

OBSERVATIONS OF GROUND MOVEMENTS WITHIN THE OVERBURDEN STRATA ABOVE LONGWALL PANELS AND IMPLICATIONS FOR GROUNDWATER IMPACTS

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ABSTRACT

Longwall mining is recognised to cause disturbance to the overburden strata as the overburden strata moves downward into the void created by mining. These ground movements have been observed as surface subsidence over many decades and by numerous researchers through numerous surface and sub-surface monitoring programs, in a wide variety of different geological settings, using a wide variety of monitoring techniques. This monitoring provides an excellent database of experience from which to characterise the nature and extent of disturbance within the overburden strata above longwall panels. This characterisation is intended to provide a basis for better understanding the effects of longwall mining on the surrounding strata and, particularly in the context of groundwater interactions, the formulation of hydrogeological models used to predict groundwater impacts about longwall panels.

The extent and nature of zones within the overburden are characterised in this paper on the basis of the level of disturbance and the nature of this disturbance. Zones characterised by tensile changes or stretching behaviour are found to be located directly above each panel with the level of disturbance above the mining horizon graduated as a function of panel width from the mining horizon through to about three times panel width above each individual longwall panel. These stretching zones and their influence on the hydraulic conductivity of the overburden strata contrast with zones of increased compression located directly above the chain pillars that separate individual longwall panels.

INTRODUCTION

Longwall mining is widely recognised from subsidence monitoring and associated surface impacts to cause disturbance to the overburden strata as the overburden strata moves downward into the void created by mining. The nature of these ground movements have relevance to groundwater interactions and the formulation of hydrogeological models used to predict mining impacts on groundwater and potential inflows into the mine because the fracturing that develops influences the hydraulic conductivity of the overburden strata. This paper is focused on the broad characterisation of zones of disturbance about longwall panels. It is recognised that individual sites will have their own specific characteristics which may vary from the norm. However, there appears from the numerous monitoring programs that have been conducted in a wide variety of geological setting to be a pattern of ground behaviour that is sufficiently well defined to be useful as a general indicator of the type of ground movements that can be expected.

This paper is structured to provide a review of surface subsidence monitoring and the various components of subsidence that are implied by this monitoring, a review of the types of monitoring systems that have been used to characterise overburden behaviour and the results obtained, and a summary of the characteristics of ground movement evident from the various studies that have been conducted.

SURFACE SUBSIDENCE

Surface subsidence monitoring has provided an extensive database of experience characterising the general form of ground movements at the surface for a wide range of overburden depths and panel geometries. The behaviour of the ground behaviour below the surface can be inferred from a composite of the behaviours at various overburden depths.

Monitoring of surface subsidence has led to the recognition that vertical subsidence in single seam longwall operations is comprised of two main components with two other components that occur in special circumstances (Mills 1998).

The main components are:

- Sag subsidence over each individual panel.
- Elastic strata compression of the chain pillars and the strata above and below the chain pillars.

The less commonly observed components are:

- Failure of pillar systems including failure of the immediate roof or floor strata.
- Topography related dilational effects that cause uplift and uplift.

Sag Subsidence

Sag subsidence occurs as draping over the void created by each individual longwall panel. The relationship between maximum subsidence divided by seam thickness and panel width divided by overburden depth is shown in Figure 1.

