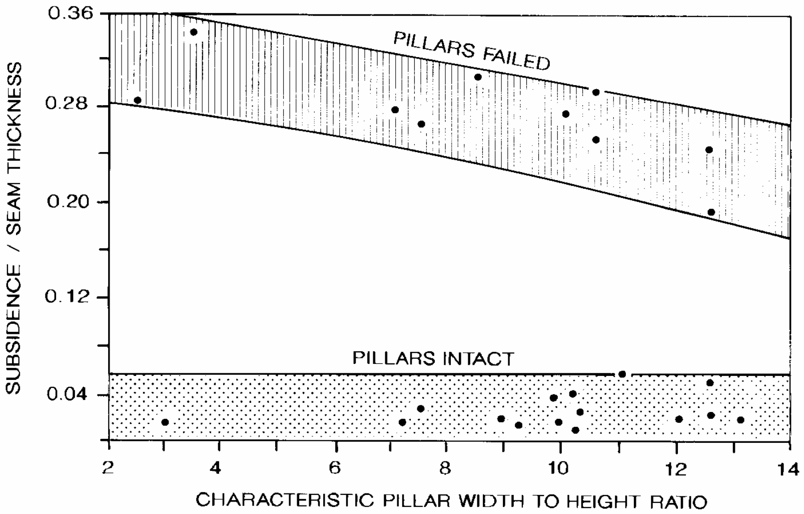


Fig. 3 – Subsidence due to pillar failure. (After Mills & Edwards, 1997).

In most longwall mining operations, chain pillars are sized to meet operational requirements such as acceptable roadway conditions about the gateroads rather than pillar stability per se. The pillar sizes required to achieve acceptable roadway conditions are typically large enough that pillars remain stable when isolated in the goaf. Stability is often further improved by the confining effects of the fallen goaf. Stress change monitoring of pillars indicates that, when geological conditions permit, very high loads can be developed in chain pillars isolated in the goaf (Gale & Mills 1994).

In the author's experience, subsidence due to chain pillar failure is uncommon, often being mistaken for elastic compression. However, it is conceivable that in weaker geological conditions or under very high chain pillar loading conditions, pillar failure could contribute to surface subsidence.

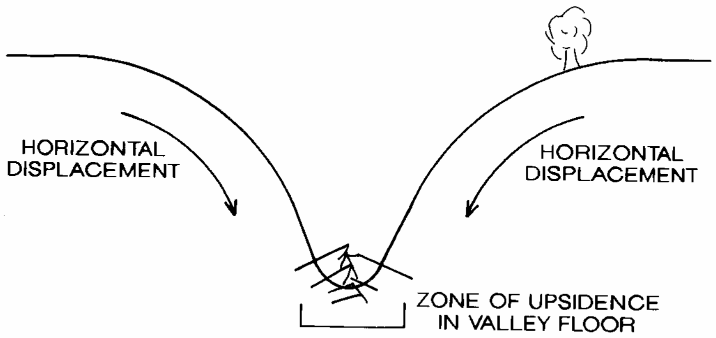
Topographic Effects

In steep terrain, horizontal movements contribute to a significant component of vertical subsidence commonly referred to as "upsidence". Upsidence occurs most often in the bottom of valleys and gorges. It is usually only one component of the overall subsidence, so that the ground subsides, but not as much as the surrounding area. The magnitude of upsidence is usually less than 200mm.

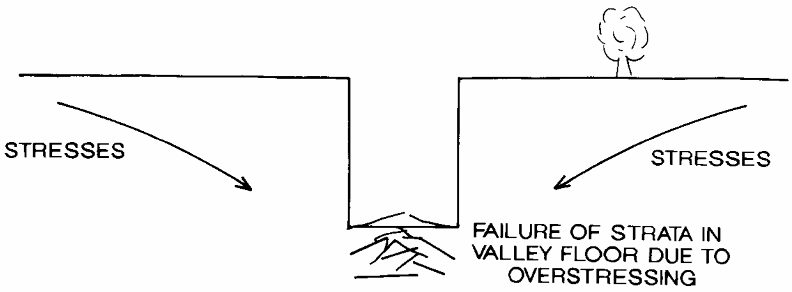
When steeply sloping valleys are undermined, there is a large component of horizontal movement in a downslope direction on either side of the valley. In the bottom of the valley, the movements occur from both sides resulting in compression of the ground surface and upward movement through a combination of buckling and heaving. Because downslope horizontal movements may occur well outside the area of mining, it is not uncommon to see the effect outside of the area immediately above the goaf.

