Developments in Understanding Subsidence with Improved Monitoring

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Summary

Ground movements associated with coal mining have been occurring since coal mining was first practiced but the ability to interpret these movements and develop an understanding of the mechanics involved was initially limited by irregular mining geometries and the vagaries of pillar behaviour. The introduction of longwall mining to Australia with its regular geometries, full extraction, and single seam extraction has provided opportunities to eliminate many of the mining related variables that are present in pillar extraction operations and so provide a much more controlled environment in which to conduct measurements and develop understanding of the mechanics of overburden caving and subsidence processes. The understanding of these processes has developed as a result of improvements in surveying and monitoring techniques and the application of these techniques to satisfy the requirements of regulatory authorities in response to changing community expectations. This paper presents as overview of the developments in monitoring technique for characterising subsidence and sub-surface ground movements and the developments in understanding of subsidence related ground behaviour that have been possible as a result.

1. Introduction

There is insufficient space in a single paper of this type to present all the detail of the array of techniques and monitoring systems that have been developed and applied at specific sites or to delve into the detail of the understanding that has developed from the large body of monitoring work conducted in N.S.W. and elsewhere.

There is nevertheless value in stepping back and reflecting on how our understanding of ground movements has developed on the back of improvements in monitoring technique, the limitations of some of these techniques, how these limitations have guided our thinking, and the various benefits provided by the broad range of different approaches that are now available.

Such a review is necessarily somewhat general but it does provide an opportunity to consolidate the understanding that has been developed so far.

This paper is structured to provide an overview of the development of surface subsidence monitoring technique in Section 2 including several techniques that are not yet widely used. An overview of sub-surface monitoring techniques that have become available and are used to develop understanding of the ground movements below the surface are presented in Section 3. The general understanding of vertical subsidence behaviour, horizontal ground movements, and sub-surface ground movements are discussed in Section 4, 5, and 6 respectively.

2. Subsidence Monitoring

Subsidence monitoring has conventionally been conducted by repeatedly surveying the movement of a line of fix points on the ground. The relative freedom of surface access in most longwall mining areas in N.S.W. has allowed subsidence lines to be located in areas that provide data that is geometrically aligned with the longwall panel either as a cross-line or a longitudinal line. This alignment combined with the repetition of multiple panels of similar geometry side by side has helped significantly with developing understanding of the subsidence mechanics.

2.1. Level and Peg to Peg Chaining

Subsidence monitoring technique in Australia was initially imported from the United Kingdom and based around the survey instruments that were readily available at the time. The standard technique involves measuring vertical displacement by levelling pegs and measuring differential horizontal movements by incrementally chaining between pegs.

This approach was reasonable given the survey instruments available, but unfortunately it has hampered the development of understanding horizontal movements because the assumptions implicit in the technique effectively preclude measurement of most of the horizontal movements that are now recognised to occur.

The levelling and strain technique involves installing a line of pegs at a nominal spacing of $1/20^{th}$ overburden depth either perpendicular to or parallel to a longwall panel or, occasionally, at some other angle to suit practical surface constraints. The line ideally extends across the panel out to a distance either side of the extracted panel to a point where there is deemed to be no further subsidence.

The line is surveyed before and after mining and at various stages during mining using conventional levelling. Changes in vertical elevation at each peg are calculated and a subsidence profile is developed. The line of pegs is extended sufficiently far to ensure that vertical subsidence is less than the nominal survey tolerance, typically accepted as 20mm.

A profile of vertical subsidence also allows determination of tilt and curvature, the first and second derivatives of subsidence. Both these parameters were correlated with damage to structures based on the vast experience of mining and measured subsidence impacts in the United Kingdom and both are still useful for assessing potential subsidence impacts to structures.

Until recently, surveying technique did not allow absolute horizontal position to be measured directly without going to extraordinary lengths which, for routine subsidence monitoring, is typically not warranted. Instead, relative movements between adjacent pegs are measured by chaining – direct distance measurement – between adjacent pegs. By dividing these relative movements by the original horizontal distance, a differential horizontal measurement called strain is derived and this too is correlated with damage to structures based on the United Kingdom and subsequently local experience in Australia.

Two assumptions are implicit in the level and peg to peg chaining technique:

- The pegs at either the ends of the line do not move horizontally and so by implication horizontal movements only extend as far as the ends of the subsidence line.

- All horizontal movements and strains occur in the direction of the subsidence line because that is the only direction measured.

With the development of three dimensional surveying technique, it is has become clear that neither of these assumptions is valid. Horizontal subsidence movements are routinely observed to extend well beyond the point where vertical subsidence is no longer significant and the direction of horizontal movement is controlled by a complex interaction of multiple factors and not the orientation of the subsidence line.

2.2. Total Station Surveying

Three dimensional surveying of distributed points was used for specialist subsidence monitoring applications in the late 1980's and early 1990's (Kay 1992, Reid 1991, Mills 2001), but it wasn't until total station survey instruments became readily available to mine surveyors in the late 1990's that routine subsidence monitoring in three dimensions on conventional subsidence lines became more commonplace and a database of experience was able to be accumulated.

