2017

# Insights into the mechanics of multi-seam subsidence from Ashton underground mine

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## Publication Details

Ken Mills and Stephen Wilson, Insights into the mechanics of multi-seam subsidence from Ashton underground mine, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 17th Coal Operators' Conference, Mining Engineering, University of Wollongong, 8-10 February 2017, 51-66.

# INSIGHTS INTO THE MECHANICS OF MULTI-SEAM SUBSIDENCE FROM ASHTON UNDERGROUND MINE

Ken Mills[1] and Stephen Wilson[2]

*ABSTRACT:* Examples of subsidence monitoring of multi-seam mining in Australian conditions are relatively limited compared to the extensive database of monitoring from single seam mining. The subsidence monitoring data now available from the mining of longwall panels in two seams at the Ashton Underground Mine (Ashton) provides an opportunity to significantly advance the understanding of subsidence behaviour in response to multi-seam mining in a regular offset geometry. This paper presents an analysis and interpretation of the multi-seam subsidence monitoring data from the first five panels in the second seam at the Ashton Underground Mine. The methods used to estimate subsidence effects for the planned third seam of mining are also presented.

Observations of the characteristics of multi-seam subsidence indicate that although more complex than single seam mining, the subsidence movements are regular and reasonably predictable. Movements are constrained within the general footprint of the active panel. They are however sensitive to the relative panel geometries in each seam and to the direction of mining. In an offset geometry, tilt and strain levels are observed to remain at single seam levels despite the greater vertical displacement. At stacked goaf edges tilt and strain levels are up to four times greater. Latent subsidence recovered from the overlying seam has been identified as a key contributor to the subsidence outcomes. Some conventional single seam concepts such as angle of draw and subcritical/supercritical behaviour are less meaningful in a multi-seam environment.

## INTRODUCTION

An environmental assessment of subsidence impacts and consequences to the natural and built surface and sub-surface features is required for all mining approvals in New South Wales (NSW). The prediction of subsidence effects to inform environment and infrastructure risk assessments is one of the first steps in the approval pathway. Prediction of subsidence effects for single seam coal mining in NSW has a basis in analysis of the extensive empirical subsidence monitoring databases by Holla and others (Holla 1987, Holla 1991, Holla and Barclay 2000) for the Newcastle, Western and Southern Coalfields. The Holla approach provides for the estimation of the main subsidence parameters; vertical displacement, tilt and strains.

No such databases currently exist for multi-seam mining. Case studies of longwall mining in multi-seam environments by Li *et al* (2007 and 2010) and MSEC (2007) have generally involved irregular longwall geometries or a combination of longwall and pillar extraction (bord and pillar) areas. While the effects of multi-seam mining to tilt and strain levels have been discussed, the recommendations of these previous studies by Li et al (2007) are mainly restricted to methods of estimating the magnitude of vertical displacement.

At Ashton, a conservative approach based on 85% of the combined seam or mining heights (after Li *et al* 2010) was used to estimate vertical subsidence. In the absence of published guidelines for multi-seam tilts and strains, estimations of these subsidence parameters were made using the Holla (1991) approach for single seam mining in the Western Coalfield with inputs of vertical subsidence derived from the Li *et al* subsidence approach.

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Site specific monitoring data now available from the mining of the first five longwall panels in the second seam at Ashton, indicates that the Li *et al* (2010) method provides a generally conservative estimate of vertical displacement at this site. The Holla (1991) approach overestimates tilt and strain for an offset geometry but underestimates tilt and strain for a stacked geometry. The monitoring undertaken at Ashton allows these estimates to be refined for particular geometries.

The Ashton site is unique when compared to other multi-seam sites for a number of reasons. These include:

- modern, reliable mine plan records
- no areas of irregular pillar extraction (bord and pillar mining)
- no potential for small pillars (or 'stooks') to fail and contribute to risk of pillar run or pillar creep
- only longwall mining in a regular, parallel layout with substantial remaining chain pillars
- gradually increasing overburden thickness toward the west, so that the depth to panels increases with each subsequent panel
- longwall panels with different starting and finishing positions and goaf edge geometries that enable a range of mining scenarios to be studied.