In gorges with steep sides, a similar phenomenon may occur through a slightly different mechanism. The gorge acts as a stress riser to horizontal stresses. Overstressing of the rock in the bottom of the gorge causes rock failure and natural deepening of the gorge occurs. In this process, rock strata in the bottom of the gorge is always in a state of marginal stability. Elevations in horizontal stress about the bottom of the gorge caused by longwall mining activity may elevate the horizontal stresses sufficiently to cause additional failure. Rock failure is evidenced by buckling and upward movement of the strata in the floor of the gorge.

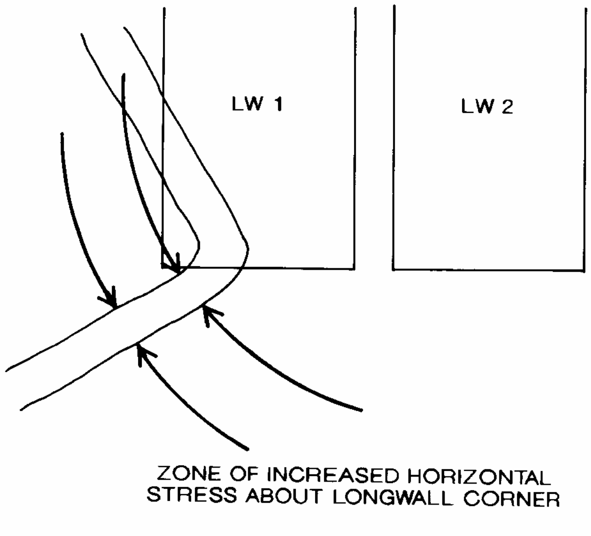
Figure 4 illustrates the effect of downslope movement in steep terrain and the effect of stress concentration at the bottom of steep sided gorges. Horizontal stress concentrations typically occur about the corners of longwall panels and may extend a considerable distance outside the area of mining.



a) Steeply Sloping Terrain.



b) Deep Gorge in Sandstone.



c) Example of zone of overstressing about extracted longwall panels.

Fig. 4 – Topographic effects influencing upsidence.

Subsurface Monitoring

Subsurface monitoring of overburden movements using multipoint extensometers installed and monitored from the surface provides a context in which to further interpret the movements seen on the surface as vertical subsidence. Recent extensometer monitoring at Clarence Colliery (Mills & O'Grady) shows that an arch shaped zone of large downward movement develops over each longwall goaf. While the shape of this zone may be modified by local geological variations, the uniformity of subsidence experience suggests that the mechanics of overburden behaviour are consistent over large areas of New South Wales.

The shape of the arch that develops over each longwall panel is similar to the fall geometry that develops over a fallen roadway except that over a longwall panel the magnitude of the displacements relative to the dimension of the mined void are much less than for a fallen roadway. Disturbance to the strata within the arch shaped zone of downward displacement above a longwall panel is consequently also much less.

The shape and height of the arch shaped zone of large downward movement depend strongly on the geological setting and in situ stresses present. In strong massive strata that is lightly stressed, the overburden strata may span across an entire longwall panel. If the panel width is too wide to allow spanning, a shallow arch shaped fall geometry may develop.

In geological environments typical of the Southern and Western Coalfields, the height of the arch shaped zone of downward movement approaches 1.0-1.2 times the panel width. This type of arch shaped zone is consistent with the subsidence behaviour typically observed in the Southern and Western Coalfields and helps to provide a context in which to understand sag subsidence.

Figure 5 shows an arch shaped zone of large downward movement developed over a goaf. When the overburden depth is such that the surface is above the top of the arch shaped zone of large downward movement, the surface subsidence is minimal consistent with overburden bridging across the panel.

When the overburden depth is less and the surface skims across the top of the arch shaped zone, bridging is no longer possible and the onset of the transition zone shown in Figure 1 begins. As the overburden depth decreases further, subsidence increases rapidly through the top of the arch shaped zone of downward movement. The dynamic nature of this phase of the subsidence process is highlighted by the marginal stability of the strata at the top of the zone of large downward movement.

As the overburden depth decreases further, a point is reached when the sagged overburden material is resting on the goaf. When the panel width is increased, there is no further subsidence. This point corresponds to critical panel width. Below this horizon, caved material rests fully on the goaf except near the panel edges where it is partly supported on the abutments.

