A Perspective on the Mechanics of Mine Subsidence Above Longwall Panels

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Summary

This paper presents a perspective on current understanding of the mechanics of overburden caving processes above longwall panels in Australia and the influence of these processes on surface subsidence movements. Experience of monitoring vertical subsidence, horizontal ground movements, sub-surface ground movements, and groundwater interactions is reviewed to explore the mechanics of the underlying processes that contribute to the ground movements observed on the surface as subsidence. Part of this perspective involves reflecting on the journey to gain this understanding, the culture we are fortunate to enjoy in NSW, and the people who have pioneered the transition of subsidence engineering from art to science.

Key to the progress of understanding subsidence mechanics is the development of measurement tools and the confidence to deploy them. Five decades ago, the measurement of subsidence movements relied on levelling and peg to peg distance measurement as the only practical methods available for routine monitoring. Now we have available state-of-the-art systems for surface surveying, sub-surface monitoring, prediction of ground movement and management of subsidence impacts. These systems are underpinned by comprehensive and ever-growing databases of subsidence monitoring experience and a legislative framework that supports the development of understanding.

1. Introduction

The close proximity of NSW coal resources to areas of urban development has meant that mining-related subsidence impacts inevitably become a source of conflict between the underground coal mining industry and the community. Subsidence events in the Newcastle area between 1896 and 1925 (Baker and Ditton, 2022) are an early example of this type of conflict. Following a series of such events, a legislative framework called the Mine Subsidence Act (1928) was set up as a community-based insurance scheme funded by residents (Wilson, 1973). A more equitable scheme called the Mine Subsidence Compensation Act (1963) created an insurance scheme funded by mining companies. This fund was administered by NSW Mine Subsidence Board (MSB) and more recently its successor Subsidence Advisory NSW (SANSW). This support for the community is not enjoyed by communities in other states of Australia.

The ongoing interactions between mining subsidence and communities in NSW has led to an ongoing focus on monitoring subsidence behaviour for better predictions and better management of subsidence impacts.

This focus was initially directed only at impacts to built features and mining operations but has evolved to include impacts to natural features such as stored waters, cliffs, rivers, upland swamps and groundwater systems.

To manage subsidence impacts to built features, government regulators and mining companies initially relied on expertise and monitoring systems developed overseas, principally in the United Kingdom, the USA and South Africa. In 1973, the AusIMM held a conference "Subsidence in Mines" in Wollongong. In his opening address, Professor Gray noted that to his knowledge, that conference was the first time that a conference on subsidence had been held in Australia. The conference was attended by experts in subsidence from the UK, USA, France, Germany, India, Japan together with Australia's first expert in subsidence, W.A. Kapp.

To manage subsidence impacts to natural features has required understanding of the mechanics of overburden caving behaviour. This understanding has been acquired locally within Australia from the bottom up. By understanding the component mechanisms that contribute to the ground movements seen on the surface as subsidence, it becomes possible to more reliability predict the scale of impacts to natural features, develop appropriate and effective mitigation and remediation options, and develop appropriate monitoring and management systems. This process has enabled understanding of overburden caving behaviour with implications well beyond simply managing subsidence impacts.

However, such understanding develops gradually and takes time to gain widespread acceptance. The Reynold's Inquiry into "Coal Mining under Stored Waters" is an early example of how understanding from field measurements that confirm the nature and extent of mining impacts on the overburden strata has been slow to be accepted. These results and understanding were available in 1977 but are still not widely accepted or included in many contemporary models of overburden caving and groundwater behaviour.

A figure presented by Orchard (1973) reproduced here as Figure 1 shows the nature of deformations expected above a longwall panel inferred from subsidence and confirmed by extensometers monitoring of 64 anchors at 8 horizons (Dowdell, 1968). It is interesting that more than 50 years later there is still debate above the nature of ground movements above longwall panels.

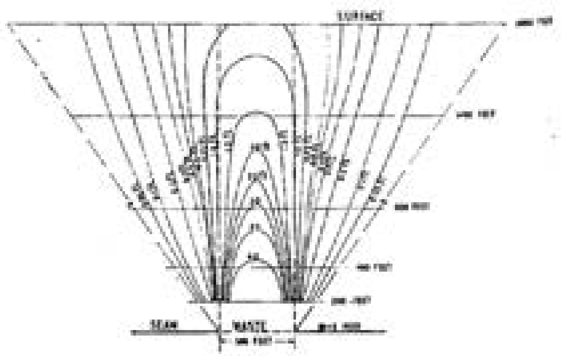


Figure 1 Overburden movements interpreted from observations of subsidence (after Orchard 1973).

It is clear that our subsidence engineering community must be vigilant to avoid past knowledge being eroded and lost. This paper attempts to capture the state of current understanding as it is in 2022.

Inevitably, a keynote review of current understanding involves presenting work that has been presented previously. This review is no different. The structure of the paper and some of material presented are drawn Mills and Barbato (2020) and Mills (2012) to inform a different audience. The interested reader is referred to these earlier works for more detail.

The paper is structured as four sections looking at vertical subsidence, horizontal ground movements, overburden caving behaviour and groundwater interactions. An overview of the mechanics is provided together with examples of key studies that illustrate the capability that now exists to monitor, model and manage subsidence impacts.

The understanding presented in this paper is a tribute to the many pioneers who have challenged the accepted understanding and looked deeper and in so doing have propelled the discipline of subsidence engineering from an art to a science.

2. Vertical Subsidence

This section describes the key developments in conventional subsidence monitoring and how they have guided improvements in understanding subsidence impacts to natural features.

Vertical subsidence movements above coal mining operations have been observed and quantified for almost two centuries (Whittaker and Reddish, 1989), primarily because vertical movements could be readily measured using levelling techniques available throughout this period. Initial subsidence monitoring practices in Australia were imported from overseas and principally from the United Kingdom (UK).

Vertical subsidence is measured by repeatedly levelling a line of pegs spaced at intervals across the surface and using the differences measured over time to determine subsidence movements. Ground tilt and curvature are determined as the differential and double differential of subsidence. Horizontal strains are measured by chaining between pegs.

Holla (1985, 1988, 1991) presents summaries of characteristic subsidence behaviour for the Southern, Newcastle and Western coalfields based on this system of measurement. Holla confirmed experience from overseas that shows conventional subsidence parameters including maximum subsidence, maximum tilt, and maximum strain are readily predicted from simple linear relationships based on seam thickness, panel width and overburden depth. These relationships are still widely used today for the prediction of subsidence parameters.

Waddington and Kay (1995) describe a method known as the incremental profile method to predict subsidence and subsidence parameters. They found repeatable patterns in the increment of subsidence observed when each successive longwall panel is mined. With suitable allowances for panel plus chain pillar width and overburden depth, the increments are able to be reconstructed as a predictive tool to reliably generate subsidence profiles for new mining geometries. The success of the incremental profile method as a predictive tool attests to the consistent, repeatable nature of vertical subsidence processes across a broad range of geological settings.

The variable nature of impacts to the overburden strata from longwall mining is more easily understood when the mechanism generating subsidence are able to be separated. Mills (1998) describes four separate processes recognised to cause vertical subsidence:

- sag subsidence over individual panels
- compression of the chain pillars and the strata above and below the chain pillars
- failure of pillar systems including failure of the immediate roof and floor strata
- unconventional subsidence effects.

These separate processes are discussed in the following sections.

2.1 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 2.

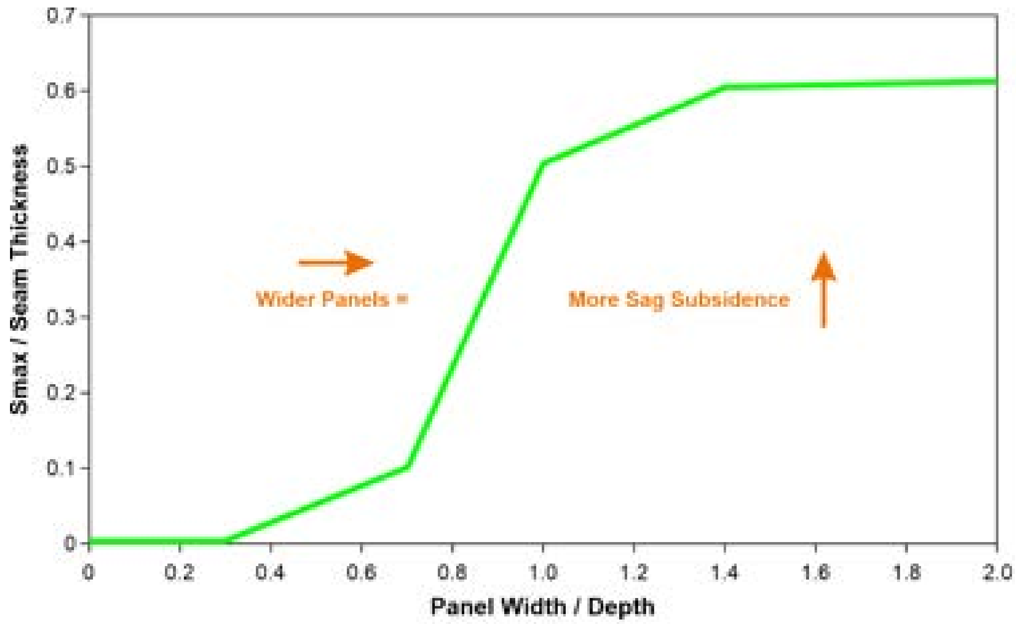


Figure 2 Sag subsidence plotted conventionally as the ratio of maximum subsidence divided by seam thickness plotted against panel width to depth ratio.

This relationship is observed to be similar across many different geological settings with few exceptions. Combining subsidence results from a wide variety of sites and overburden depths provides insight into ground movements within the overburden strata above individual longwall panels.

The relationship is characterised as comprising four zones:

- When the panel width is less than approximately 0.3 times depth, surface subsidence is effectively zero.

- When the ratio of panel width to overburden depth ratio increases from 0.3 to 0.7, maximum subsidence above the centre of the panel increases linearly from 0 to 0.1 times the mining height (sometimes represented as seam thickness).

- When the panel width to overburden depth ratio increases from 0.6-0.7 to 1.0-1.2, maximum subsidence increases from 0.1 to typically 0.5-0.65 times mining height and in some environments more. The term critical width is applied to panels with a width generally in the range 1.0-1.2 times overburden depth but frequently greater.