## BACKGROUND AND SITE DESCRIPTION

Ashton Coal Operations Pty Ltd (ACOL), owned by Yancoal Australia Ltd, operates the Ashton Underground Mine near Camberwell in the Hunter Valley of NSW. The mine operates via modified development consent for the Ashton Coal Project (ACP). The mining approval covers the mining of four seams. In descending order these seams are the Pikes Gully (PG), Upper Liddell (ULD), Upper Lower Liddell (ULLD) and Lower Barrett (LB).

Figure 1 is a site plan showing the outline of the longwall panels for the PG, ULD and ULLD seams with the position of subsidence monitoring lines on a topographic map of the surface area.

The first longwall in the uppermost PG Seam commenced extraction in 2007. A series of eight longwall panels have been mined in the PG Seam. The longwalls in the second seam (ULD Seam) started in 2012. ACOL commenced mining the fifth longwall (Longwall 105) in the ULD Seam below the previous PG Seam panels in 2016.

The panels in each of the four seams were originally approved to be arranged in a regular, parallel, stacked (superimposed) geometry. The layout design has been modified to an offset (staggered) geometry to reduce subsidence impacts and take advantage of reduced stress conditions during roadway development.

In this offset geometry the 1$^{st}$ (PG) and 3$^{rd}$ (ULLD) seams are superimposed. The 2$^{nd}$ (ULD) and 4$^{th}$ (LB) seams are also superimposed but with a 60 m offset, to the west, relative to the other two seams.