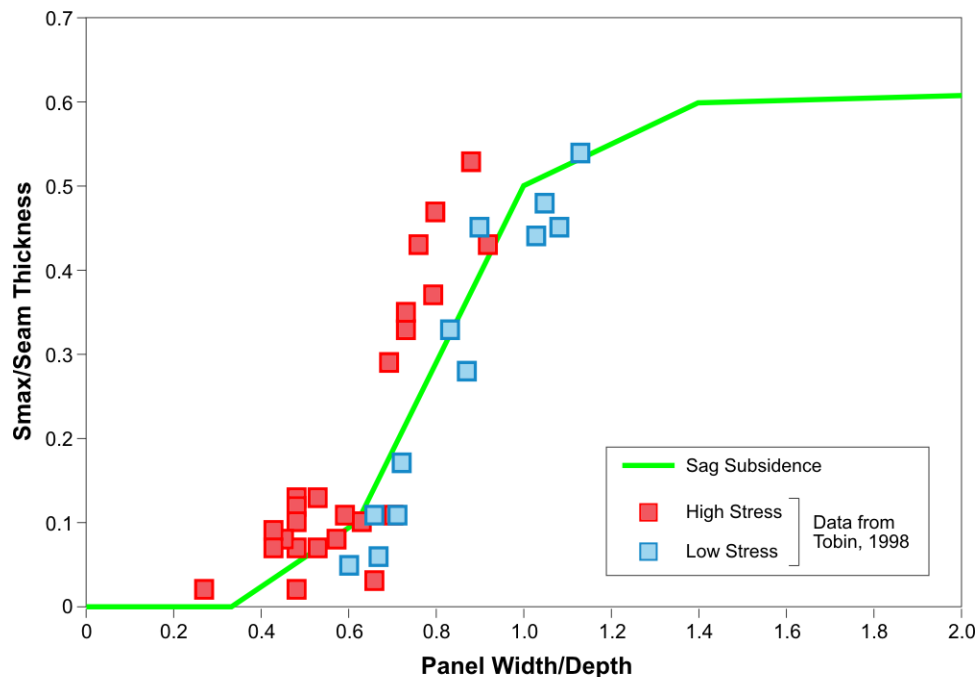


Figure 1: Sag subsidence characteristics above single longwall panels in NSW .

This presentation was used by the National Coal Board in the United Kingdom and has been widely used to represent subsidence behaviour in Australia for many years. Usually there is no differentiation between sag subsidence and elastic strata compression, which unfortunately has complicated interpretation of the mechanics involved.

The general form of the sag subsidence behaviour shown in Figure 1 is characteristic of a wide range of geological settings. Shifts in the characteristic curve are recognised to occur as a result of changes in horizontal stress magnitude within the overburden strata and changes in the nature of the overburden strata, but the general characteristics remain similar.

Data presented by Tobin (1998) for longwall subsidence in the Newcastle area in essentially similar geological conditions is reproduced in Figure 1. This data illustrates the effects of horizontal stress on caving and subsidence behaviour. The characteristic curve for panels oriented in the same direction as the major principal stress (NNE) is shifted to the right, i.e. lower subsidence for the same geometry, compared to the panels oriented across the major principal stress (NW).

Figure 2 shows a more intuitive way of presenting the same data. Depth is plotted on the vertical axis as depth over panel width and subsidence is plotted on the horizontal axis. In this presentation, it can be seen that the height of fracturing for each zone increases in the higher stress environment in much the same way that the height of softening above an underground roadway increases with increasing horizontal stress (Gale 1986).

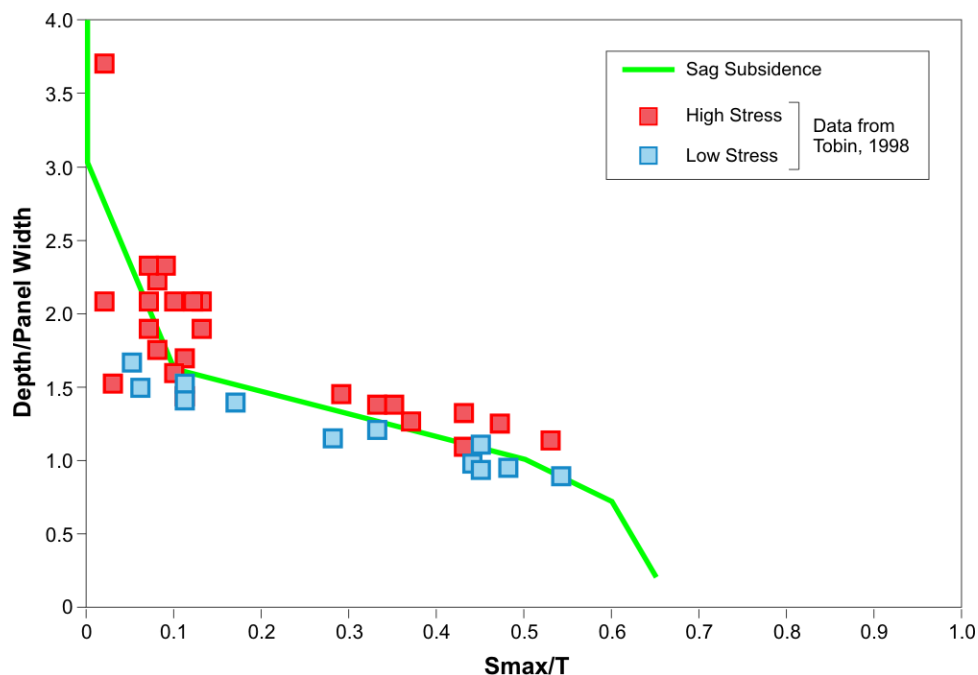


Figure 2: Downward movement within overburden strata implied by sag subsidence data over single longwall panels.

Elastic Compression Subsidence

Elastic compression subsidence above and below chain pillars occurs when multiple longwall panels are mined adjacent to each other (Holla et al. 2000). The ground directly above and

below each chain pillar is subject to the increased vertical stress concentrated onto the chain pillars by the extraction of adjacent panels.

The chain pillar comprises coal, a material with relatively low elastic modulus compared to the rock strata above and below the coal seam. Coal that forms the chain pillars is typically only a few metres thick, so the vertical displacement resulting from elevated stresses in the chain pillar is typically less than a few tens of millimetres.