Although the accuracy of total station measurements are not necessarily as strong as levelling and chaining, the benefits in terms of generally understanding of ground movement are significantly better.

Three dimensional surveying has showed that as well as systematic subsidence movements associated with vertical subsidence, horizontal stress relief and surface topography have a strong influence on the magnitude and direction of horizontal subsidence movements.

2.3. Improved Survey Control

When three dimensional surveying was first used for subsidence monitoring, it was still assumed that the ground movements were substantially limited to within the area of vertical ground movements so survey control remained within relatively close proximity of the subsidence line to minimise surveying errors associated with traversing long distances from remote control pegs. Unfortunately, this practice meant that many three dimensional subsidence surveys were not necessarily measuring the full horizontal movements. The development of understanding horizontal ground movements associated with mining, particularly far-field movements, was therefore significantly degraded and the magnitude of far-field movements was routinely underestimated as a result.

Only when survey control was established on both sides of the mining area did it become apparent that there was a need for reconciliation of the horizontal movements at either end of subsidence lines.

Fortunately, the deployment of the US Government's Global Positioning System (GPS) and particularly the turning off of selective availability on 1 May 2000 provided a practical method for mine subsidence surveys to be controlled over large areas without the accumulation of survey errors associated with bringing survey control in from points remote from mining activity. While it took some years before GPS technology became readily available and was able to be routinely used for subsidence monitoring at a high enough resolution, the improvement in monitoring accuracy across broad areas has been profound.

Anderson et al (2007) describe the use of concentric networks of survey control remote from mining and located on all sides of the mining areas at Illawarra Coal. This approach is based on the concept of a GPS coordinated ring of control points remote from mining activity that can be used to control one or more inner rings of survey control points that are more conveniently located close to mining activity but still remote enough and located on all sides of the active mining areas to remain substantially unaffected by mining induced ground movements. The relative location of these control pegs can be checked against each other from time to time to ensure no relative movement and that any movement that does occur for any reason on individual pegs within the control network can be recognised and accounted for.

The survey control network such as the one described by Anderson et al provides a means to identify any horizontal ground movements that may occur. The location of the network on all sides of a mining area means that any mining induced horizontal ground movements that occur can be detected. This system was recently introduced at Ulan Coal Mine (Mills et al 2011) allowing a very significant improvement in the understanding of ground movements at the mine. Numerous other mines in the Hunter Valley have similar systems in place.

2.4. High Resolution Measurement

Subsidence monitoring is frequently directed toward managing mining impacts on specific surface infrastructure and natural features such as cliff formations and watercourses. In these situations, there is a need for high resolution measurements targeted at specific locations that do not necessarily need to be referenced to an external coordinate system.

Kay et al (2007) report the use of optical fibres embedded in road pavements for high resolution monitoring of strains over multiple bays to an accuracy of about 0.1mm/m once thermal effects are removed. The system can be automated and has many advantages for monitoring subsidence impacts on surface infrastructure.

Nicholson (2010) has recently used a high resolution direct distance measuring survey technique to confirm relative ground movements across a natural feature sensitive to valley closure movements. High precision distance measuring instruments with sub-millimetre accuracies are capable of straight line point to point measurements over distances of up to several hundred metres with nominal strain resolutions of the order of 0.01-0.1mm/m.

These techniques involve direct high resolution measurement of relative horizontal movement across or along the feature of interest. The focus is on one dimensional distance measurement between fixed points and as such is best deployed where there is other conventional subsidence monitoring to confirm the general pattern of ground movement and reference this ground movement to an external coordinate system.

2.5. Broad Area Monitoring

Conventional subsidence monitoring is based around measurements of fixed points. There are practical limitations to how many pegs can be installed around any given longwall panel and how often they can be surveyed. The spatial and temporal distribution of observation points is limited by these practicalities.

Widely scattered arrays of individual pegs provide a way of more broadly distributing survey pegs than is possible with subsidence lines but there are then challenges associated with maintaining survey accuracy across such arrays. All conventional ground surveys are time consuming and labour intensive if a dense survey network or frequent surveys are needed over a large area.

Airborne and satellite based remote sensing techniques provide a capability to see across larger areas. Soole et al (2001) report using terrestrial photogrammetry to observe ground movements on cliff formations at Baal Bone Colliery. Holt and Clark (1998) report using airborne photogrammetry for subsidence monitoring of grazing land with accuracies of ±50mm considered possible.

Airborne LiDAR monitoring has developed as a commercially available method for mapping ground surfaces to an accuracy of about ±100mm with capability to determine vertical subsidence as the differential between repeat surveys over broad areas. LiDAR appears to have some advantages over photogrammetry and is particularly useful for determining subsidence behaviour in areas that are difficult to access for conventional subsidence monitoring and where determining the extent of subsidence is the primary goal, such as around irregular mining geometries (e.g. longwall mining below pillar extraction operations).

Both photogrammetry and LiDAR are also useful as baseline information where there is potential for some future subsidence caused by for instance pillar collapse in old abandoned workings. The extent and magnitude of the event can be determined with confidence at a later time should it ever occur.