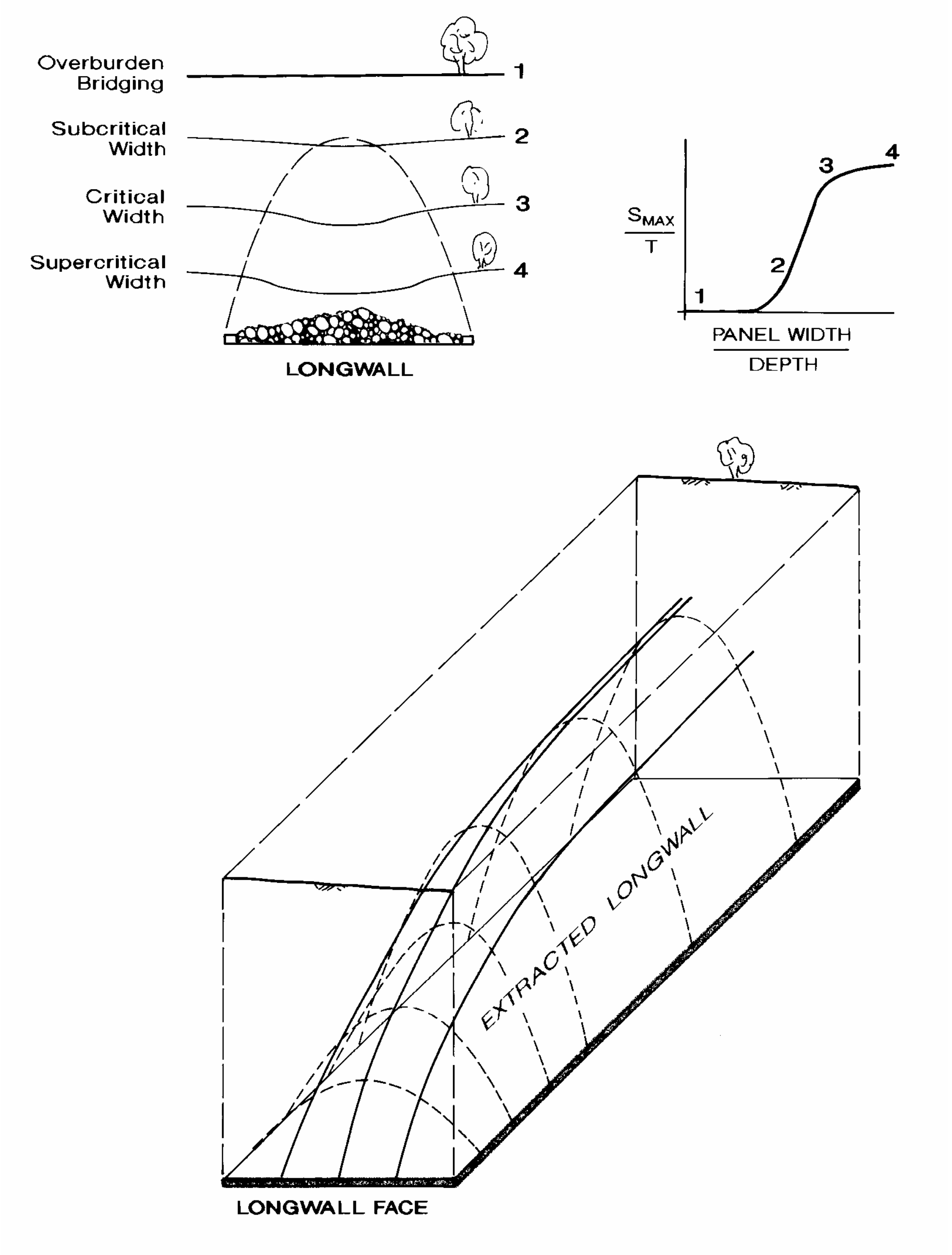


Fig. 5 – Zones of downward displacement above longwall panels.

Discussion

The various components of subsidence have been individually described. The combination of these components give rise to the range of subsidence profiles typically observed in the field.

At shallow depth, the subsidence profile observed over a series of longwall panels is typically very humpy. Each row of chain pillars stands out clearly. The elastic compression over each chain pillar is small. The panels are individually wide enough that they are supercritical in width. Full sag subsidence occurs in the middle of each panel. Strains and tilts are usually extreme in these circumstances.

At moderate depths of 150-200m, the elastic compression of the chain pillars is typically in the range 150-400mm. In a multipanel geometry, the surface subsidence cannot be limited to less than these values even if the overburden strata is able to bridge across individual panels. In most cases, the longwall panels are individually subcritical in width but too wide to allow bridging. The maximum subsidence over each panel is a combination of elastic compression of adjacent chain pillars and subcritical width sag. Maximum subsidence in this situation is difficult to estimate precisely because of the sensitivity of sag subsidence to panel width, changes in depth and overburden geology. Changes in pillar width can influence chain pillar compression.