- When the panel width to depth ratio is greater than critical width, panels are referred to as being of supercritical width and maximum subsidence in the centre of the panel remains constant at a maximum typically in the range 0.5-0.65 times mining height but in some environments higher.

This presentation was used by the National Coal Board (NCB) in the UK and has been widely used to summarise the characteristics of subsidence behaviour in Australia. Li et al. (2020) find that the maximum subsidence and maximum subsidence parameters are best defined for multiple longwall panels using the single panel width over depth ratio. This correlation confirms the expectation that the sag subsidence over individual panels gives rise to the highest values of subsidence, tilt, curvature and strain compared to the gentler subsidence across multiple panels.

This diagram sometimes causes confusion and misunderstanding. In some forms of the presentation, the maximum subsidence presented as a ratio of seam thickness on the vertical axis is the maximum subsidence over multiple panels of the same width rather than just the single panel implied. The presentation then gives the impression that high levels of subsidence can occur over a single narrow panel at depth. In practice, sag subsidence does not occur over a single panel until the panel width to depth ratio exceeds about 0.3 and only becomes substantial at a panel width to depth ratio of greater than about 0.7.

Figure 3 shows a more intuitive and informative way to present the same data. The axes are swapped and the panel width to depth ratio is inverted to be a depth on panel width ratio. Presentation of the data in this format provides insight into the caving mechanics above individual longwall panels. The four zones are apparent as:

- a zone of no subsidence at a height above the mining horizon of more than 3 times the panel width
- a zone of slowly increasing downward movement between 1.6 to 3 times panel width above the mining horizon
- a zone of rapidly increasing downward movement from 1 to 1.6 times panel width
- a zone of maximum downward movement from 0 to 1 times panel width above the mining horizon.

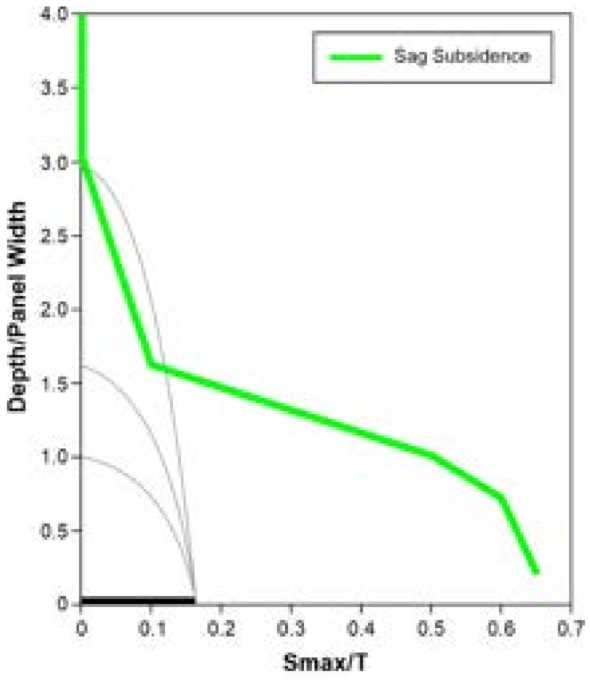


Figure 3 Subsidence experience shown in Figure 2 replotted with axes reversed and panel width to depth ratio inverted (after Mills 2012).

There is a zone of maximum subsidence or downward movement that occurs between the mining horizon and a height above the mining horizon equal to panel width. Above this horizon, there are two other zones where downward movement decreases with height above the mining horizon.

Subsidence data presented by Tobin (1998) from the Newcastle area provides further insight into caving processes when presented in this format (Mills, 2012). Tobin observed that even though the geological setting is similar for all the panels for which subsidence data is available, panels oriented in a north-northeast (NNE) orientation generated less subsidence than panels oriented in a northwest (NW) orientation. In the Newcastle area, the major horizontal stress is known to be oriented in a northeast direction. The axis of the NNE oriented panels is parallel to the major horizontal stress so only the minor horizontal stress is acting across the panel. In the NW oriented panels, the major horizontal stress is acting across the panel.

Figure 4 shows the subsidence data for the two data sets plotted in the format of Figure 3. Greater downward movement is evident in the NW oriented panels where the horizontal stresses acting across the panel are greater. These observations indicate the processes causing subsidence are rock failure processes that are influenced by the magnitude of the horizontal stresses acting within the overburden strata.

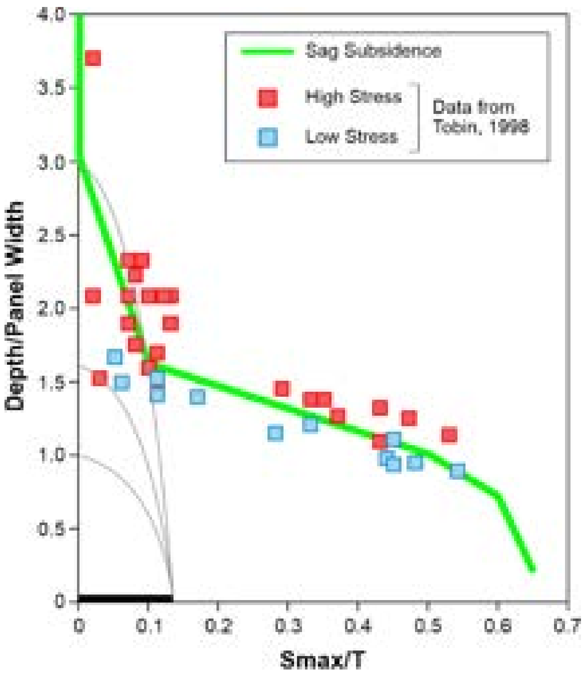


Figure 4 Subsidence from longwall panels in the Newcastle area oriented across and parallel to the major horizontal stress (after Mills 2012).

Similar behaviour is observed in underground roadways. Gale (1986) describes greater deformations in the failed roof strata of underground roadways when the roadways are aligned perpendicular to the major horizontal stress. The biased deformation patterns in the roof of underground roadways are commonly used to determine the direction of the major in-situ horizontal stress.

Mills et al. (2011) shows how the bias in subsidence data across individual panels is routinely used at Ulan Coal Mine to characterise the direction of the major horizontal stress across the site. This information has been helpful to forecast geological structures that adversely impact underground mining conditions. These structures are observed to elevate the magnitude of the secondary principal stress to be greater than the background major principal stress. This reversal in the stress direction is apparent in the subsidence profiles.

2.2 Strata Compression

Holla (1992) recognised the influence of chain pillar compression in the subsidence profile and showed how this compression is related to strata compression caused by the side abutment loading from two adjacent extracted longwall panels. The chain pillars are compressed slightly by the additional loading, but they also concentrate load in the roof and floor strata where most of the compression movements occur. Lambe and Whitman (1969) show that the vertical stress below a strip loading, such as chain pillars, is still 20% of the strip load at a distance below the strip load of three times the strip load width. In other words, the stress in the chain pillars creates a stress increase for a considerable distance into the floor. By implication, a similar distribution of load occurs into the roof. The additional load on the strata causes cumulative compression that is expressed at the surface above the chain pillar as subsidence.

Mills (1998) explained the strata compression for chain pillar widths used in contemporary mine designs as being entirely elastic in nature. However, advances in numerical modelling discussed in Heritage (2017) and recent field monitoring experience show that non-elastic deformation of the strata above the chain pillars can also contribute significantly to surface subsidence above chain pillars.

At overburden depths of 100m, strata compression is typically less than 50 mm because the loads concentrated onto the chain pillars are small. At overburden depths of 200-300m, deformations above chain pillars are commonly in the range 200-500mm. At overburden depths of 400-500m, strata compression subsidence can lead to subsidence above the chain pillars in the range 700-1200mm.

Subsidence movements above the chain pillar involve a vertical compression process whereby the strata is compressed. This strata compression is opposite to the vertical stretching behaviour directly above each longwall panel observed as sag subsidence. This change from compression to stretching behaviour is significant in the context of various strata failure mechanisms and groundwater impacts.

2.3 Pillar System Failure

Historically, the failure and subsequent collapse, or creep, of panels of standing pillars was a common source of subsidence. Longwall mining does not commonly create pillar geometries subject to this type of failure and so surface subsidence caused by pillar collapse is less common. Figure 5 shows subsidence monitoring data from six longwall panels at Kemira Colliery presented in Kapp (1973). This subsidence profile shows the effect of chain pillar failure when the pillars are small and strata compression when they are larger.

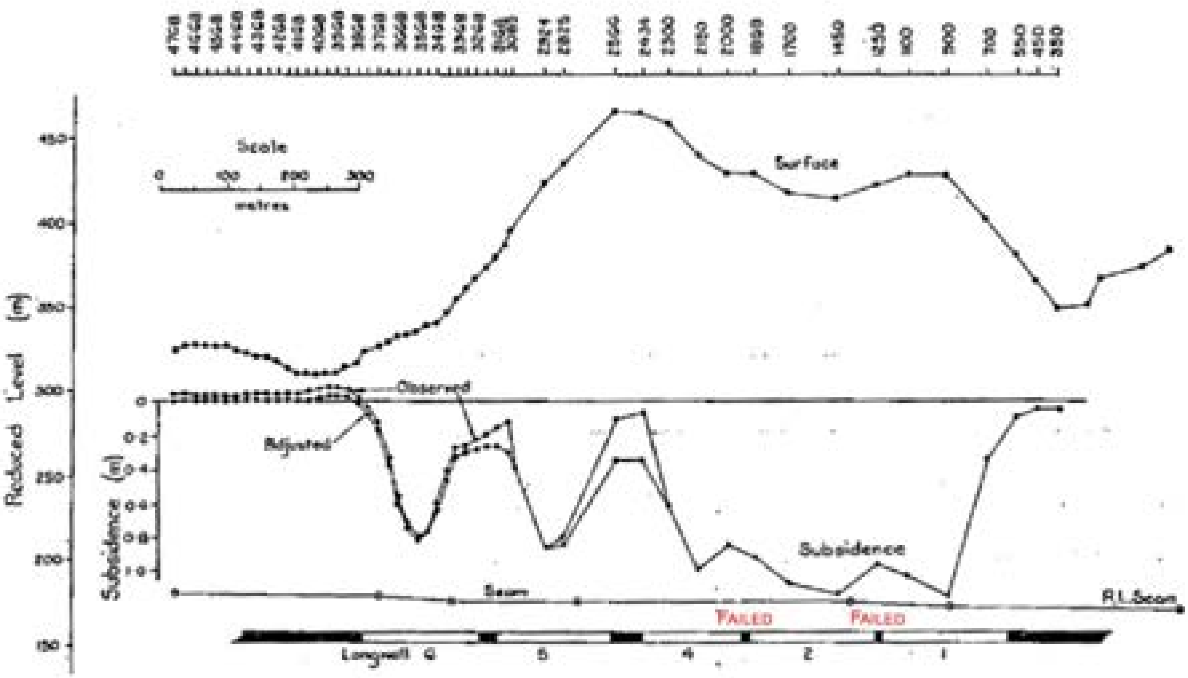


Figure 5 Subsidence profile from Kemira Colliery showing the influence of failed chain pillars on the subsidence profile (after Kapp 1973).