The chain pillar presses on the roof and floor strata with stresses in the range 10-50MPa for typical longwall geometries and overburden depths. These increased vertical stresses diminish with distance above and below the chain pillar but the zone of compression typically extends for several hundred metres up and down. Elastic compression of the chain pillar and the column of rock above and below the chain pillar subject to increased vertical stress accumulates through the overburden section to contribute to the vertical subsidence observed on the surface directly above each chain pillar.

At shallow depths of less than 100m, the elastic compression subsidence is typically in the range 50-100mm. At depths of 500m, the accumulated elastic compression may increase to be in the range 700-1400mm because of the higher loads involved and the greater column of rock that is compressed (Mills 1998).

Subsidence Due to Pillar Failure

Subsidence due to pillar failure is less common in longwall operations than it was in pillar extraction operations because of the large pillar sizes required to maintain acceptable roadway conditions in the tailgate of longwall operations and the confinement provided to pillars by the goaf. Nevertheless, there are recognised to be some circumstances where the caving characteristics of the goaf do not provide sufficient confinement to the pillar system, typically the strata above the pillar, to prevent non-linear deformations that contribute to additional subsidence at the surface (Gale 2010). Failure of the chain pillars does not significantly change the zones of vertical stretching and compression within the overburden strata, but it does increase the vertical subsidence over the chain pillar.

Local Subsidence Effects Due to Surface Topography

Upsidence and uplift are phenomena that are recognised to cause changes in the vertical subsidence profile in areas where there is topographic variability. However, these processes are driven by horizontal ground movements and are not discussed in this paper.

SUB-SURFACE MONITORING

A range of techniques have been used to monitor sub-surface ground movements associated with mining subsidence. These techniques are discussed in this section.

Surface Extensometers

Surface extensometers have been deployed for monitoring mining induced ground movements for several decades. Extensometer systems comprise a number of anchor points installed at various depths in an open borehole. These anchor points are connected to the surface by

wires. Relative displacements between the anchors and the borehole collar are monitored at the surface allowing downward movement within the overburden strata to be monitored.

The challenges with these systems relate to maintaining stable borehole conditions, avoiding the wires becoming intertwined during installation, and compensating for shear movements in the borehole. Nevertheless, the results have been very useful for characterising the nature and extent of sub-surface ground movements.

Initial attempts by Gurtunca (1984) at South Bulli and West Cliff Collieries and Schaller and Hebblewhite (1981) at Angus Place Colliery were unsuccessful because of borehole instability, but Holla and Armstrong (1986) made successful measurements at Ellalong Colliery using a system of hanging weights that was later deployed at Tahmoor Colliery, Invincible Colliery, and Angus Place Collieries in the 1980's, also with good results. Mills and O'Grady (1998) describe the use of rotary spring surface extensometers for monitoring longwall caving behaviour at Clarence Colliery. Much shorter versions of these instruments have been used to characterise ground movements in rockbars subject to valley closure and upside (Mills and Huuskes 2004).

The results obtained from extensometer monitoring are entirely consistent with observations from surface subsidence monitoring at a range of overburden depths. There is a zone of large downward movement and significant disturbance that extends to a height above the mining horizon equal to the width of each individual longwall panel in an arch shape as shown in Figure 3 (from Mills and O'Grady 1998). Outside and above this zone, there is a zone of lower level ground movement that extend higher into the overburden strata, often right through to the surface.

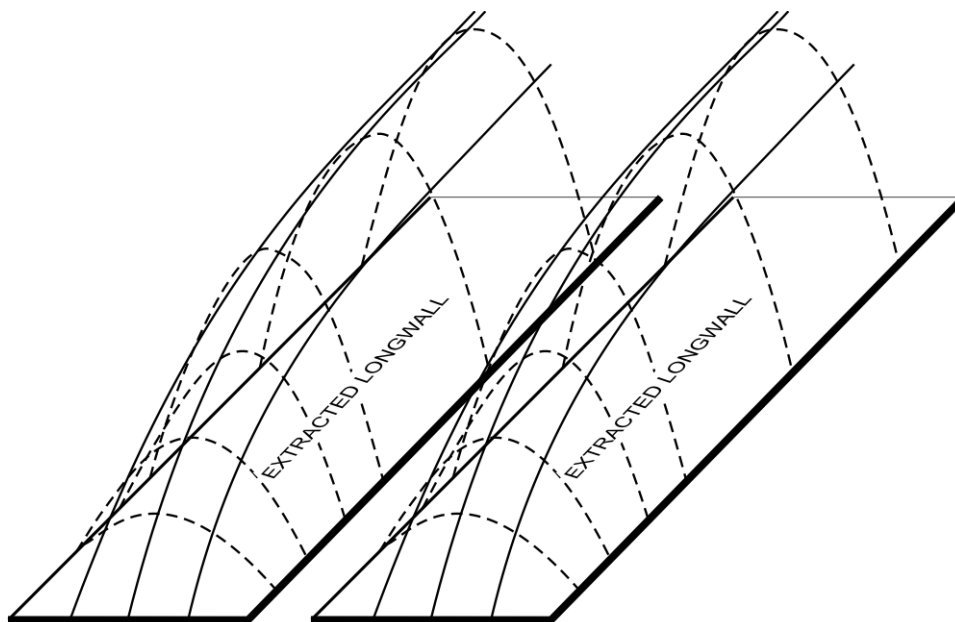


Figure 3: Zones of large downward movement above longwall panels.