At depths in the range 300-400m, chain pillar compression becomes the most significant component. Sag subsidence over individual panels decreases to the point where overburden bridging may occur over individual panels. There may still be some sag subsidence over individual panels giving the subsidence profile some waviness.

At depths in excess of 400m, the overburden strata is typically able to bridge over individual panels. Once this happens, surface subsidence develops in response to a superpanel geometry as illustrated in Figure 6. The amount of subsidence is controlled by elastic compression of the chain pillars and is typically of the order of 1000mm. The maximum subsidence is no longer controlled by seam thickness, but rather by chain pillar compression.

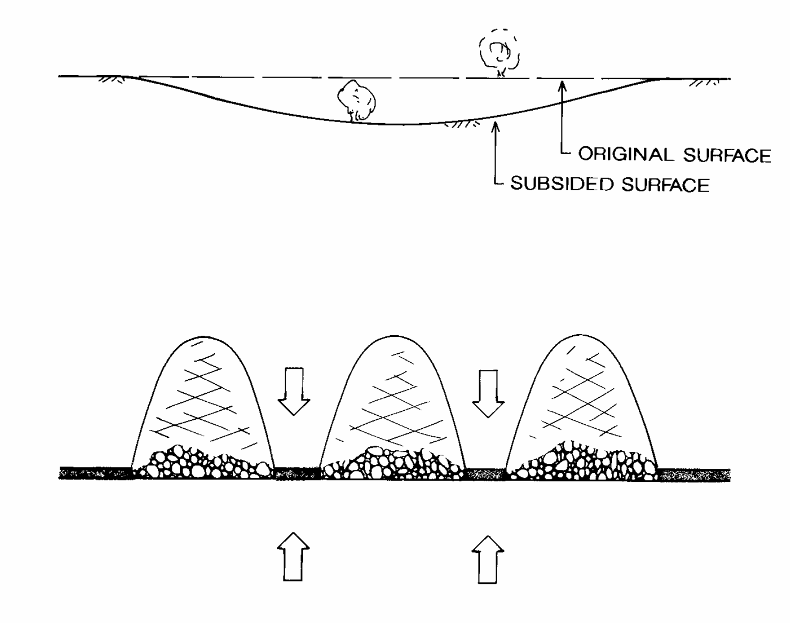


Fig. 6 – Multiple panels at depth subside to generate a super panel. N.B. Maximum subsidence is controlled by elastic compression of the chain pillar not seam thickness.

Additional subsidence may occur when chain pillars fail. However, as previously indicated, this is very uncommon for typical chain pillar geometries unless the geological environment is particularly weak.

A reduction in subsidence may occur in the bottom of valleys due to horizontal compression effects. The magnitude of the subsidence reduction (or "upsidence" as it is called) is typically less than 200mm but is nevertheless noticeable and may be sufficient to influence structures spanning across valleys and gorges.

Conclusions

Vertical subsidence observed over longwall panels in New South Wales is a combination of four essentially independent components:

1. Sag subsidence, which is controlled by panel width, overburden depth and seam thickness.

2. Elastic compression of the chain pillars which is a function of chain pillar geometry, panel width and overburden depth. At depth, elastic compression can have a large magnitude and may be mistaken for chain pillar failure.

3. Chain pillar failure which is uncommon in longwall geometries in New South Wales because of the operational requirements for chain pillar to maintain acceptable gateroad conditions.

4. Topographic effects that occur in steep terrain and gorges where upward movements of 100-200mm may occur in the bottom of valleys even well outside the area mined.

Surface extensometer monitoring indicates the development of an arch shaped zone of large downward movement above each individual longwall panel. This behaviour is consistent with observations of sag subsidence over individual panels and elastic compression of the chain pillars between.

References

Holla, L., 1985b. Mining subsidence in New South Wales, 1. Surface subsidence prediction in the Southern Coalfield, December (NSW Department of Mineral Resources: Sydney).

Holla, L., 1987a. Mining subsidence in New South Wales, 2. Surface subsidence prediction in the Newcastle Coalfield, January (NSW Department of Mineral Resources: Sydney).

Holla, L., 1991c. Evaluation of surface subsidence characteristics in the Western Coalfield of New South Wales, The Coal Journal, No 31, pp 19-32.

Mills, K.W., and O'Grady, P., 1998. Impact of longwall width on overburden behaviour, 1st Australasian Coal Operators Conference, Wollongong, NSW.

Mills, K.W., and Edwards, J.L., 1997. Review of pillar stability in claystone floor strata, Symposium on Safety in Mines: The Role of Geology, Newcastle, NSW.

Gale, W.J., and Mills, K.W., 1994. Coal Pillar Design Guidelines – P351, SCT Report No AMI0157.