Satellite based differential interferometry using synthetic aperture radar (DInSAR) is another remote sensing technique that can deliver broad area measurement of ground movements to resolutions of only a few centimetres. Radar imaging systems are able to operate 24 hours per day in all weather conditions. The coverage of a standard satellite radar image ranges from about 70km by 70km to about 100km by 100km with a pixel resolution of between 1m and 30m.

Synthetic Aperture Radar (SAR) is a side-looking radar system that uses the flight path of the aircraft or satellite on which it is mounted and multiple radar reflections gathered as a series of transmit/receive cycles to electronically simulate (hence the term synthetic) an extremely large antenna (aperture) that can generate high-resolution remote sensing imagery. The signal processing uses magnitude and phase of the received signals over successive pulses to create a high resolution image of the terrain below.

Satellite borne DInSAR has already been used for many ground deformation monitoring applications because of its high precision and high spatial resolution. The technique is well developed for vertical displacement monitoring and is particularly useful where the displacement gradients are relatively gradual. Research in this area has shown accurate measurements of three dimensional ground movement can be achieved with accuracies comparable to ground based GPS measurements (Ge 2008).

In subsidence monitoring applications there are several characteristics of mine subsidence that currently complicate the routine use of DInSAR for full three dimensional subsidence monitoring, but it is envisaged that within the next decade or so there will be sufficient number of satellites with sufficiently different orbits to enable all three components of ground movements over entire coalfields to be measured at intervals of only a few days (ACARP 2011).

3. Sub-Surface Monitoring

The line between surface subsidence monitoring and sub-surface monitoring becomes blurred when monitoring natural features such as rockbars in river channels or cliff formations because these features exist below the ground. The line becomes even more blurred when discussing the impacts of mining induced ground movements on groundwater systems which by their very nature exist within the overburden strata. Nevertheless, a range of techniques have emerged that have application to the monitoring of ground movements associated with mining subsidence. These techniques are discussed in this section.

3.1. Stress Change Monitoring

Stress change monitoring is essentially point measurements of small deformations that occur in response to ground movements in the rock strata around boreholes. There are several types of stress change monitoring instrument that have been used for monitoring stress changes associated with mining subsidence. Most of these instruments are suitable for deployment at depths up to a few tens of metres from the collar of the borehole or have capability to measure the stress change in one direction only so their application for subsidence monitoring has been relatively limited.

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. Once failure occurs, the stresses no longer continue to increase with deformation and may even decrease in magnitude depending on the circumstances. However, by this time the magnitudes of ground movement are typically detectable by other means.

For many natural features that require protection, monitoring in the elastic range is precisely what is required.

3.2. 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.

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 upsidence (Mills and Huuskes 2004).

3.3. Borehole Cameras

Borehole cameras, televiewers, 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 nearby in undisturbed ground 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.

3.4. Piezometers

Piezometers are primarily used for monitoring groundwater behaviour. 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 above 120m wide longwall panels.

3.5. 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. More fractured ground takes more water. The test interval may 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 was clearly evident from this approach. These results correlate closely with more recent measurements over wider panels.

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.

3.6. Borehole Inclinometers

Inclinometers are devices that are lowered into special casing installed and grouted into, typically vertical, boreholes. Small changes in vertical alignment are able to be detected and repeat surveys allow the detection and quantification of shear movements within the overburden strata.

These instruments have been successfully used to monitor mining induced ground movements. They have been successfully deployed outside the high deformation zones that develop directly over longwall panels. Shear movements about longwall panels tend to be concentrated on specific horizons and the magnitude of horizontal shear movements experienced around longwall panels is often enough to prevent the instrument from moving beyond the uppermost shear horizon.

4. Vertical Subsidence

Monitoring of surface subsidence, sub-surface movements, and pillar behaviour has led to the recognition that vertical subsidence in single seam longwall operations is comprised of two essentially different 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 less commonly observed components are:

- Failure of chain pillar systems including the immediate roof and floor strata.

- Topography related dilational effects that cause upsidence and uplift.

4.1. 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 1.

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 has complicated interpretation of the mechanics involved.

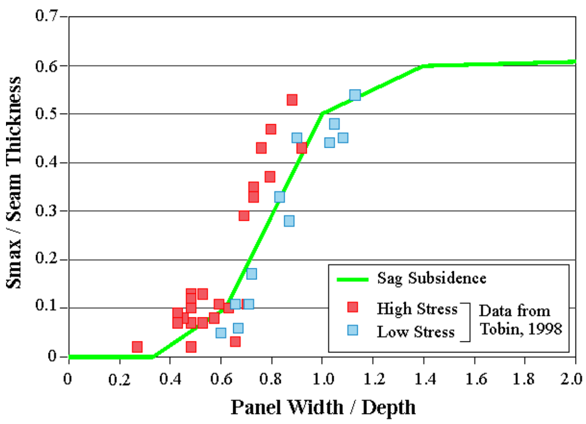


Figure 1: Generic sag subsidence.

The behaviour shown in Figure 1 is characteristic of strata behaviour in a wide range of geological settings. Shifts in the characteristic curve are recognised to occur as a result of horizontal stress magnitude within the overburden strata and the material property characteristics of the overburden strata.

Data presented by Tobin (1998) for longwall subsidence in the Newcastle area in essentially similar geological conditions is reproduced in Figure 1 shows 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 curve for panels oriented across the major principal stress (NW).