Other examples of pillar failure in longwall operations tend to occur in geological settings where low strength bedding planes are present in the roof and floor strata. These types of failure are most common in large development panels of similar sized pillars such as main headings. They are an issue that needs to be considered in the design of such pillars but are not of particular interest in a subsidence context.

2.4 Unconventional Subsidence

Kapp (1973, 1980) identified horizontal strain concentrations at topographic low points and upward movement in these areas relative to the surrounding strata. The horizontal movement has come to be known as valley closure and the upward movement as upsidence. Shear movements on bedding planes are infrequently observed at the surface as ripples and overrides. These features lead to unconventional subsidence that is typically difficult to predict in advance. These unconventional effects are usually a consequence of horizontal movements and are discussed in Section 3.

2.5 Combinations of Vertical Subsidence Components

Figure 6 shows an example of how the combination of strata compression subsidence and sag subsidence combine to give the subsidence profile observed at the surface. In this example, the overburden depth is effectively uniform at approximately 400m. The sag subsidence above individual panels is a function of the panel width. Three of the panels are 158m wide and four are 185m wide. The strata compression subsidence is inferred as the difference between sag subsidence over individual panels and the final subsidence profile. Strata compression subsidence is effectively uniform and a function of the geometry of the 45m wide centre to centre chain pillars between all the extracted panels.

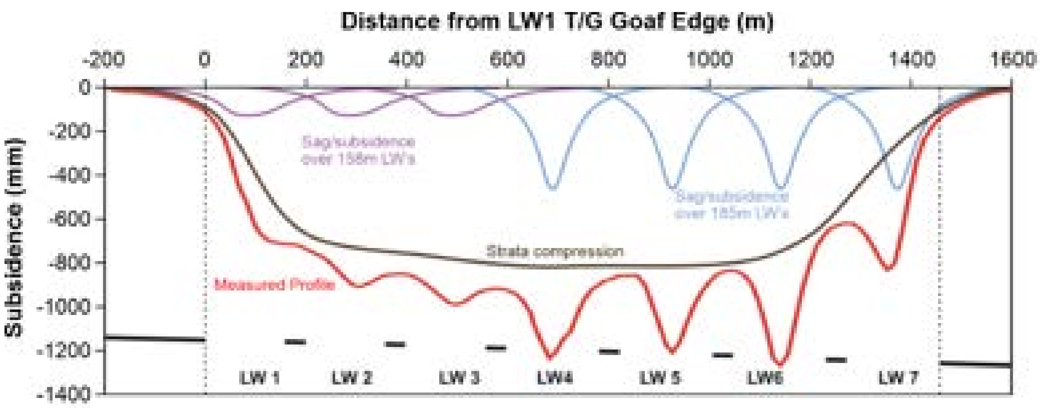


Figure 6 Sag and strata compression subsidence components of the measured subsidence profile.

3. Horizontal Movements

Understanding of the mechanics of horizontal subsidence movements has tended to lag behind the understanding of vertical subsidence movements. The monitoring systems used to measure subsidence and reporting protocols for subsidence were, and still tend to be, focused on parameters of relevance to built features. These parameters, vertical subsidence, its derivatives tilt and curvature and horizontal strain in the direction of the subsidence line are less helpful in the context of impacts to natural features.

One of the primary reasons for this lag in understanding relates to the systems available to measure horizontal movements. For most of the last century routine measurement of horizontal subsidence movements were based on measurement of peg-to-peg distance along subsidence lines and converting changes in this distance to strain (change in length over length). Precise surveying tended to be limited to high value structures such as dam structures (Reid 1998, 2001). Routine peg-to-peg chaining used for subsidence monitoring does not measure or even allow for the existence of horizontal movement perpendicular to the line. The absence of this information limits the understanding that can be derived from the measurements in relation to horizontal movement.

Measuring both components of horizontal movement became practical once total station survey instruments became widely used for subsidence monitoring in the 1990s. When GPS, now GNSS, survey systems became widely used for survey control of subsidence measurements from about 2000, three-dimensional subsidence movements including the effects of far-field movements became available. In the last decade, dedicated stand-alone GNSS units have become available to monitor the location of fixed points in three dimensions and relay this information in near-real-time through the internet (Nicholson, 2022).

This section describes the mechanics of the three independent components recognised to contribute to horizontal subsidence movements above longwall panels. These three components are referred to as systematic horizontal movements, stress relief movements, and horizontal movements in a downslope direction (Mills, 2014).

3.1 Systematic Horizontal Subsidence Movements

Systematic horizontal movements refer to horizontal movements associated with sag subsidence above individual panels and trough subsidence above multiple panels. These movements involve a change of direction soon after the longwall face has passed. The magnitude of systematic horizontal movements is typically in the range 100-200mm.

Systematic horizontal subsidence movements are most readily observed in flat terrain and low horizontal stress conditions when the other two processes that cause horizontal movements are not present.

Figure 7 illustrates the horizontal movements typically observed above a single retreating longwall panel in flat terrain. Initial movements are in a direction toward the active mining area from all sides. The magnitude of this initial movement is typically of the order of 10% of the eventual vertical subsidence; 100-150mm of initial movement is typical for subsidence of 1-1.5m.

When the vertical subsidence has reached about half of its maximum, typically some 0.3 times depth after the longwall face has passed, there is a change in direction so that subsequent horizontal movements occur in a direction toward the retreating longwall face. Above the central part of the longwall panel, this change causes a complete reversal in direction. The magnitude of the subsequent movement is typically larger than the initial movement so that there is a permanent offset in the direction of mining. In other places around the panel, the change in direction is more subdued. At the start of the panel, both the initial movement and the subsequent movement are in the same direction so the two are additive. Systematic horizontal movements are therefore typically greatest at the start of a panel. At the finishing end of the panel, only the initial movement occurs. The subsequent movement does not eventuate because the longwall does not continue past the finishing line.

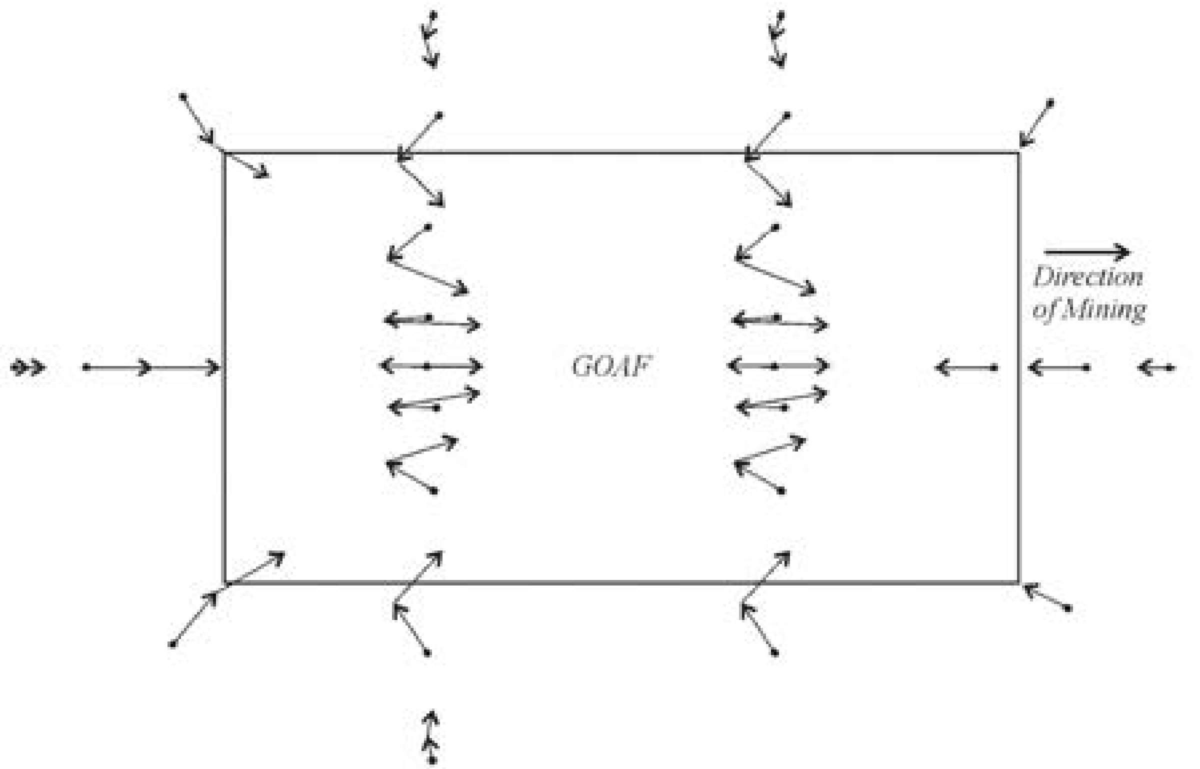


Figure 7 Systematic horizontal movements around an extracted longwall panel in flat terrain (after Mills 2001).

Systematic horizontal movements over the finishing rib of the panel tend to have lower magnitude than elsewhere around the panel edge.

Barbato et al. (2017) present a methodology for estimating the magnitudes of these movements and generating the magnitude of the horizontal strains that these movements generate.

3.2 Horizontal Stress Relief Movements

Horizontal stress relief movements are associated with release of horizontal tectonic stresses within the overburden strata as the overburden strata moves to re-establish equilibrium with the far-field in-situ stresses. The magnitude of these movements is typically less than 200-300 mm at the goaf edge tapering to zero with distance from the goaf edge. Stress relief movements are observed to increase with the depth of mining. At 100m overburden depth, stress relief movements are typically not discernible from normal systematic subsidence. At 500m deep, stress relief movements are still perceptible up to 3km from the edge of the active panel for longwall mining.