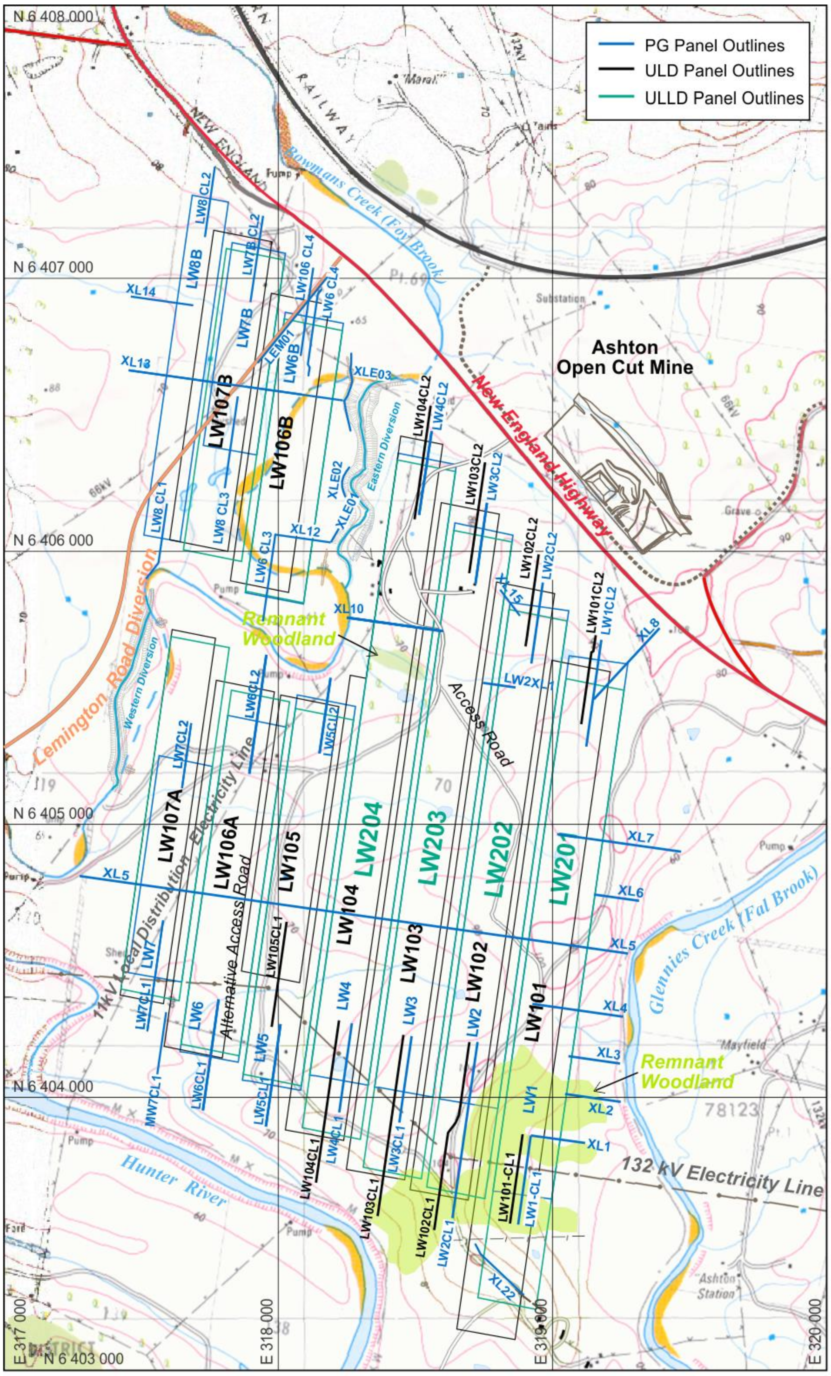


**Figure 1: Site Plan showing longwall panels within the PG, ULD and ULLD seams with subsidence monitoring lines superimposed onto a 1:25,000 topographic series map of the area.**

All longwalls panels form a void that is nominally 216 m wide. All inter-panel chain pillars are 24 m wide (coal rib to rib). The panels are aligned in a general north-south direction. The longwall face retreats from south to north. The panel sequence is from the east to the west. The naming convention for corresponding panels is Longwall 1 in the PG Seam, Longwall101 in the ULD Seam and Longwall 201 in the ULLD Seam.

The overburden depth to the PG Seam increases from around 40 m in the northeast corner of Longwall 1 to around 180 m in the southwest corner of Longwall 7. The interburden thicknesses are generally around 35-40 m for the PG to ULD seams, 20-25m for the ULD to ULLD seams and 35-45 m for the ULLD to LB seams.

The mining height for each seam is approximately 2.5 m ±0.3 m. Mining heights are either a function of the seam thickness or the practical operating range of the mining equipment.

The strata dip moderately to the west at around 1 in 10. This strata gradient is generally greater than the gradients of the surface topography.

The surface topography above the mining area is dominated by a steeply rising ridge line adjacent to Glennies Creek in the east from which the ground slopes west toward Bowmans Creek and the Hunter River to the south.

The longwall mining area is bounded by consideration of the subsidence impacts and consequences to both the natural and built surface and sub-surface features. The main features include the New England Highway and infrastructure in the north, Glennies Creek to the east, the Hunter River to the south and to the west, a combination of Bowmans Creek, Bowmans Creek Diversions and adjacent mining operations.

## OVERVIEW OF SUBSIDENCE MONITORING

Subsidence monitoring began with the commencement of PG Seam longwall operations in early 2007 and has continued above all the panels mined since then. Subsidence monitoring above the ULD Seam Longwalls 101-104 commenced in 2012.

The monitoring data provides significant insight into the mechanics that drive the magnitude and the distribution of subsidence movements in the multi-seam environment at the site. Effects such as:

- difference in behaviour between strata that is undisturbed by previous mining and strata that has already been subsided
- recovery of latent subsidence from the overlying seam
- particular behaviour that occurs above stacked goaf edges
- the effect of mining direction on subsidence above stacked goaf edges.

### Subsidence monitoring and observation

A comprehensive subsidence monitoring program involving high confidence three dimensional (3D) survey measurements has been in place since the inception of longwall mining at the Ashton site.