4.2. Elastic Compression Subsidence

Elastic compression subsidence above and below chain pillars occurs when multiple longwall panels are mined adjacent to each other. 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 to give the majority of 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 50-100m. At 500m, the accumulated elastic compression may increase to be in the range 700-1400mm (Mills 1998) because of the higher loads involved and the greater column of rock that is compressed.

4.3. 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).

4.4. Topographic Effects

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 discussed in the next section.

5. Horizontal Movements

The mechanics of horizontal ground movements has developed significantly in recent years as a result of the improvements in subsidence monitoring technique described in Sections 2 and 3.

In essence, horizontal movements are driven by the release of potential energy when the overburden strata subsides and/or by the release of tectonic energy stored as horizontal stresses within the rock mass.

The manifestation of this released energy varies with circumstance but can be grouped into three components:

- Systematic horizontal movements associated with vertical subsidence that occur in all types of terrain but are most clearly evident in flat terrain where the other two components are absent.
- Horizontal ground movements associated with surface topography that are driven by unbalanced dilational forces within the subsiding rock strata above the horizon of adjacent topographic low points (Mills 2001).
- Stress relief movements that are primarily driven by the release of horizontal stress either toward the goaf or toward topographic low points such as that described by Hebblewhite et al (2000).

5.1. Systematic Horizontal Movement

In areas where the surface topography is essentially flat and free from geological structure, horizontal movements are regular, systematic and relatively predictable. There is initial movement in a direction toward the goaf and then as mining proceeds a short distance past a given point, there is a reversal with subsequent movement toward the retreating face that leaves a permanent offset in the direction of mining.

The two stages of movement are complementary at the start of the panel and combine to cause larger horizontal movements in this area with typically higher strains. Beyond the finishing end of the panel, only the first stage of movement develops so the horizontal ground movements in this area tend to be less than equivalent points at the starting end of the panel.

5.2. Topographic Movement

Longwall mining causes vertical subsidence to develop incrementally as the longwall retreats. This incremental subsidence has the effect of causing the subsiding rock strata to dilate laterally – expand sideways – as a result of the differential vertical movement. The mechanics of this process have long been recognised in the soil and rock mechanics literature as being sensitive to the confining stress so that outward dilation is only significant at low confining pressures.

In flat terrain, the confining stresses and the action of systematic ground movements are high enough to suppress any tendency for lateral dilation. However, in terrain where there is topographic variability, the subsiding rock mass in the hillsides above the base of adjacent valleys is not laterally constrained or highly confined and is able to dilate laterally as the hillside subsides as illustrated in Figure 2.

The presence of horizontal bedding planes within the rock strata typically located above longwall operations provides additional freedom for the rock strata in the hillside to move laterally in a direction of least resistance which is typically in a downslope direction. The movement itself is horizontal, but the direction of movement is toward the valley or in other words down the slope, hence the term downslope movement.

GPS referenced three dimensional surveying, stress change monitoring, high resolution surveying, and general observations have shown that the lateral movements in a downslope direction toward a valley are generated as soon as mining proceeds under the side of the hill that leads down to the valley.

The lateral movements manifest themselves as shear along one or more bedding planes that are located at close to the base of the valley and extend back under the centre of the adjacent ridge, as stretching or tensile cracking along the top of the ridge, and as compression in the valley floor. Seedsman and Watson (2001) show this effect by removing the systematic horizontal movements from measured data at Newstan Colliery.

Hebblewhite et al (2000) present survey measurements in the Cataract Gorge showing the entire side of the gorge moving a distance of several hundred millimetres on a basal shear plane that daylights in or close to the bottom of the gorge. The movements in that case include a high proportion of stress relief, but the behaviour illustrates the significance of bedding plane shear at the base of topographic lows.

The compression that occurs in the base of valleys causes upsidence when rockbars caught in the compression zone become overloaded and fail as reported in Mills (2007). The shear movement on bedding planes is apparent as uplift – broad scale upward movement that increases with proximity to topographic low points.

The magnitude of horizontal movements that occur in a downslope direction is typically much higher than systematic ground movements. The magnitude of the downslope movement is sensitive to the direction of mining because of the sensitivity of dilation to confinement.

When mining occurs toward a valley, the systematic ground movements are of a stretching nature during the period of vertical subsidence so the lateral dilation and resulting horizontal movements are large. When mining away from a valley, the vertical subsidence causing dilation occurs when the systematic ground movements are compressional so that dilation and lateral movements are suppressed (Mills 2001).