Horizontal tectonic stresses within the overburden strata store considerable energy as evidenced by the damage caused when these stresses are released suddenly during earthquake events. The rock strata overlying the longwall panel fails in horizontal compression as part of the mining process. The reduced horizontal stresses able to be carried by the failed strata create a force imbalance in the overburden strata. Horizontal movement occurs toward the extracted longwall until equilibrium with the in-situ stress is re-established. The far-field in-situ stresses are eventually balanced when enough cumulative resistance is generated by residual shear stresses acting on horizontal shear planes at, or near, the mining horizon.

Figure 8 shows the mechanics of the process that generates the far-field horizontal movements associated with stress relief.

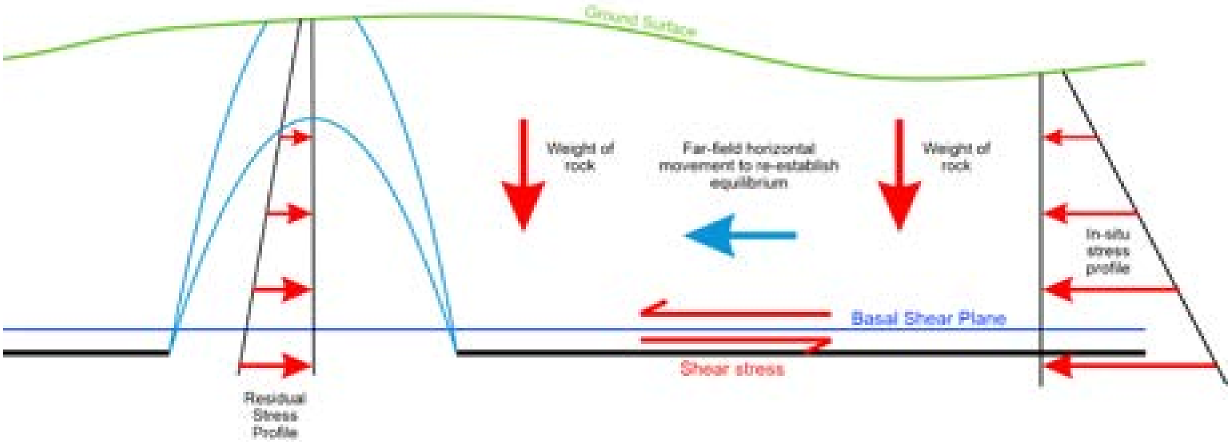


Figure 8 Mechanics of process that causes far-field horizontal movements associated with stress relief.

Reid (1998, 2001) reports on first order surveys conducted in the Southern Coalfield of NSW by the DSC showing perceptible horizontal movements up to about 1.5km from active mining. The direction of movement observed is predominantly northeast-southwest consistent with the horizontal stress direction in this area.

Pells (2011) presents the results of far-field horizontal subsidence monitoring from Appin West Colliery in NSW. A simple elastic model is shown to be capable of explaining the far-field movements. These movements have a magnitude at the goaf edge of about 200mm and are detectable using a well-controlled survey network for several kilometres outside the mining area.

Far-field horizontal movements observed at Ulan Coal Mine (Mills et al., 2011) and elsewhere indicate that initial stress relief occurs suddenly during mining of the first panel or panels in a new area as one or more discrete events. The sudden release of energy has been observed at other mines as a significant seismic event. Strong shaking, gas outbursts and sudden roadway deformation have been correlated with first-time stress relief events in new mining areas.

Once the first stress relief event has occurred, the increments of horizontal stress relief horizontal movements over subsequent panels are observed to have the same magnitude and form (UCM, 2016). This finding implies the residual shear strength of bedding planes at or near the mining horizon are uniform across large areas. An interesting consequence of horizontal stress relief movements is that faults, monoclines, and other similar structures disturbing the process of uniform movement become sites where strain energy is concentrated. Very difficult mining conditions are commonly observed in these areas.

The magnitude and extent of far-field horizontal movements are observed to decrease significantly with overburden depth. At shallow depth, the horizontal in-situ stresses have lower magnitude and equilibrium of the failed strata over the extracted longwall panels is able to be established with less movement. At overburden depths of less than 100 m, far-field movements are typically not discernible from systematic horizontal movements.

3.3 Horizontal Movement Due to Strata Dilation

In sloping terrain, a component of horizontal movement caused by subsidence is commonly observed to occur in a downslope direction. This movement is referred to here as dilational, downslope or valley closure movement. Dilational movement can be much larger than either systematic or stress relief movement ranging up to the magnitude of vertical subsidence in steep terrain and usually less than about 0.3-0.5 times the vertical subsidence in moderately sloping terrain. Occasionally, dilational movements are observed to occur in an upslope direction when the coal seam dips relative to the ground surface.

The effects of topography are widely recognised to modify subsidence behaviour although the mechanics of the processes have only recently become apparent.

3.3.1 Historical Observations

Kapp (1973, 1980) reported high compressive strains at topographic low points in NSW consistent with valley closure. Holla and Barclay (2000) note similar experience in the USA reported by Gentry and Abel (1978) and Ewy and Wood (1984). Holla and Barclay observe that given the varying geological settings, the occurrence of large ground strains and reduced vertical subsidence in topographic low points appears to be due to forces generated by topography rather than being a unique characteristic of the geological setting.

Holla (1997) describes the results of horizontal movements in steep terrain in NSW based on levelling and peg to peg strain measurements. Holla recognised the effect of horizontal movements but with only having strain measurements in one direction, the mechanics were difficult to discern.

Kay (1991) presents the results of a program of three-dimensional surveying at Baal Bone Colliery. This work involved measurements of horizontal movements in steep terrain. These measurements and other conducted subsequently at the colliery (Mills, 2001) show that horizontal movements in steep terrain exhibit a component of ground movement toward the valley (i.e., in a downslope direction).

Hebblewhite et al. (2000) report on horizontal ground movements around the Cataract and Nepean Gorges at Tower Colliery in the Southern Coalfield. These movements are aligned with movement toward the free surface of the Nepean Gorge. Seedsman and Watson (2001) illustrated this topographic effect at Newstan Colliery in the Newcastle Coalfield by removing systematic horizontal movements calculated for flat terrain from the measured subsidence vectors in an area where a topographic ridge had been mined under. The resulting vectors showed that the residual movement not associated with systematic subsidence occurred as movements in a downslope direction off both sides of the ridge sympathetic with the topography.

Waddington and Kay (2004) present a handbook reviewing the experience of mining under cliffs and river channels. The effect of valley closure is recognised in this work and an empirical method for predicting an upper bound magnitude is presented. This method remains a primary method for estimating the magnitude of valley closure in NSW and is widely used. Improvements to this methodology are expected to be able to capture some of the nuances of ground movements around longwall panels.

Mills and Huuskes (2004) present the results of monitoring valley closure impacts at two rockbars on Waratah Rivulet. These and other observations are included in ACARP (2009).

3.3.2 Mechanism

The mechanism for horizontal movements in a downslope direction relates to the dilation that occurs in incrementally subsiding strata. The incremental caving progress associated with longwall mining leads to inclined fractures within the overburden strata being created above the longwall face and above the sides of the panel. These fractures occupy volume that was not present prior to mining. The increased volume of the fractures leads to an increase in volume or dilation of the overburden strata. The immense energy released by the subsiding rock strata provides the energy to drive this dilation.

In flat terrain, strata dilation is resisted by the intact strata on either side of the longwall panel and the only pathway to accommodate the dilation is bulking up of the subsiding strata and reduced vertical subsidence. Long-panel subsidence profiles commonly show there is more subsidence at the starting end of the panel than in areas where caving is fully developed. The larger subsidence at the start of the panel occurs because strata dilation occurs mainly on horizontal bedding planes during the early stages of mining and is more recoverable. Once the caving process fully develops so that fractures form incrementally off the longwall face, dilation becomes less recoverable, and vertical subsidence is less as a result.

In sloping terrain, the same strata dilation occurs during the caving process, but now there is a less energy intensive way for the strata dilation to be accommodated. Instead of the dilating strata pushing upward toward the surface and reducing subsidence, the dilating strata can more easily push sideways toward the free surface of the valley causing the ground to move sideways toward that free surface. The direction of movement that requires the least energy to accommodate strata dilation in sloping terrain is typically in a downslope direction.