For the PG Seam longwalls, some 35 monitoring lines have been installed and regularly surveyed. These subsidence monitoring lines are aligned both along the panels (longitudinal) and across the panels (transverse). Additional 3D monitoring has also been conducted at other surface features or infrastructure.

For the ULD Seam mining a series of around 10 longitudinal lines have been established adjacent to the PG Seam lines at both the southern and northern ends of panels. Measurements have regularly been recorded on these ULD Seam monitoring lines to supplement further surveys on the cross panel lines previously installed for the PG Seam mining.

The main cross panel line (XL5) extends over all the southern longwalls in both seams. This line was resurveyed along its full length at the completion of the PG Seam longwalls and again after the fourth longwall in the ULD Seam.

Subsidence behaviour observed for the PG Seam mining has been consistent with the subsidence behaviour expected in panels of supercritical width and within the range as indicated by the Holla (1991) Western Coalfield guidelines.

The results of the ULD Seam monitoring show that subsidence behaviour falls into two categories depending on the relative geometries of the mining in the two seams. In most areas, subsidence behaviour can be categorised as general background subsidence behaviour with tilts and strains of similar magnitude to those observed in the PG Seam. Where the goaf edges in the two seams are located directly above each other, a different style of behaviour is apparent.

**General subsidence behaviour**

Figure 2 shows recent subsidence monitoring results from XL5 Line, the main cross-panel subsidence line over all the southern panels.

Measurements at the ACP site indicate single seam mining of undisturbed ground causes surface vertical subsidence of generally about 50-60% of the seam thickness mined.

Where panels in two seams overlap in the offset geometry, mining a second seam below already disturbed ground causes maximum cumulative subsidence from mining both seams of about 62-72% of the combined mining thickness. The general incremental subsidence for the second seam mined is in the order of 72-83% of the mining height.

Near goaf edges in the overlying seam, maximum incremental subsidence is observed to increase as a result of what is referred to as latent subsidence; subsidence which did not occur during mining of the first seam owing to the support provided by nearby chain pillars but is recovered when the second seam is mined. Subsidence as high as 92% of the second seam mining height is apparent when latent subsidence occurs, but the magnitude of this additional subsidence is not a function of the seam mining height in the lower seam so representing it as such is somewhat misleading.

Remote from pillar and goaf edges the maximum values of tilt and strains are typically of a similar or lower magnitude to the tilt and strains measured for the first seam mined despite the greater total vertical subsidence. The maximum values of tilt and strain are typically less than the maximum calculated assuming single seam mining conditions but occasionally increase to the same magnitude as those measured during mining in the PG Seam. This behaviour is thought to be due to a general softening effect of the multi-seam mining and the difference in behaviour between strata that is undisturbed by previous mining and strata that has already been subsided (disturbed or modified).

**Behaviour at stacked goaf edges**

A different behaviour is observed in areas where overlying goaf edges interact to form a stacked goaf edge. At these stacked goaf edges and particularly when the deeper seam has undercut the upper seam by a distance about equal to the interburden depth between seams, transient tilts and strains have been recorded as being much higher than elsewhere.

Figure 3 shows subsidence monitoring results from the northern end of Longwall 102 where this panel mined directly under an existing goaf edge in the PG Seam so that the goaf edges in the PG and ULD Seams were momentarily stacked directly above each other before being undercut.

At a stacked goaf edge where the lower seam is mined into solid from below an existing goaf in the upper seam, a double goaf edge is formed. Maximum tilts in these areas are observed to be about double the maximum general background levels. Horizontal strains are observed to peak at about four times the background levels observed more generally along the panel. These maxima are observed when the goaf edge in the upper seam is undercut by a distance equal to about 0.7 times the interburden thickness.

Where mining in the lower seam has continued beyond the stacked goaf edge and beyond the undercut these high values associated with the stacked goaf edge decrease towards the more general levels measured elsewhere along the panel.