5.3. Stress Relief Movement

Stress relief movements are primarily driven by the release of horizontal stress either toward the goaf or toward topographic low points. Stress relief movements are likely to

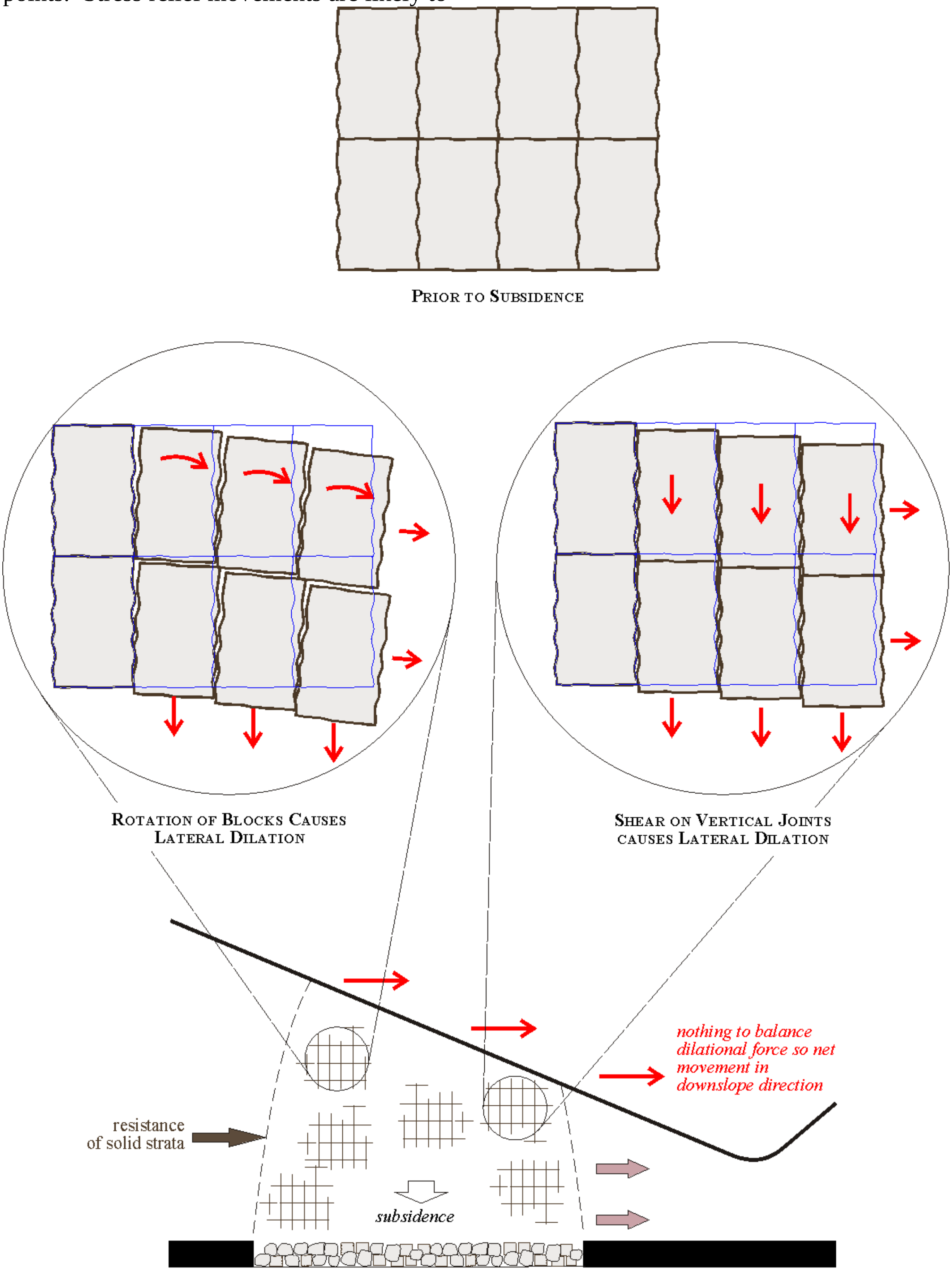


Figure 2: Imbalance of dilational forces in sloping terrain.

occur as relatively sudden events in the first instance and then incrementally as the extracted longwall geometry changes to allow further movement.

Such far-field horizontal movements have been observed and reported in the past by Reid (1991) and others to distances of the order of 1.5km from active mining. It is considered likely that such movements could extend considerably further when the longwall geometries and in situ stresses are favourable.

Mills et al (2011) report on far-field ground movements observed during the mining of the first panel in a new area at Ulan Coal Mine. Horizontal movements of 20mm are observed at a distance of approximately 1.6km from the edge of the panel. These movements are upslope and up dip so they are not considered to be associated with topographic effects or systematic horizontal movements.

Figure 3 shows the strains measured during a stress change monitoring program conducted recently at Ulan Coal Mine.