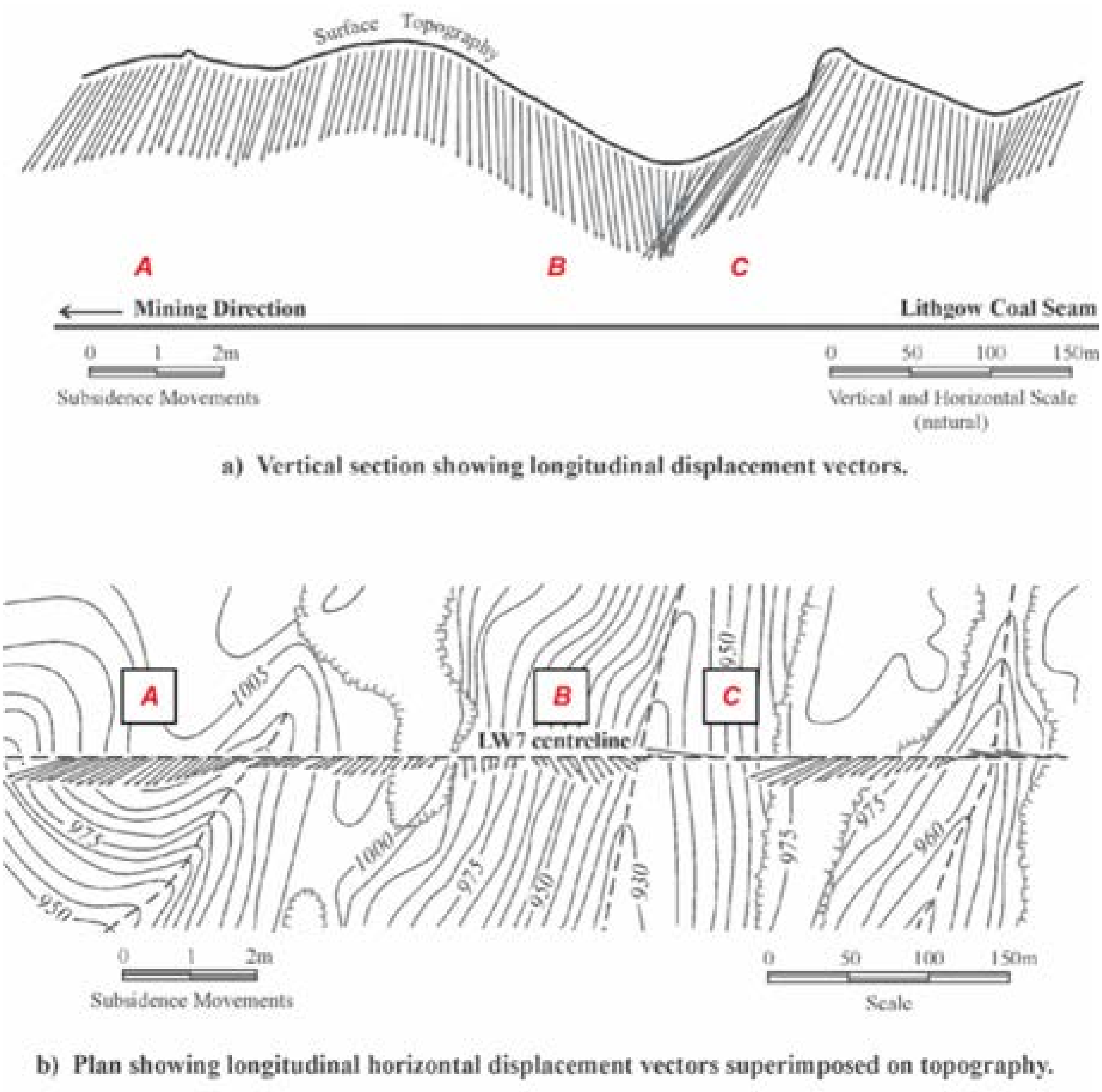
There are circumstances, such as at Ashton Underground Mine in the Hunter Valley described in Mills and Wilson (2022), where the strata dips more quickly than the topography and strata dilation is accommodated as up-slope movement. At Ashton this up-slope movement has reached 1.4m for 5m of cumulative subsidence. The energy involved in moving 250×10^6 m^3 of rock some 1.4m up a 1 in 10 slope attests to the scale of the dilational energy available. However, even this huge dilational energy is small by comparison to the potential energy ultimately driving the subsidence, the weight of 250×10^6 m^3 of rock moving 5m vertically down.

Valley closure is the result of dilation of strata under the sides of a valley concentrating as closure at the base of a valley. Valley closure occurs when mining occurs below one or both sides of a valley. As soon as mining begins below a slope leading to a valley, there is potential for valley closure to begin. All the dilating strata below the valley side is available to push the valley sides outward in the direction of least resistance. Consideration of the valley geometry relative to the mining geometry allows the direction of greatest closure to be determined.

3.3.3 Dilational Effect in Three Dimensions

Figure 9 shows the horizontal movements measured in section at natural scale and in plan above Longwall 7 at Baal Bone Colliery. The subsidence line was surveyed in three dimensions before and after mining. The displacement vectors shown are exaggerated in magnitude but are drawn at natural scale so that both the vertical and horizontal components are at the same scale. The overburden depth ranges from 100m in the valley to 175m on the ridge tops. The longwall panels create a mined area that is 211m wide. The seam section mined is approximately 2.5m thick.

These measurements show that there is a general tendency for horizontal movement in the direction of mining as in flat terrain. Superimposed on this general tendency is a downslope component that responds to surface topography. However, the dilation movements are not uniquely related to slope. There is another process at play.



a) Vertical section showing longitudinal displacement vectors.

b) Plan showing longitudinal horizontal displacement vectors superimposed on topography.

Figure 9 Horizontal movements caused by strata dilation in sloping terrain (after Mills 2001).

In the area where the direction of mining and the slope coincide (C), the horizontal movements occur directly downslope and are large, as large as the vertical subsidence in this case. In areas where there is a cross-slope (A), there is a component of horizontal movement in the direction of this cross-slope. In areas where the slope is opposite to the direction of mining (B), there is still some downslope movement, but the absolute magnitude is significantly lower that it was on the opposite side at C.

Strata dilation is recognised to be sensitive to confining pressure with greater dilation observed when the confinement is less. This phenomenon contributes to the different horizontal movement observed in Figure 9 on either side of the valley.

In the stretching phase of the systematic subsidence cycle that occurs ahead of and immediately behind the longwall face, confinement is reduced and so the potential for strata dilation is greater than during the compression phase of the systematic cycle that occurs subsequently over the subsiding panel. As mining approaches the valley from under the hill, the slope is being stretched at the same time as the hillside is subsiding and strata is dilating laterally so horizontal movements are large.

As mining proceeds from the valley toward the hill (B), there is no dilatant lateral push to cause downslope movement when the slope is being stretched in the systematic subsidence cycle. By the time dilation occurs below the hill, the slope is in the compressive phase of the systematic subsidence cycle and dilation is suppressed. The horizontal movements are then much less.

Three hourly subsidence monitoring of an array of pegs located on a slope above a longwall at a depth of 40m confirms that the downslope movement occurs during the initial stretching phase of the systematic subsidence cycle (Mills, 2001). There is no significant downslope movement evident during the compression phase of this cycle.

Mills (2001) shows how horizontal movement in a downslope direction is observed in areas where the in situ horizontal stresses have been measured and the magnitude is small and insufficient to give rise to the magnitude of movements observed. These observations confirm that dilational movements are not caused by pre-existing in situ stresses. The magnitude of dilational movements is much larger than the very small movements caused by stress changes in the elastic range.

3.3.4 Case Study at Sandy Creek Waterfall

The observation of valley closure implies that there is a basal shear plane to accommodate the displacement discontinuity that must exist above and below the base of the valley. Mills (2014) describes multiple observations that support the presence of such shear planes. Monitoring conducted at Sandy Creek Waterfall (Walsh et al., 2014) provides an example of the definitive confirmation of these horizontal shear horizons and mining induced subsidence movement localised onto these planes.

The bed of Sandy Creek drops about 30m in elevation at a waterfall. When horizontal closure movements were first detected on inclinometers distributed across the site up to 350m from the creek, they were localised onto two horizons that corresponded in elevation with approximately 6m below the base of Sandy Creek upstream of the waterfall and about 10-15m below Sandy Creek downstream of the waterfall.

The effects of nearby longwall mining were closely monitored using a range of instruments including several manual inclinometers and a shaped accelerometer array (SAA). First evidence of closure movements was observed at these inclinometers on two main shear horizons when the longwall panels approached the waterfall. The initial movements were of low magnitude and did not have potential to significantly affect the integrity of the waterfall rock structure. Mining continued for several hundred metres more before the movements were considered large enough to be a potential threat to the integrity of the waterfall and the longwall was stopped (Walsh et al., 2014).

The SAA inclinometer recorded lateral movement at 0.5m intervals over a 50m vertical section at 1 minute intervals. Initial movements were observed at 9:56pm on 16 November 2012. Movements since then continued incrementally with additional longwall retreat and then more gradually once the longwall finished. After the completion of mining, there have been several high intensity rainfall events, each accompanied by small increments of shear.

At the Sandy Creek Waterfall site, the level of monitoring data available is sufficient to allow an analysis of the body forces acting on a two-dimensional slice through the site. Recognising that increases in pore pressure recorded following rain events cause small increments of movement, the friction angle of the basal shear plane is able to be estimated. The geometry of the free-body diagram is shown in Figure 10.

Horizontal stresses were measured at several locations including high up on the slope and in the valley floor. Piezometers measured the groundwater level and a 4m rise in water level due to two high intensity rainfall events that occurred after mining was complete.

These two rainfall events were sufficient to remobilise downslope movement and shear on the basal shear plane indicating that the slope is at limiting equilibrium. By considering the balance of horizontal forces at limiting equilibrium in the two cases of no movement prior to the rainfall events and movement following a 4m rise in pore pressure, the friction angle on the basal shear plane can be estimated with a high degree of confidence.

This analysis indicates that the friction angle on the basal shear plane is in the range 9°-14°, depending on assumed pore pressure conditions within the rock mass. This friction analysis is consistent with the range that would be expected for bedding planes in Hawkesbury Sandstone based on laboratory shear tests.

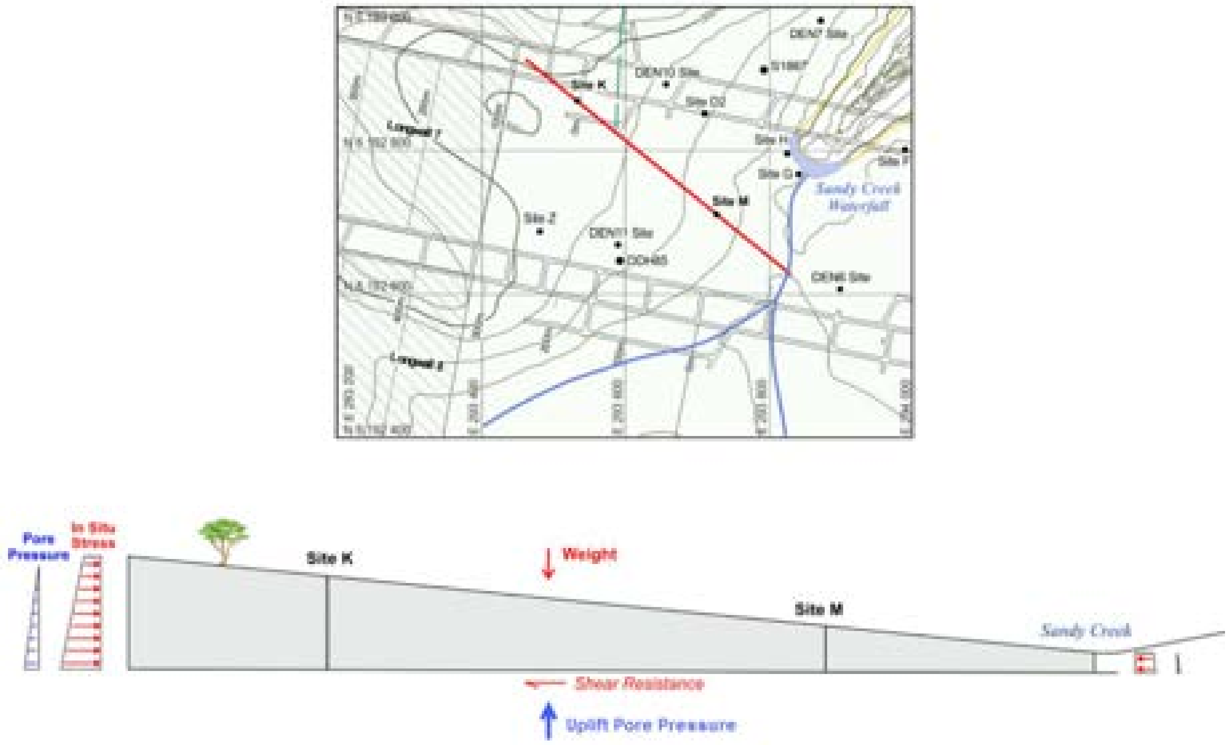


Figure 10 Free body diagram of slope leading down to Sandy Creek that shows friction angle on the basal plane is in the range 9°-14° (after Walsh et al. 2014).