Borehole Cameras and Geophysical Logging Tools

Borehole cameras, televiwers, and other borehole imaging devices have proved very useful for characterising zones of ground movement observed above longwall panels. To measure the nature and extent of sub-surface ground movements using these devices, it is necessary to drill a hole into a longwall goaf, typically in the centre of the panel to a depth about 20m above the mining horizon. It is good practice to drill a second hole in undisturbed ground nearby as a control and to run a similar survey in this hole as well so that the difference in the fracture patterns observed in the two holes is immediately apparent.

The various zones of ground movement are clearly apparent and able to be correlated with zones of displacement evident from observations of surface subsidence.

Piezometers

Piezometers are primarily used for monitoring groundwater behaviour. The effectiveness of open hole piezometers tends to be compromised by mining induced fracturing that migrates upward from the mining horizon. However, the development of fully grouted multiple piezometer strings (McKenna 1995) and their deployment around longwall panels has proved very useful for tracking the upward progressing ground movements as a longwall goaf develops at the start of a panel in a new, previously undisturbed area.

The interaction between the ground movements and stratigraphic units with high hydraulic conductivity is apparent as the ground displacements move upward through the overburden. Byrnes (1999) describes the application of multiple piezometers at South Bulli Colliery to measure the height of ground deformations that extended to 120m above 120m wide longwall panels.

This work and other similar studies demonstrate that there is significant interaction with the groundwater within a distance above the mining horizon equal to the longwall panel width. A zone of large downward movement from the mining horizon to a height above the mining horizon equal to the longwall panel width typically shows significant hydraulic depressurisation because of the fracture network that is created by mining. Above this zone, there is typically a zone of slight depressurisation below hydrostatic consistent with low level flow in a downward direction. Recharge from rainfall is sometimes sufficient to substantially maintain groundwater levels in the upper levels of the overburden strata.

Packer Testing

Packer testing involves pressurising a closed section of borehole with water and measuring the flow of water into the test interval, and by implication the ground, at several different pressures. The more fractured the ground, the more water flows out of the packer interval. The test interval may be located at the end of the hole using a packer system deployed at intervals as the hole is drilled or between two packers once the hole is complete.

Reynolds (1977) describes a program of packer testing and core inspection conducted in two holes, one located above a goaf and one in adjacent ground. Reynolds reports that the height of strata disturbance in K6 drilled from the surface above a 117m wide goaf was clearly evident as heavy fracturing “which must be attributed to mining” within 106m of the mining horizon and there would certainly be hydraulic connection to the workings within this zone.

These results correlate closely with more recent measurements over wider panels, which also show a high level of vertical hydraulic connection within one panel width of the mining horizon.

Holla and Buizen (1991) describe an extensometer monitoring program at Tahmoor Colliery where packer testing was conducted to examine the impact of ground movements on the hydraulic conductivity of the overburden strata.

Similar programs have been run at other sites. The key challenges with this approach relate to the practical limitations of the packer testing equipment for characterising the hydraulic conductivity of highly fractured ground typically observed above longwall panels. The upper bound of the equipment is not sufficient to accurately measure the hydraulic conductivity of open fractures, but it is nevertheless sufficient to show where mining induced fractures have developed.

Micro-Seismic Monitoring

Micro-seismic monitoring provides an indication of areas within the overburden strata where rock failure is occurring about longwall panels. Typically the largest micro-seismic signals are generated during compressive or shear failure of rock strata because of the larger levels of energy released during compressive or shear failure (Gale et al 2001). Tensile failure tends not to release as much energy so the micro-seisms are not as easily detected. Nevertheless, micro-seismic monitoring has been successfully used to monitor the height of ground movement about longwall panels (Kelly et al 1998).

Stress Change Monitoring

The development of the ANZI stresscell (Mills 1997) to the stage where it can be deployed in boreholes to depths ranging from a few metres to in excess of 150m has opened up a capability to monitor three dimensional stress changes within the overburden strata that was not previously possible. The concurrent development of logging systems have allowed these instruments to monitor stress changes at intervals ranging from once every few seconds to twice a day depending on the application with resolutions ranging in strain terms from about 0.005mm/m to 0.05mm/m depending on rock and other environmental conditions.