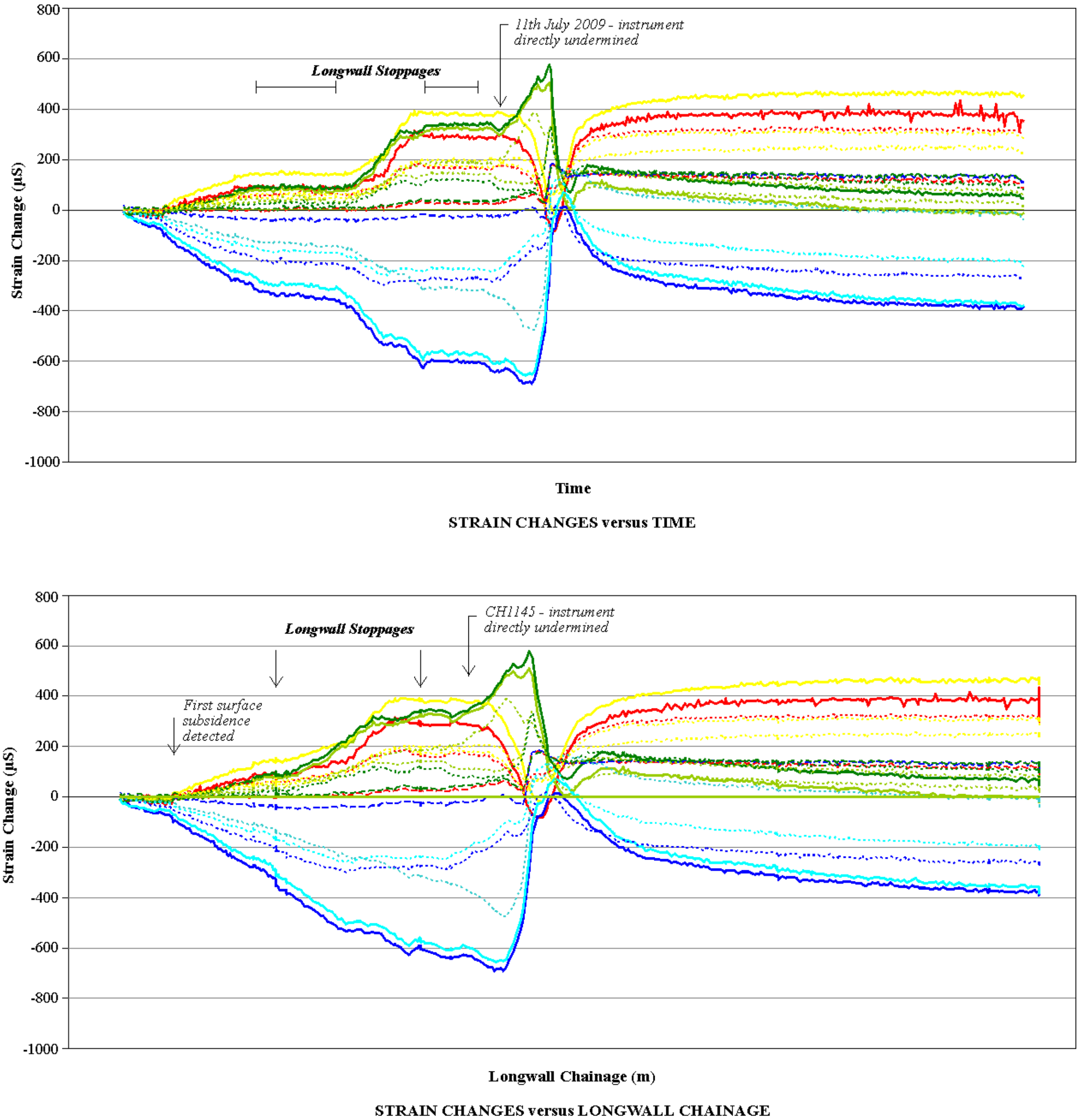


Figure 3: Strain changes measured by ULA22 monitoring cell during period of mining Longwall 25.

The instrument was located 12.9m below the surface. The longwall commenced mining 700m to the east at a depth below the surface of approximately 260m. Longwall operation was interrupted for a period of several weeks on two occasions. The observed strain changes cease as soon as the longwall stops mining and recommence again as soon as mining resumes.

The implication of these two sets of data is that horizontal stress changes within the overburden strata are perceptible to large distances from the longwall, develop in direct relationship to the mining geometry, at least in relatively flat terrain, and have the potential to occur as stick slip type movements.

6. Subsurface Movements

Subsidence monitoring provides an excellent view of the ground movements at the surface. By combining subsidence data from many different sites, it is possible to build up a montage of ground behaviour at a range of different overburden depths.

The characteristic curve shown in Figure 1 is replotted in Figure 4 in a way that is perhaps more intuitive. The data shown in Figure 4 is exactly the same data as shown in Figure 1, just plotted with depth over panel width on the vertical axis and subsidence over seam thickness on the horizontal axis. The data presented by Tobin (1998) is also plotted.

Synthesising the subsidence data from different sites with a variety of different overburden depth to panel width ratios as shown in Figure 4 provides a plot of ground movement in a composite overburden section. This composite shows that the ground movements above each panel can be divided into five zones starting at the top:

- A zone above 3.0 times panel width where there no ground movement (Zone 5).
- A zone of much smaller ground movements from 1.6 to 3.0 times panel width above the mining horizon (Zone 4).
- A zone of transitional ground movement from about 1.0 to 1.6 times panel width above the mining horizon (Zone 3).
- A zone of large downward movement from seam level to a height above the mining horizon approximately equal to the panel width (Zone 2).
- 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 (Zone 1).