The key observations of interest from the Sandy Creek Waterfall monitoring in terms of characterising the shear horizons are:

- The nature of the shear movements observed is consistent with movement on near horizontal shear surfaces at an elevation just below the base of the valley.
- A step in the elevation of the valley floor leads to the development of two shear horizons, each just below the floor of the valley.
- The timing and magnitude of the shear movements are consistent with the valley closure movements observed.
- The movement observed is consistent with shear on a residual shear surface without the large energy release that would be associated with fracturing fresh rock.
- The remobilisation of shear movement following rainfall events and the gradual reduction in shear over time indicate that the shear surface is in a state of limiting equilibrium where even very small changes in horizontal load are capable of causing additional horizontal movement.
- The basal shear horizon extends outward from the valley as far as is required to accommodate the horizontal movements observed on the surface.

4. Sub-Surface Ground Deformations

In this section, the results of observations from a range of different techniques are presented to characterise the impacts of longwall mining on the overburden strata followed by a discussion of the challenges of terminology when describing sub-surface ground deformations and groundwater behaviours.

4.1 Surface Extensometers

Surface extensometers have been deployed for monitoring mining induced ground movements for more than 50 years. 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. These movements are observed to correlate closely with the profile of ground movements inferred from subsidence data that is presented in Figure 3.

Orchard (1973) describes work by Dowdell (1968) where 64 anchors deployed at 8 horizons were used to measure ground movements above a longwall panel in the UK. In Australia, initial attempts by Schaller and Hebblewhite (1981) at Angus Place Colliery and Gurtunca (1984) at South Bulli and West Cliff Collieries were affected by borehole instability. However, Holla and Armstrong (1986) made successful measurements at Ellalong Colliery using a system of hanging weights. This system was later deployed at Tahmoor Colliery, Invincible Colliery, and Angus Place Collieries in the 1980s, also with good results. Mills and O’Grady (1998) describe the use of rotary spring surface extensometers for monitoring longwall caving behaviour above two longwall panels of different width at Clarence Colliery, including three extensometers above one panel to define the shape of the cave zone.

Mills and O’Grady (1998) showed there is an arch-shaped 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. Outside and above this zone, there is a zone of lower-level ground movement that extends higher into the overburden strata right through to the surface at this site.

The incremental monitoring shown in Figure 11 illustrates the nature of high-angle fractures that extend upward from the longwall face throughout the arch-shaped zone of large downward movement.

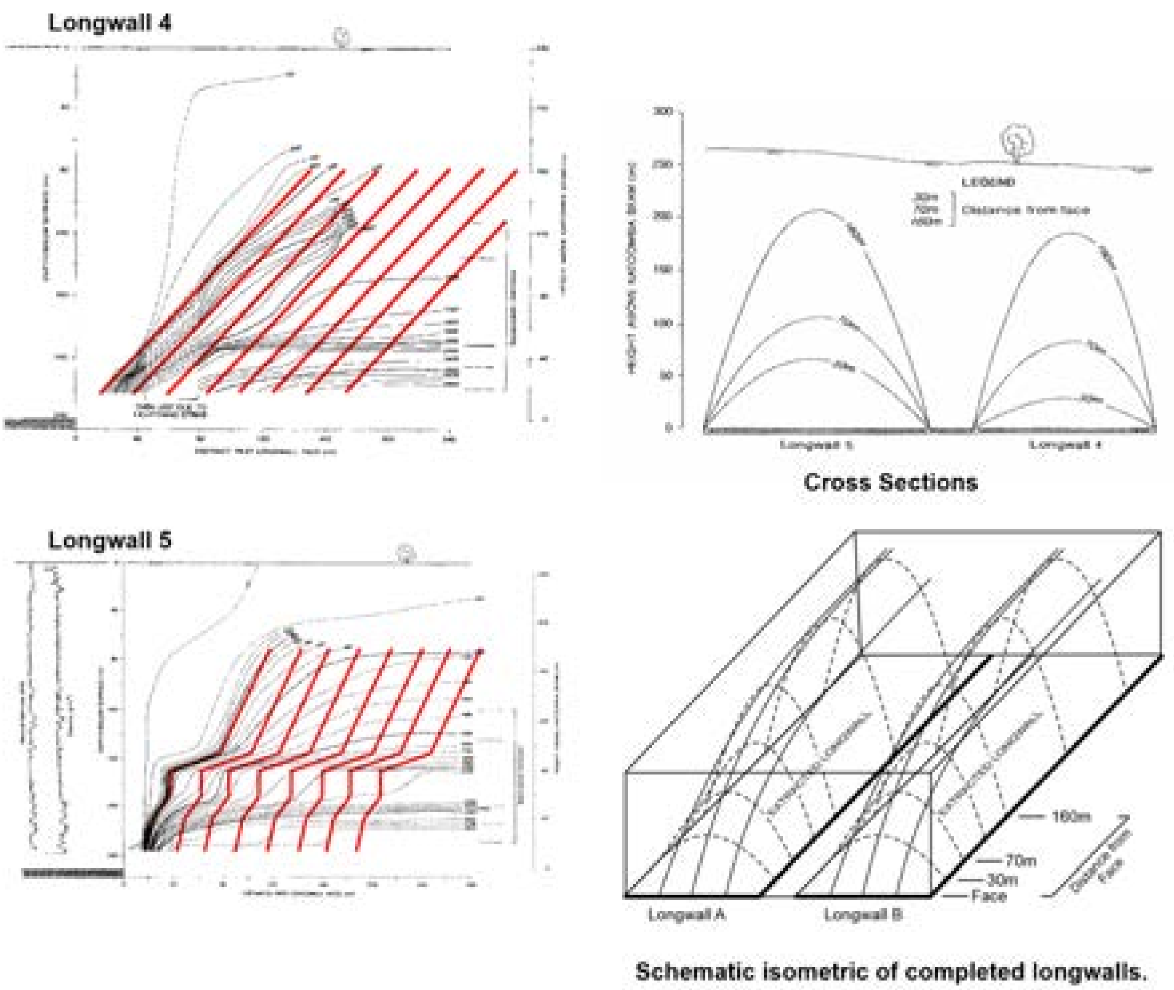


Figure 11 Fracture pattern (in red) within the zone of large downward movement indicated by extensometer monitoring above a retreating longwall face (after Mills and O'Grady 1998).

4.2 Borehole Cameras and Geophysical Logging Tools

Borehole cameras, televiewers, and other borehole imaging devices have proved useful for characterising zones of ground movement observed above longwall panels. To measure the nature and extent of sub-surface ground movements above a longwall goaf using these devices, it is necessary to drill a hole into a longwall goaf, typically in the centre of the panel to a depth, ideally, to 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. Movement of groundwater into and out of the borehole have also provided evidence of groundwater interactions with fractured strata above longwall panels.

Brown (2019) describes the results of borehole geophysics measurements above extracted longwall panels in an environment where fracturing extends through the full overburden section. These measurements show the orientation of fractures within the subsided overburden strata are dominated by high angle fractures dipping toward the longwall face in the centre of the panel and towards the chain pillars near the edges of the panel. The fractures around the edges of the extracted longwall panel remain open and hydraulically conductive. The steeply dipping fractures in the centre tend to be more closed, but the imperfections of having been opened and closed leaves some permanent dilation. The vertical hydraulic conductivity of the subsided strata is significantly increased as a result.

4.3 Inclinometers

Inclinometers are borehole devices that measure changes in verticality of the ground into which they are installed. Changes in verticality are used to identify shear horizons and measure the magnitude of shear movements.

There are several systems available. The most commonly used involves installing a special casing into the borehole and either grouting it in place or backfilling outside the casing with pea-gravel. The casing has four oriented grooves that allow a high precision tool to be run into the hole. Repeated surveys of the hole show changes in verticality over time. There are several more sophisticated systems that can record changes over time.

Shallow inclinometers are routinely used to measure subsidence related ground movements. Leventhal et al. (2014) and Walsh et al. (2014) present examples of their use.

Mills et al. (2015) describe the results of monitoring surface-to-seam inclinometers. These measurements show the existence of two types of shear horizon:

- Shear horizons that are continuous across more than 1km and mobilised soon after the commencement of longwall mining.
- Shear horizons that become mobilised throughout the overburden strata at increasingly closer vertical spacing within about 60m of the longwall goaf.

The first type are consistent with horizontal stress relief and usually occur at or near the mining horizon, in most cases slightly above the coal seam rather than in the floor below.

The second type are associated with strata deformations close to the goaf edge.

4.4 Stress Monitoring

Strain measuring instruments are able to be deployed in boreholes to depths of more than 1km below surface. The strain changes measured on these devices can be used to calculate the in-situ stresses in the rock and stress changes associated with longwall mining. The instruments are most useful for monitoring intact rock prior to failure. These instruments are able to resolve three-dimensional stress changes that occur over short durations of hours, days and sometimes weeks to resolutions of better than 0.01mm/m.

The use of such instruments for measuring changes in stress are described in Walsh et al. (2014), Puller et al. (2015) and Mills et al. (2015). ACARP (2020) presents the results of measuring a profile of the in-situ stresses through the subsided rock strata above an extracted longwall panel.

4.5 Piezometers

Piezometers are primarily used for monitoring groundwater behaviour. Fully grouted multiple piezometer strings (McKenna, 1995) and their deployment around longwall panels have proved useful for understanding the interaction of groundwater and fracturing above and to the sides of extracted longwall panels. The interaction between the ground movements and stratigraphic units with high hydraulic conductivity is apparent in the piezometer records as the ground displacements move upward through the overburden strata.