Stress change monitoring is particularly useful when the ground movements are in the elastic range. For instance, stress change monitoring at the start of a longwall panel provides an indication of the height of ground movement affected by longwall mining as the panel length increases toward square.

SUB-SURFACE GROUND MOVEMENTS

The various zones of ground movement associated with sag subsidence over each individual panel can be identified by synthesising the subsidence data from different sites with a variety of different overburden depth to panel width ratios into a composite overburden section as shown in Figure 4. This composite shows that the ground movements above each panel can be divided into five zones starting at the top:

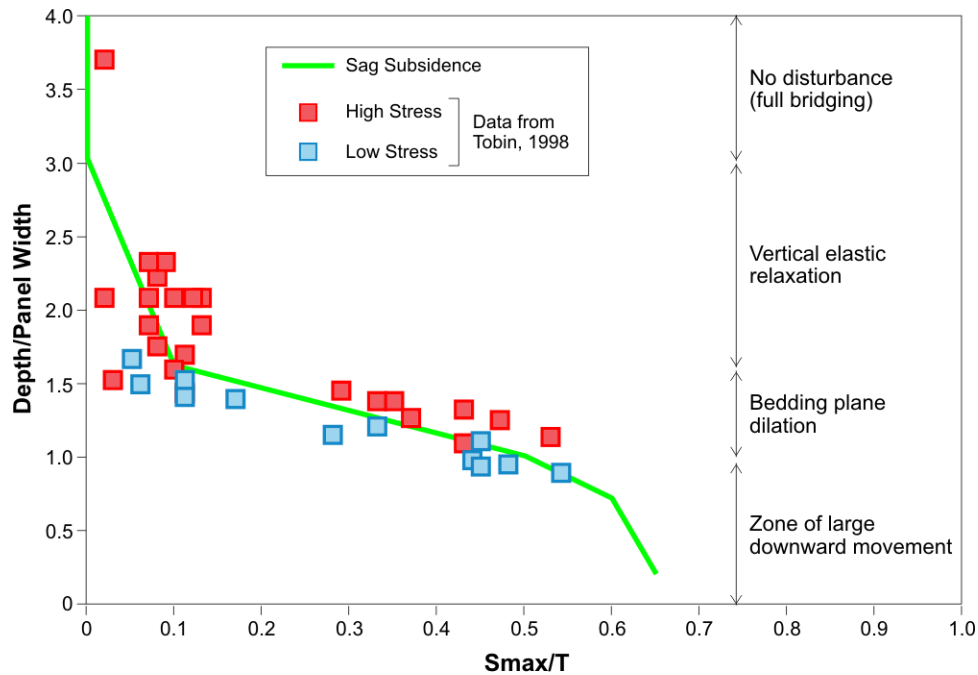
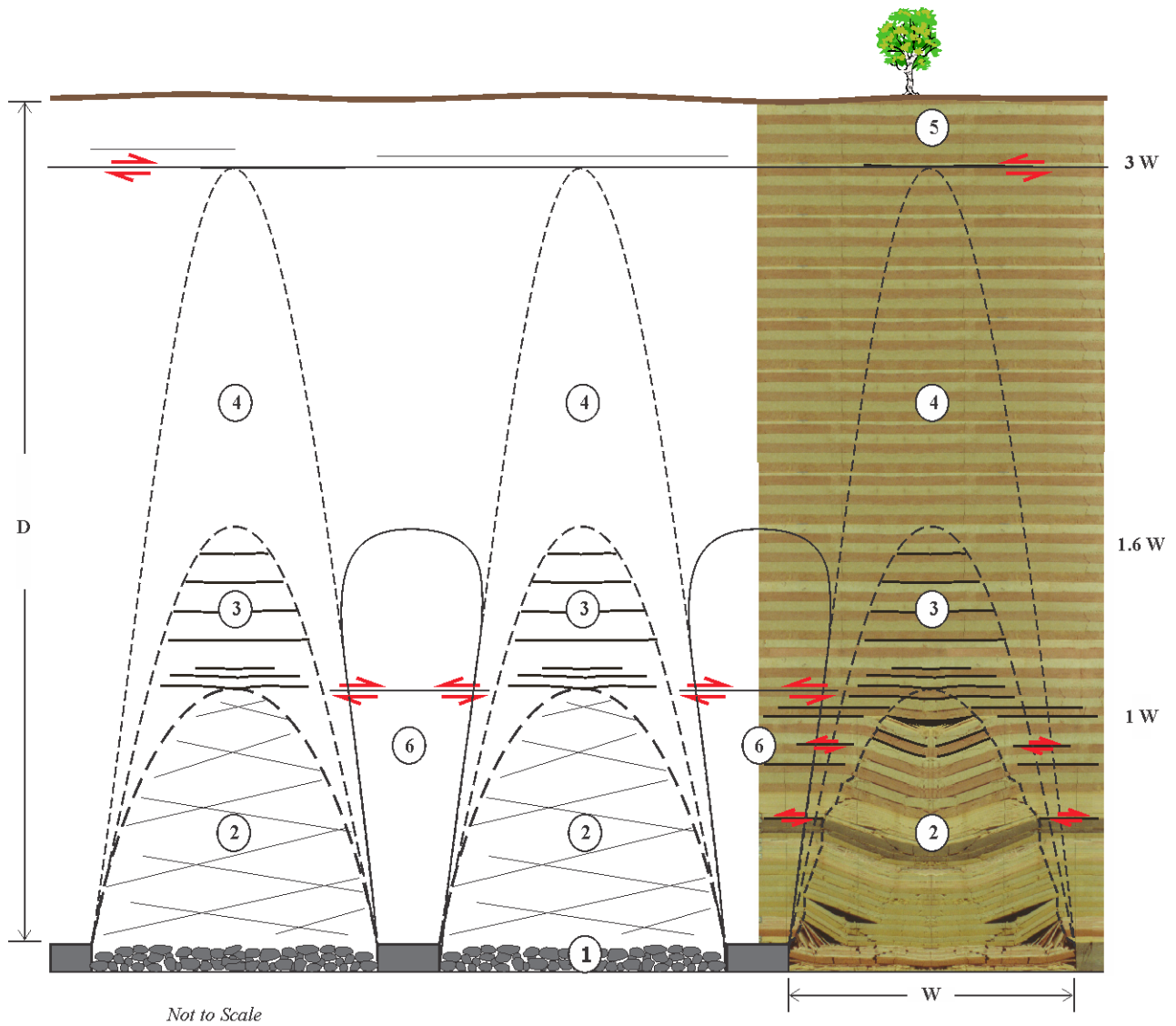