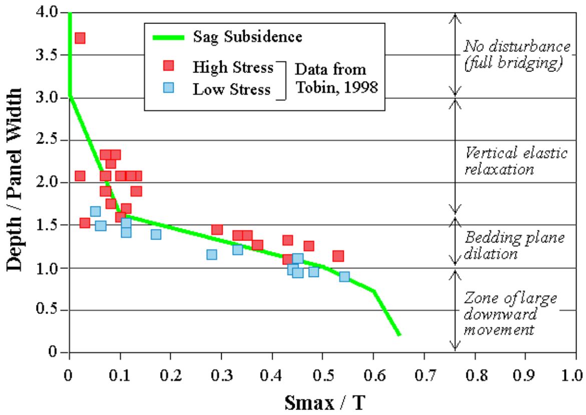
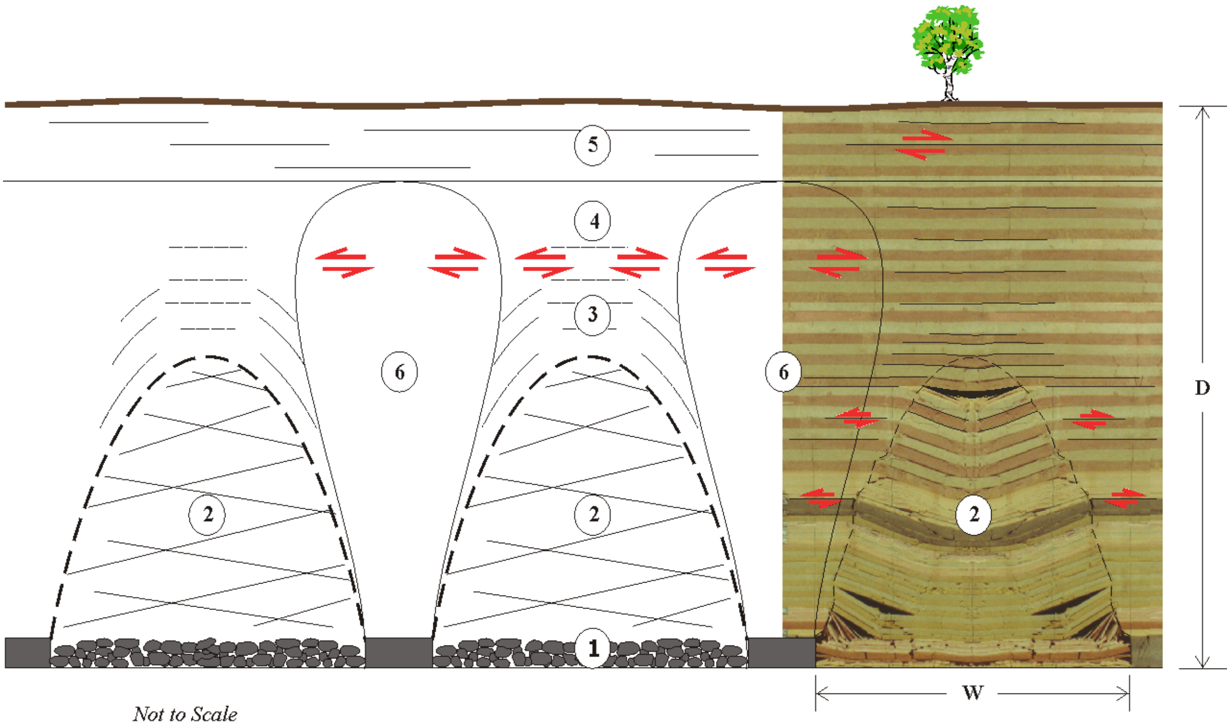


Figure 4: Downward movement within overburden strata implied by subsidence monitoring.

Figure 5 shows a schematic of the zones of ground displacement above multiple longwall panels differentiated in subsidence monitoring and characterised using camera observations, packer testing, piezometer data, and extensometer monitoring. The upper zones shown in Figure 5 are not to scale.

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



LEGEND

1. Zone of chaotic disturbance immediately above mining horizon (0-20m).
2. Zone of large downward movement (→1.0 x panel width).
3. Zone of vertical dilation on 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 during elastic compression subsidence of multiple panels.
6. Zone of compression above chain pillars.

Figure 5: Overburden caving behaviour inferred from surface extensometer monitoring at Clarence Colliery (Mills and O'Grady) and experience elsewhere.

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.

In Zone 4, between 1.6 and 3.0 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 about 1.0 times panel width, is the 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.

The Newcastle data presented by Tobin (1998) indicates that 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 reported by Gale (1986).

The implication of these results is that 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 overburden, 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 is reduced.

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.

7. References

ACARP 2011 “ACARP Project C15025 Effects of Surface Topography on Mining Subsidence Damage to River Channels” Australian Coal Association Research Program.

Anderson, L., Patterson, D., and Nicholson, M. 2007 “Measuring Mine Subsidence – BHP Billiton Illawarra Coal’s Diversified Approach” Proceedings of the 7th Triennial Conference on Mine Subsidence, Wollongong 25-27 November 2007 pp53-67.

Byrnes R.P. 1999 “Longwall Extraction Beneath Cataract Reservoir” UNSW Master of Engineering Science Thesis, July 1999, Student Number 2132875.

Gale, W.J. 1986 “The application of stress measurements to the optimisation coal mine roadway driveage in the Illawarra coal measures” Proceedings of the International Symposium on Rock Stress and Rock Stress Measurements, 1-3 September 1986, Stockholm, pp. 551-560.