Byrnes (1999) describes the installation of multiple piezometers at South Bulli Colliery. These piezometers showed the height of ground deformations extended to 120m above 120m wide longwall panels.

Mills and Blacka (2017) describe a study that included the use of borehole cameras and piezometers to characterise the groundwater interaction above a longwall panel at Tahmoor Colliery in the Southern Coalfield that was mined 20 years previously.

This work and other similar studies demonstrate that there is significant interaction between the groundwater and the fracture network above extracted longwall panels.

4.6 Packer Testing

Packer testing involves pressurising a closed section of borehole with water and measuring the flow of water into the test interval. Packer testing is subject to many influences and is not regarded as a high-quality test. However, notwithstanding the limitations of packer testing, allows the post-mining profile of hydraulic conductivity above extracted longwall panels to be compared with the pre-mining profile. This comparison indicates that increases in hydraulic conductivity of several orders of magnitude are typical.

Packer testing programs described by Reynolds (1977) and Holla and Buizen (1991) are early examples of these types of programs. Packer testing is now used routinely to determine changes in hydraulic conductivity above extracted longwall panels. Examples of their use are presented in other papers within these proceedings.

The practical limitations of packer testing equipment for characterising the hydraulic conductivity of highly fractured ground such as fractured ground above extracted longwall panels needs to be recognised. Packer testing equipment is typically limited to measuring hydraulic conductivities in the range $1x10^{-10}$m/s and $1x10^{-5}$m/s. Hydraulic conductivities greater than $1x10^{-5}$m/s should be regarded as a lower limit and could be several orders of magnitude greater than indicated.

4.7 Core Logging

Logging of core recovered from boreholes drilled into the strata above extracted longwall panels provides insight into the fracture patterns generated by longwall mining.

Reynolds (1977) describes a program of core inspection conducted in two holes, one located above a goaf of an extracted pillar panel and one in an adjacent unmined area. 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. He concluded that there would certainly be hydraulic connection to the workings within this zone.

Core recovery from drill holes drilled into the strata above extracted longwall panels routinely indicates a high proportion of angled fractures to a height above the mining horizon equal to about one times the panel width and an increase in horizontal fractures above this height (typically through to the surface).

4.8 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, 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).

4.9 Terminology

Galvin (2017) notes the challenges of finding a common terminology for processes and mechanisms. These challenges are particularly evident in relation to describing zones with the subsided overburden strata where a consistent naming convention has yet to be established.

Many authors describe the subsided overburden strata using the terminology adopted in Forster and Enever (1992) as comprising:

- a "caved zone" to mean the highly disturbed ground evident in the goaf immediately behind the longwall supports

- a "fractured zone" that extends to a height above the mining zone that is either undefined or defined as a multiple of seam height

- a "constrained zone" where there is no change in vertical hydraulic conductivity

- a "surface zone" between the constrained zone and the surface.

Figure 12 shows the extent of these various zones. Forster and Enever (1992) present descriptions of the changes in horizontal and vertical hydraulic conductivity that may be expected within these zones. The vertical height above the mining horizon of each zone is not defined. Further work presented in Mills (2012) indicates that the zones described by Forster and Enever are consistent with more recent observations of sub-surface deformations if the diagram is stretched vertically by a factor of 2.2.

The terminology used by Forster and Enever conveys behaviours that can be easily misinterpreted. The terms “caved” and “fractured” are commonly interpreted to mean that caving or fracturing is limited only within these zones. With no reference to height, the height of the fractured zone is easily underestimated from the diagram.

The term “constrained” is commonly interpreted to mean there is no change in vertical hydraulic conductivity within or above this zone and therefore hydraulic conductivity effects do not extend above this horizon. Field measurements and numerical modelling indicates that the height of the constrained zone indicated in Figure 12 is consistent with post-mining hydraulic conductivity being lower than elsewhere within the post-mining profile of hydraulic conductivity. However, the post-mining hydraulic conductivity of the constrained zone is still commonly several orders of magnitude (100t to more than 10,000 times) higher than the pre-mining hydraulic conductivity, noting that this conductivity is not purely vertical hydraulic conductivity and may include significant horizontal conductivity as well.

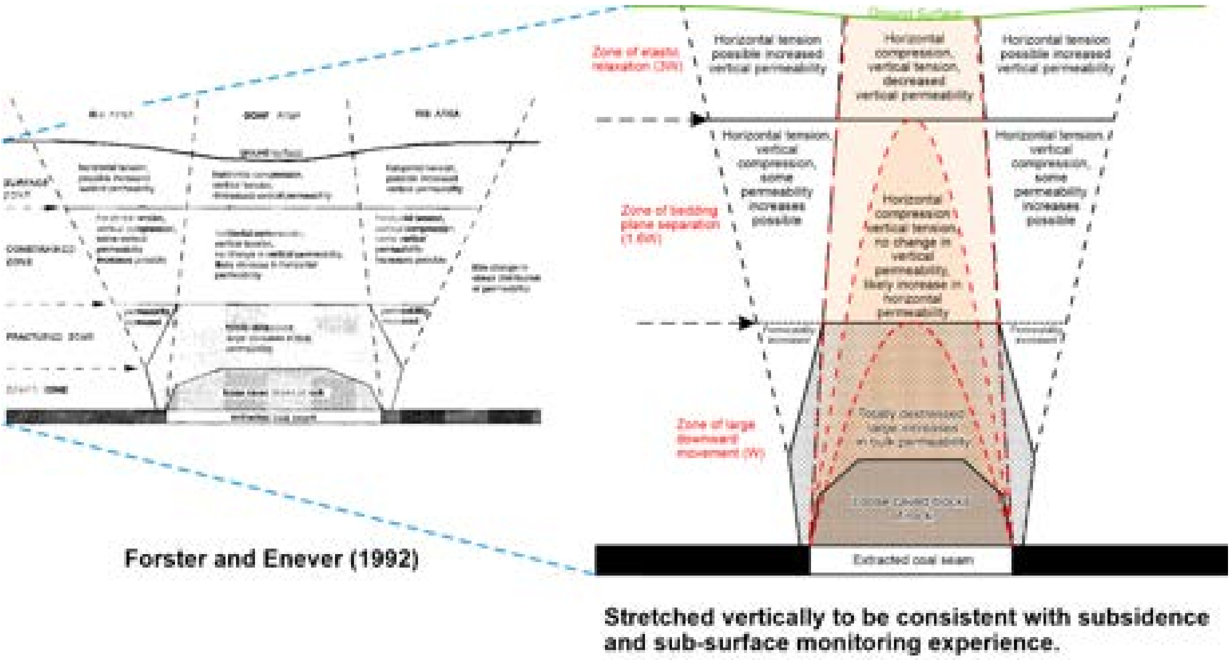


Figure 12 Zone of permeability change indicated by Forster and Enever (1992) are consistent with subsidence and sub-surface observations when stretched vertically as shown.

Mills (2012) adopts a terminology to describe the fracturing above a single longwall panel that is intended to convey the mechanics of the processes involved.

- 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 bedding plane separation 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 above the mining horizon where the ground is completely disturbed by mining (effectively the zone immediately above the longwall supports).

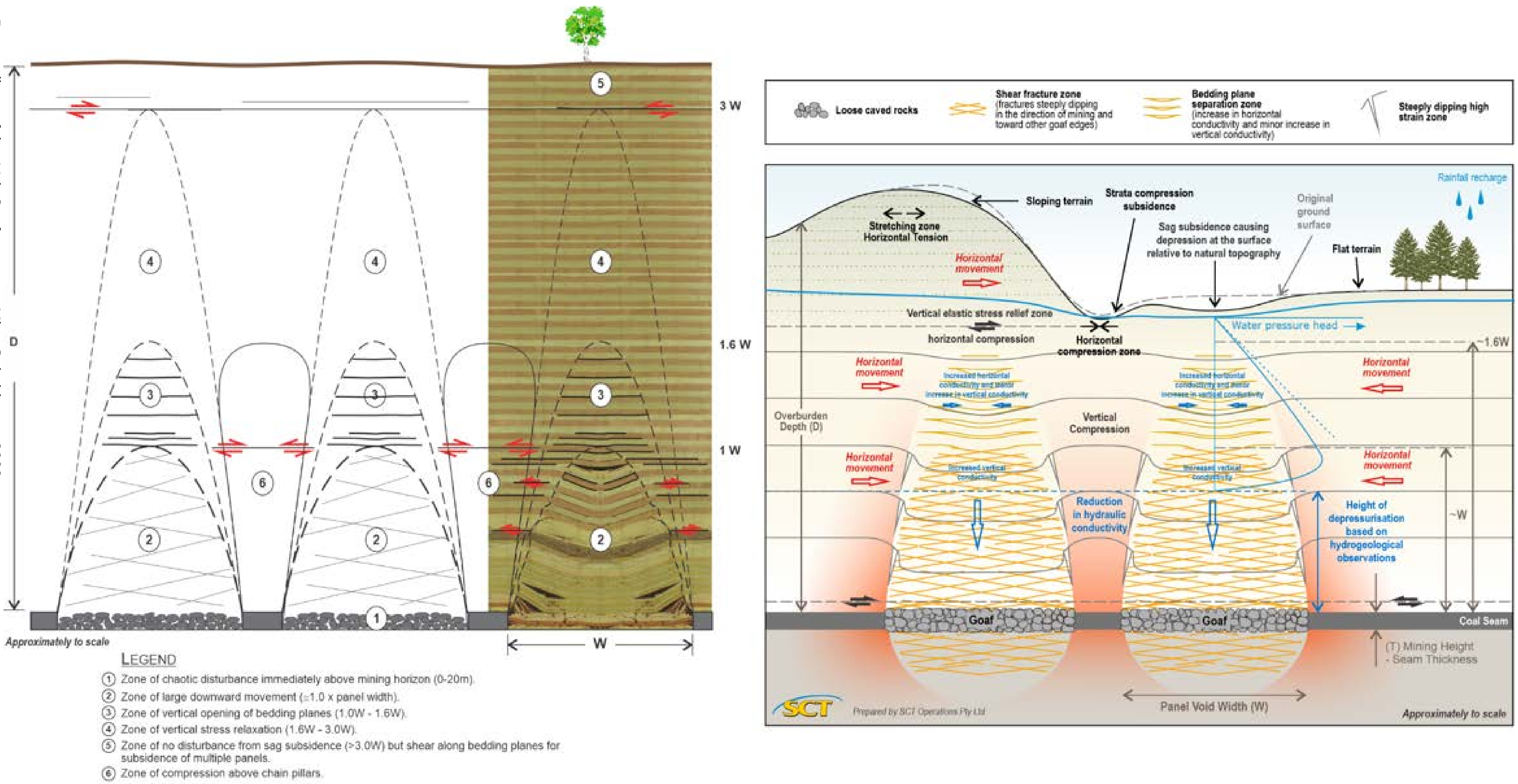
The terminologies adopted in the groundwater modelling literature should not be considered to represent the physical ground movements associated with mining.