Figure 4: Zones of downward movement within overburden strata implied by sag subsidence data over single longwall panels.

- A zone above 3 times panel width where there is no ground movement.
- A zone of small ground movements from 1.6 to 3 times panel width above the mining horizon.
- A zone of transitional ground movement from about 1.0 to 1.6 times panel width above the mining horizon.
- A zone of large downward movement from seam level to a height above the mining horizon approximately equal to the panel width.
- A fifth zone immediately adjacent to the mining horizon can be added to this list. This zone is not represented in subsidence data because longwall mining does not occur at overburden depths less than 10-20m where this highly disturbed zone occurs.

Figure 5 shows a schematic of the zones of ground displacement above multiple longwall panels inferred from subsidence monitoring and characterised using camera observations, packer testing, piezometer data, micro-seismic data, extensometer monitoring, and stress change monitoring.

Zone 5, the uppermost zone is essentially undisturbed above single panels. However, when multiple longwall panels are mined adjacent to one another at depth, there is typically significant elastic strata compression subsidence. The broad area subsidence associated with elastic strata compression results in differential shearing on bedding planes within this upper zone. The freeing up of these bedding planes contributes to the stress relief movements controlled by topography that tend to be the dominant type of ground movement whenever mining is deep enough for Zone 5 to be present.



LEGEND

- ① Zone of chaotic disturbance immediately above mining horizon (0-20m).
- ② Zone of large downward movement ($\rightarrow 1.0 \times$ panel width).
- ③ Zone of vertical opening of bedding planes ($1.0W - 1.6W$).
- ④ Zone of vertical stress relaxation ($1.6W - 3.0W$).
- ⑤ Zone of no disturbance from sag subsidence ($> 3.0W$) but shear along bedding planes for subsidence of multiple panels.
- ⑥ Zone of compression above chain pillars.

Figure 5: Overburden caving behaviour inferred from surface monitoring and other observations. (Mills 2012)

In Zone 4, between 1.6 and 3 times panel width above the mining horizon, the vertical displacements are consistent in magnitude with elastic relaxation of the pre-mining vertical stresses without the need for physical opening of bedding planes.

Zone 3, between 1.0 and 1.6 times panel width above the mining horizon, is characterised by vertical opening of horizontal bedding planes with horizontal fractures being dominant in fracture logs.

Zone 2, located between the mining horizon and a distance above the mining horizon equal to the panel width is a zone of large downward movement. Zone 2 is characterised by extensive conjugate shear fracturing with numerous open fractures, particularly around the margins of this zone, and numerous inclined fractures throughout.

Extensometer monitoring presented in Mills and O'Grady (1998) indicates that these zones are arch-shaped above each panel, similar to the doming type roadway failures observed in an underground roof fall once all the material has been removed as illustrated in Figure 3.

The height of the zone of large downward movement is higher when the horizontal stresses acting across the panel are higher, similar to the experience of increased height of softening above underground roadways subject to increased horizontal stress.