Gale, W.J. 2010 “Stress conditions and failure mechanics related to coal pillar strength.” Proceedings of Workshop on Coal Pillar Mechanics and Design, Morgantown 2010.

Ge, L. 2008 “ACARP Report – DInSAR Component CRCSI UNSW” Internal Report to SCT dated 15 October 2008.

Gurtunca, R.G. 1984 “Sub-surface subsidence investigation” NSW PhD Thesis unpublished.

Hebblewhite, B.K., Waddington, A.A., and Wood J. 2000 “Regional Horizontal Surface Displacements Due to Mining Beneath Severe Surface Topography” Proceedings of 19th Conference on Ground Control in Mining, Morgantown, August 8-10 2000, pp149-157.

Holla, L. and Armstrong M. 1986 “Measurement of sub-surface strata movement by multi-wire borehole instrumentation” Bulletin of Proceedings of Australasian Institute of Mining and Metallurgy, Vol 291 No 7 October 1986 pp 65-72.

Holla L., and Buizen, M. 1991 “The Ground Movement, Strata Fracturing, and Changes in Permeability Due to Deep Longwall Mining” International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts Vol 28 No 2/3 pp 207-217.

Holt G.E. and Clark, D. 1998 “Subsidence Monitoring at Wambo Mine using Photogrammetry” Proceedings of 4th Triennial Conference of the Mine Subsidence Technological Society: Buildings and Structures Subject to Ground Movement, Newcastle 11-13 July 1998, pp143-156.

Kay D. 1991 “Effects of Subsidence on Steep Topography and Cliff Lines” End of Grant Report Number 1446 for NERDDP Report dated December 1991.

Kay, D.J., Whelan, B., Donald, G. and Pinkster, H. 2007 “Monitoring Mining Induced Strain in a Road Pavement Using Optical Fibres” Proceedings of 7th Triennial Conference of Mine Subsidence Technological Society: A Community Issue, University of Wollongong, 26-27 November 2007, pp 69-80.

McKenna, G.T. 1995 “Grouted-In Installation of Piezometers in Boreholes” Canadian Geotechnical Journal,Vol. 32: 355-363.

Mills, K.W. 1997 “In situ stress measurements using the ANZI stress cell.” Proceedings of Second International Symposium on Rock Stress and Rock Stress Measurements, 7-10 October 1997, Kumamoto, Japan, pp. 149-154.

Mills, K.W. 1998 “Subsidence Mechanisms about Longwall Panels” Proceedings of International Conference on Geomechanics/Ground Control in Mining and Underground Construction (GGM98), 14-17 July 1998, University of Wollongong, Vol 2 pp. 745-756.

Mills, K.W. 2001 “Observations of Horizontal Subsidence Movements at Baal Bone Colliery” Proceedings of 5th Triennial Conference of the Mine Subsidence Technological Society – Current Practice and Issues, Maitland 26-28 August 2001, pp 99-112.

Mills K.W. and Huuskes W. 2004 “The effects of mining subsidence on rockbars in the Waratah Rivulet at Metropolitan Colliery” Proceedings of Mine Subsidence Technological Society 6th Triennial Conference on Subsidence Management Issues, 31 October-2 November 2004, Maitland, NSW, pp. 47-63.

Mills K.W. 2007 “Subsidence Impacts on River Channels and Opportunities for Control.” Proceedings of 7th Triennial Conference of Mine Subsidence Technological Society: Subsidence a Community Issue, Wollongong University, 26-27 November 2007, pp 207-218.

Mills, K.W., Morphew, R.H., and Crooks, R.J. 2011 “Experience of Monitoring Subsidence at Ulan Coal Mine”

Proceedings of 8th Triennial Conference on Mine Subsidence, Pokolbin.

Nicholson M. 2010 Pers. Comm.

Seedsman R.W., and Watson G. 2001 "Sensitive Infrastructure and Horizontal Ground Movements at Newstan Colliery" Proceedings of the 5th Triennial Conference of Mine Subsidence, August 2001 pp171-180

Soole, K., Poropat, G., Mills, K. & Radloff, B. 2001 "Displacement monitoring and visualisation using terrestrial photogrammetry" Proceedings of 5th Triennial Conference on Coal Mine Subsidence Current Practice and Issues, 26-28 August 2001, Maitland NSW, pp. 181-187.

Reid, P. 1991 "Monitoring of Mine Subsidence Effects Adjacent to Cataract Reservoir" Proceedings of 2nd Triennial conference of Mine Subsidence Technological Society, Maitland 25-27 August 1991 pp 46-46.

Reynolds, R.G. 1977, "Coal Mining Under Stored Waters" Report to the Minister of Public Works on an Inquiry into Coal Mining under or in vicinity of the stored waters of the Nepean, Avon, Cordeaux, Cataract and Woronora Reservoirs, New South Wales, Australia.

Schaller, H. and Hebblewhite, B.K. 1981 "Rock Mechanics Design Criteria for Longwall Mining at Angus Place Colliery" ACIRL Report 81-3, p46.

Tobin, C. 1998 "A Review of the Newcastle Subsidence Prediction Curve" Proceedings of AusIMM No 1 1998 p59-63.