The presence of the transition from goaf to solid at a goaf edge created by mining in the overlying seam appears to focus additional subsidence movements associated with mining the deeper seam into the same location. The strains and tilts reach a maximum when the lower seam has mined past the upper seam goaf edge by a distance of about 0.7 the separation between the two seams, or where the caving of the goaf at the lower seam longwall face intersects the goaf edge in the upper seam.

Figure 4 illustrates the retreat of the ULD Seam longwalls under the PG Seam goaf edge/ solid coal and how the subsiding strata interact with the overlying goaf edge as the panel retreats. In effect, the presence of the pre-existing goaf fractures from the PG Seam mining acts as a preferred separation point so that further deformations from the ULD Seam mining are concentrated at these fractures temporarily elevating the tilt and strain levels.

Where the lower seam is mined as a single seam situation and merges under an overlying goaf, a variation of stacked goaf edge is formed. The nature of the subsidence profile in this circumstance is significantly different with a large block above the start of the overlying panel subsiding en masse as the existing goaf edge is mined under in the lower seam. The subsidence parameters of tilt and strain are of similar magnitude to single seam mining.

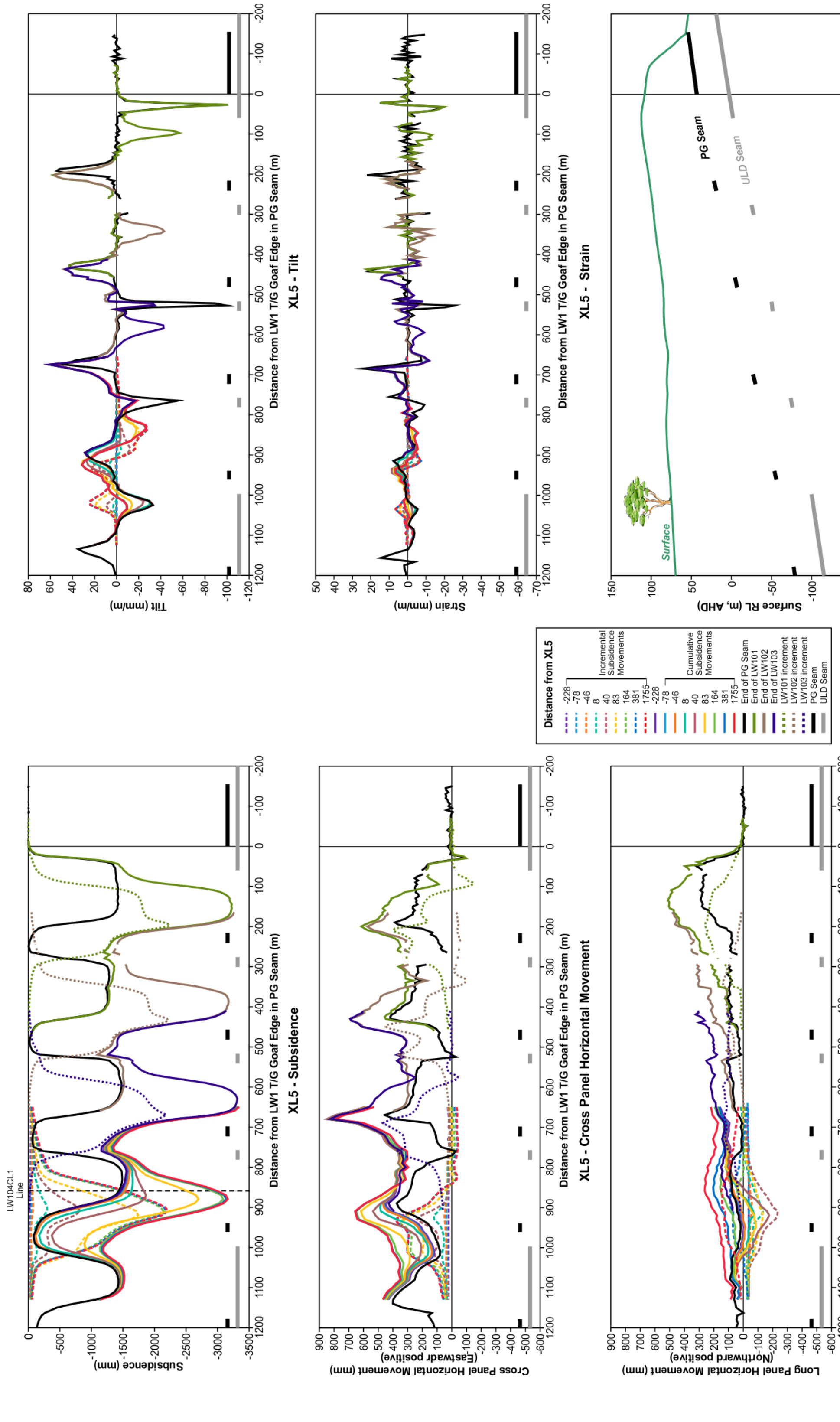


**Figure 2: Subsidence movements observed on Line XL5 during mining of Longwall 104 (including Longwalls 101-103).**

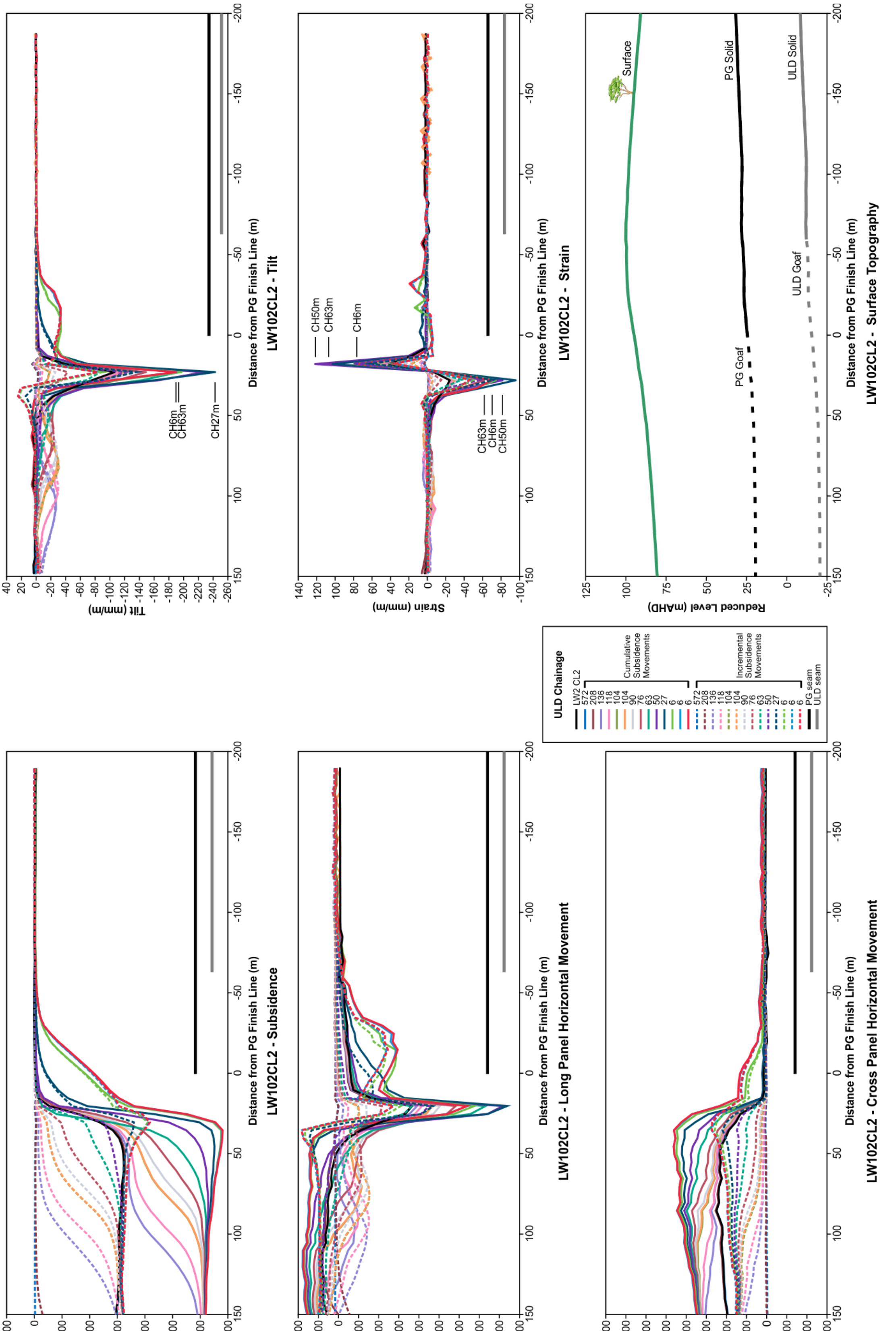


**Figure 3: Subsidence monitoring results at the northern end of Longwall 102 where this longwall mined directly below an existing goaf edge in the PG Seam to create a stacked geometry.**

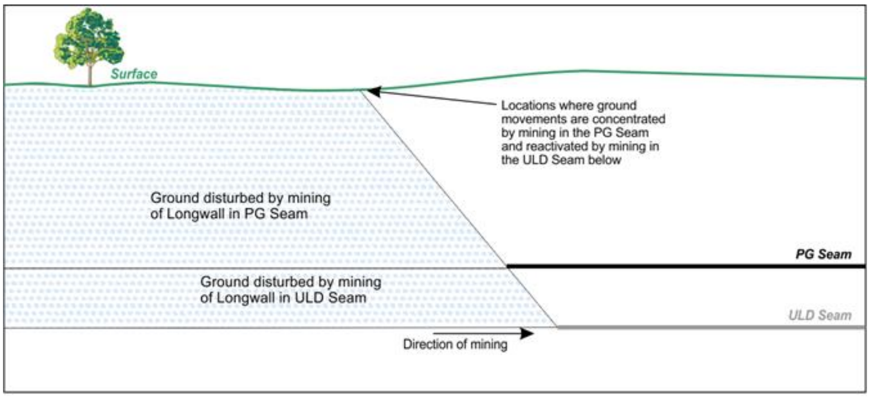


**Figure 4: Sketch illustrating the mechanism that concentrates the strata movements during mining in the ULD Seam at the same location as they were concentrated during mining in the PG Seam.