Surface subsidence is sensitive to the magnitude of horizontal stresses in the overburden strata above the longwall face in much the same way as roadway deformations underground are sensitive to horizontal stress magnitude. This sensitivity of subsidence to stress magnitude can be used to determine the direction of horizontal stress from bias in the subsidence profile in subcritical width panel geometries (Mills et al. 2011).

Greater subsidence is also routinely observed at the start of longwall panels where the maximum subsidence is typically higher than further along the panel because the full horizontal stress acts through the overburden strata at the start of the panel but is partially relieved by the goaf that has formed further along the panel.

In addition to the five zones identified above each longwall panel, there is a sixth zone (Zone 6 in Figure 5) above each of the chain pillars that has distinctly different characteristics to the five zones directly above each longwall panel. Whereas the sag subsidence directly over each panel causes the ground to be fractured in horizontal shear and stretched vertically so that there is an increase in fracture volume within the strata, the elastic strata compression over the chain pillars and around the solid edges of the longwall area cause the strata there to be vertically compressed so that fracture volume and with it hydraulic conductivity are reduced, particularly in a vertical direction.

The interface between the zone of large downward movement and the less disturbed strata above and to the sides of this zone accommodates some relatively large differential movements for rock strata within a short distance. This interface zone is characterised by open shear fractures and fractures between rotated blocks of intact material.

Whittaker and Reddish (1989) present an example of a physical model that illustrates the type of ground disturbance that is observed above a single longwall panels. The results of this physical modelling are presented in Figure 6 as an illustration. The zone of large downward movement (Zone 2) is clearly evident in this model. The shear constraints associated with the

glass side panels in a physical model reduce the height of Zone 2 to less than the full panel width, whereas field observations indicate that the height of Zone 2 is equal to about the panel width in most geological settings. Nevertheless, the level of disturbance illustrated by this model clearly shows that there is likely to be significant disturbance to the overburden strata in Zone 2 with depressurisation of the groundwater system in this zone likely.

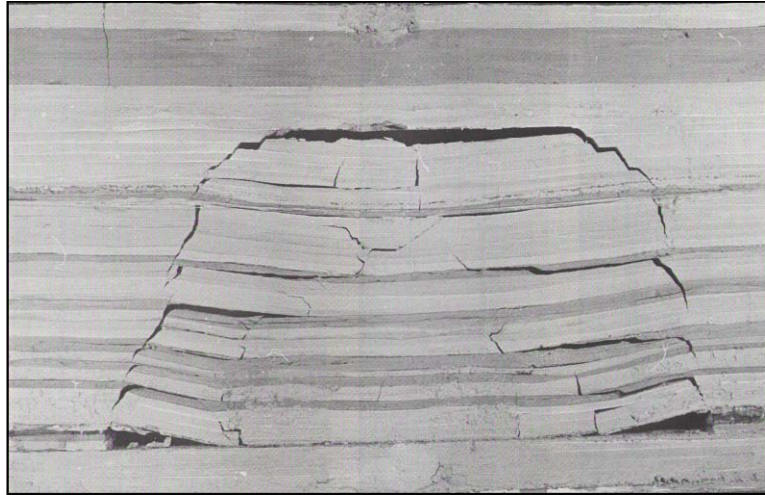


Figure 6: Physical model of overburden caving above single longwall panel (reproduced from Whittaker and Reddish 1989).

Whittaker et al (1985) recognise the influence of vertical subsidence and associated “ground strain” on the level of disturbance within the overburden strata. Figure 7 illustrates the intensity of fracturing indicated with increasing ground strain based on the results presented by Whittaker et al.