5. Synthesis and Implications for Groundwater

Figure 13 shows a representation of the zones of ground movement identified above a single extracted longwall panel using the various methods discussed in this paper. The impacts of longwall mining on the overburden strata directly above a single extracted longwall panel are predominantly stretching in nature and decrease progressively with height to no impact at a distance above the mining horizon equal to three times the panel width. The impacts to the sides of the longwall panel are more compressive in nature. The impacts from multiple longwall panels are likely to be similar to the superposition of multiple single panels. Broad subsidence across multiple panels may lead to additional shearing in the upper overburden strata above three times the width of individual longwall panels. Further work is necessary to confirm the changes in this upper zone because it is seldom investigated.

5.1 Changes in Hydraulic Conductivity

Within the zone of large downward movement to a height above the mining horizon equal to about the panel width, steeply inclined fractures are expected to develop off the longwall face as it moves incrementally along the panel and above the other goaf edges. The changes in hydraulic conductivity of strata within this zone are expected to be significant and a minimum of several orders of magnitude (1000 times) greater than the in-situ hydraulic conductivity. The height of this zone is recognised to increase with increasing in-situ horizontal stresses and may vary slightly with lithology. On average a height equal to the panel width is a reasonable first approximation.



a) Overburden caving behaviour inferred from surface monitoring and other observations.

b) Conceptualisation of overburden caving behaviour around longwall panels.

Figure 13 Representations of zones of ground movement within the overburden strata above longwall panels based on subsidence monitoring and field observations (after Mills 2012).

Within the zone of bedding plane separation (1.0-1.6 times panel width), changes in hydraulic conductivity are expected to be dominated by changes in hydraulic conductivity in a horizontal direction, but changes in vertical hydraulic conductivity are also expected. Packer testing indicates changes in hydraulic conductivity of several orders of magnitude.

In the elastic relaxation zone (1.6-3.0 times panel width), changes in hydraulic conductivity are expected to occur as a result of stress changes on joints. The magnitude of these changes is expected to be typically less than an order of magnitude, but further field measurements are required to confirm this expectation because hydraulic conductivity in this zone is seldom investigated.

Changes in hydraulic conductivity in the compression zone above the goaf edges and the chain pillars between panels are likely to reduce as a result of the increased confining pressure. The reduction in hydraulic conductivity of this strata is expected to be of a similar quantum to the increase in hydraulic conductivity within the elastic relaxation zone.

5.2 Depressurisation

A consequence of mining activity at depth is a reduction in pore pressure to zero at the mining horizon. This zone of zero pressure is referred to as the zone of depressurisation. The extent of this zone is a balance between the rate of recharge from the surface and laterally and the hydraulic conductivity of the strata through which recharge flow occurs.

During the initial development of underground roadways, the changes in pore pressure are limited in extent because the hydraulic conductivity of the in-situ strata is typically low and recharge is typically large enough to compensate. The balance between the two is enough to minimise pore pressure changes except very close to the openings.

During longwall extraction, the disturbance to the overburden strata caused by mining-induced ground movements leads to a significant change in this balance. Vertical hydraulic conductivity is increased by multiple orders of magnitude in three recognised zones that extend to a height above the mining horizon equal to three times the panel width. For most mining geometries, hydraulic conductivity directly above each panel increases through the full overburden section from mining horizon to the surface. Recharge from the overburden strata to the sides of panels though unimpacted strata and from the surface where rainfall recharge is intermittent cannot typically maintain pore pressures at pre-mining levels. Drawdown in pore pressure to zero pressure occurs as a result.

Tammetta (2012) presents a comprehensive review of depressurisation resulting from longwall mining at 33 sites worldwide where information was available to indicate the height of depressurisation and 110 additional sites where the height of depressurisation could be inferred as either above or below the indicated horizon. From this information, a relationship indicating the height of depressurisation was determined as:

$$H = f(w, t^{1.4}, d^{0.2})$$

where H is the height of depressurisation above the mining horizon, w is the panel width, t is the seam thickness mined and d is the mining depth. Tammetta developed this formula to indicate the height of complete groundwater drainage on the assumption, based on Darcy's Law, of zero pressure equalling complete drainage. Further work indicates that the assumption of complete drainage is not valid, but the formulation is nevertheless suitable to indicate the height of depressurisation. Subsequent to its release, the Tammetta formula has been validated at multiple locations as indicating the height of depressurisation.

The components of the Tammetta formula were determined from consideration of hydrogeological information without reference to the physical processes associated with subsidence. Nevertheless, the formulation is found to be entirely consistent with the physical processes that contribute to subsidence. These include a linear relationship with panel width, an exponential relationship of seam thickness extracted, and a weak relationship with depth. The linear relationship of ground disturbance with panel width is clearly evident in the discussions above. The exponential relationship of height of depressurisation with seam thickness mined is consistent with observations that ground disturbance increases exponentially with seam thickness mined (ACARP, 2009). The weak relationship with depth is consistent with the observation of a greater height of disturbance with increased in-situ stress.

5.3 Groundwater Impacts

Groundwater impacts are observed to result from the combination of:

- significant increases in hydraulic conductivity, typically throughout the entire overburden section
- the creation of a large zone of zero pressure within the overburden strata.

Prior to mining, there is effectively no hydraulic gradient to drive flow and the hydraulic conductivity of the strata is low. Post longwall extraction, there is a significant increase in hydraulic conductivity due to the ground disturbance and a hydraulic gradient, assisted by gravity, is created between the water table and the zone of zero pressure above the longwall panel. These changes inevitably lead to downward flow toward the mine.

The degree of disturbance to the groundwater depends on a combination of other effects, principally the rate of rainfall recharge and the presence of overlying aquifers capable of lateral recharge from rainfall over a larger area. Given the significant ground disturbance directly above the mining area, direct rainfall recharge is typically the more significant.

A range of observations challenge conventional understanding of groundwater interactions with longwall mining. These include:

1. For mines operating at overburden depths of up to about 300 m, significant inflows to the mine are observed soon after rainfall events and the inflow is volumetrically consistent with the intensity of the rainfall event.

2. Annual mine inflow rates to underground mines operating at overburden depths of up to about 300m typically increase linearly with area of longwall extraction at a rate that is equivalent to 25% of annual rainfall. If lateral flow was the only source of recharge through the mine perimeter, initial mine inflows would be high because the first panel mined creates the biggest perimeter change and each additional longwall mined would only contribute a small increment associated with the increased perimeter created by the addition of that panel.

3. Post-mining profiles of pore pressure indicate close to zero pressure throughout the overburden section up to the height of depressurisation.

4. The chemistry of water flowing into the mine is consistent with strata water and not initially consistent with meteoric water (rainwater). The chemistry is observed to change over extended periods of time to include an increasingly greater proportion of rainwater.

Conventional understanding of the groundwater flow is based on Darcy's Law. When there is a zone of zero pore pressure, Darcy's Law would indicate complete drainage of all stored water within that zone. Yet, although the pore pressure is zero, the water that flows into the mine following a rainfall event is strata water and not rainfall.

Further work is required to isolate the mechanics of the processes involving the storage of groundwater within the overburden strata. Current information indicates a storage mechanism based on capillary storage within unsaturated strata and flow reactivated by saturation. As a rainfall event occurs on the surface, surface water migrates downward causing saturation in the upper groundwater that enables downward flow of stored water into the deeper groundwater. This process progresses downward until a volume of strata water equal in volume to the rainwater that entered at the surface flows into the mine. Once the rainfall event is over, desaturation progresses downward and halts the flow throughout the overburden section. Measurements of water chemistry over time indicate the volume of water able to be stored within a subsided goaf is approximately equal to the fracture volume created by mining. An upper limit on this fracture volume is the difference between mining height and surface subsidence.

A mechanism of this nature would be consistent with all the various observations. However, to implement such a mechanism in numerical models of groundwater behaviour remain aspirational. In the interim, groundwater models based on Darcy's Law rely on interpretations of overburden caving processes that are not consistent with observation.

6. Conclusions

A review of subsidence mechanics indicates that there is considerable understanding of subsidence processes available to inform subsidence impact assessments. Some of that understanding was available 50 years ago and has been lost through the attrition due to age of key people. It remains a challenge to the industry to limit this loss as we approach another period of retirement of people holding key expertise within the industry.

The mechanics of subsidence processes can be divided into components on the basis of physical processes that affect vertical subsidence and horizontal movements. These processes contribute to sub-surface movements that impact groundwater.

Surface subsidence and sub-surface monitoring provide strong evidence that an arch-shaped zone of tensile/stretching ground disturbance occurs above individual longwall panels:

- to a height above the mining horizon approximately equal to the width of the longwall panel as steeply inclined fracturing parallel to the longwall face and other goaf edges,
- to a height of 1.6 times panel width as bedding plane separation, and
- to a height of three times panel width as elastic relaxation.

Strata dilation caused by mining-induced fracturing causes reduced vertical subsidence in flat terrain and lateral movement in sloping terrain. Lateral movements are not limited by panel geometry but by surface topography. Impacts to adjacent river channels become possible whenever the slopes leading to that channel are mined under.

Horizontal movements caused by stress relief and strata dilation require shear planes to develop outside the mining area. Shear planes associated with stress relief are observed to occur up to several kilometres at some sites. These shear planes are typically located just above the mining horizon. Shear planes associated with strata dilation are typically located just below the floor of adjacent valleys. Monitoring experience indicates these shear planes may be at close to limiting equilibrium prior to mining and have residual friction angle of 9°-14°.

Groundwater interactions above longwall panels are not consistent with Darcy's Law and refinement of groundwater modelling codes is necessary to faithfully represent the mechanics of processes that are routinely observed above extracted longwall panels.

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