**

Figure 5 illustrates the geometries involved and shows how the disturbance caused to the ground by mining each of the two longwall panels in two different seams leaves a triangular wedge of largely undisturbed ground above the start of the PG Seam longwall. This triangle of rock subsides gradually en-masse as mining in the underlying ULD Seam progresses.

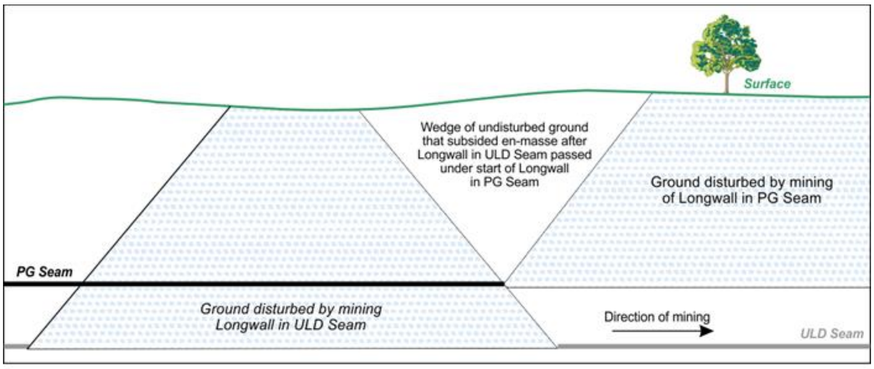


**Figure 5: Sketch illustrating the mechanism by which a wedge of undisturbed strata subsides as the ULD Seam longwalls mine under the start of the PG Seam longwalls.**

The direction of mining in the second seam under an existing goaf has a significant influence on the surface effects that develop. Mining from a goaf under solid leads to a stacked goaf edge that produces very high tilts and strains and much higher than the general background values. Mining from solid to under a goaf produces an en masse subsidence effect with tilts and strains that are comparable to general background levels.