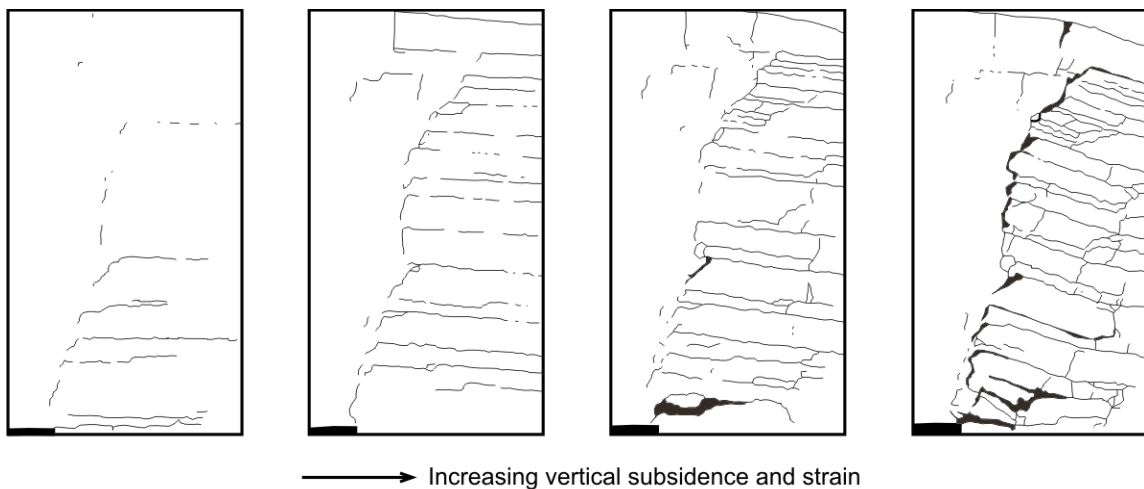
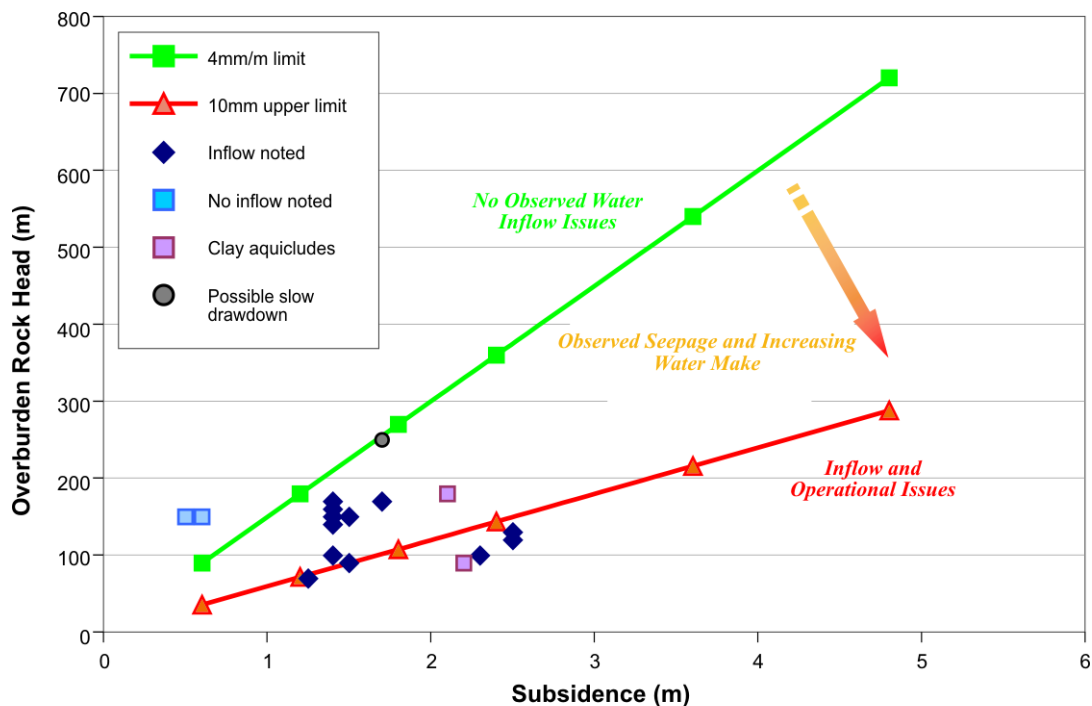


Figure 7: Fracture pattern development over ribside of longwall for progressive magnitudes of extraction height (after Whittaker, Reddish and Fitzpatrick 1985).

Gale (2012) presents a summary of the results of field observations and numerical modelling that correlate inflows into the mine with overburden depth, and vertical subsidence for a range of longwall panel widths typical of Australia mining conditions. Figure 8 shows a summary of the field experience presented. It is recognised that mine inflows are not necessarily equivalent to impact on groundwater more generally, but they do nevertheless provide a measure of the mass hydraulic conductivity in a vertical direction when this hydraulic conductivity becomes sufficiently large to be perceptible within the mine. In the context of mine inflows, Gale concludes that the frequency, networking, and aperture of fractures increases with increasing overburden strain and subsidence.



Above the top of the zone of large downward movement, there is a zone that extends up to about 1.6 times the panel width above the mining horizon. Within this zone, the ground movements primarily involve opening of horizontal bedding planes. The hydraulic conductivity within this zone is likely to preferentially increase hydraulic conductivity in a horizontal direction compared to a vertical direction.

From 1.6 times panel width to about three times panel width above each panel, the mode of deformation primarily involves vertical relaxation or reduction of the vertical stress in the ground without any physical change in the rock strata. Hydraulic conductivity is recognised to reduce with reducing stress, so there is expected to be an increase in hydraulic conductivity in all directions within this zone, but the changes are likely to be small by comparison to those associated with opening of bedding planes and creation of new fractures that occur deeper within the overburden strata.

Between panels there is a zone above and below the chain pillars where the compression stresses increase and hydraulic conductivity is reduced as a result of this compression.

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