Incremental vertical subsidence above the ULD Seam chain pillars between Longwall 101 and Longwall 104 is approximately 200-300 mm at a depth to the lower seam of around 140 m. This subsidence is much higher than the elastic strata compression of 20-30 mm observed above the chain pillars formed by mining in the PG Seam in the same area. This is considered to be a result of compression of the disturbed ground above the lower seam chain pillar and the reduced stiffness of this ground from the previous episode of mining.

**Horizontal movement**

The magnitude, direction, and form of horizontal movements are consistent with the cross-panel horizontal movement observed during mining of the PG Seam longwalls. The influences of the offset geometry and latent subsidence recovered from the PG Seam are seen in the profile as a regular pattern of incremental horizontal movements associated with the ULD Seam mining.

Horizontal subsidence movements measured above the first four longwalls in the ULD Seam are typically in the range of 20-30% of the vertical subsidence. There is a strong similarity in the characteristics and distribution of horizontal subsidence movements between these longwalls indicating a consistent mechanism driving the horizontal movements. There is also a strong influence of strata dilation in the development of horizontal movements causing a general shift in an uphill direction.

Figure 6 illustrates the mechanics of the upslope horizontal movements over longwall panels at Ashton.

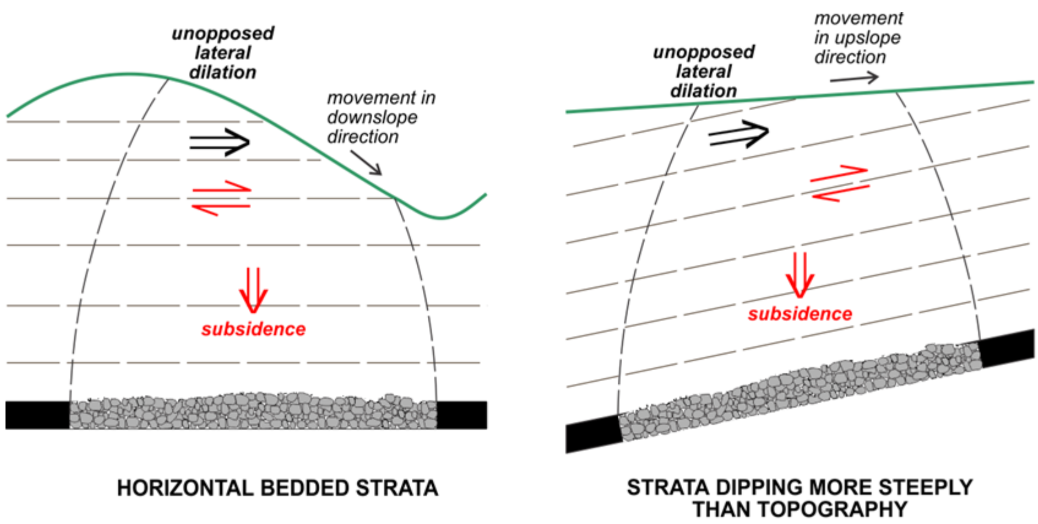


**Figure 6: Sketch illustrating the mechanics of upslope horizontal movement at Ashton.**

The incremental long panel horizontal movements are characterised by movement toward the approaching longwall face, followed by movement in the reserve direction after the longwall face has passed.

The maximum total horizontal movement above each of the first four ULD Seam longwalls is typically about 0.8 m. This total horizontal movement is dominated by the cumulative cross panel movements which generally reaches a magnitude of about 0.7 m to the east (i.e. uphill) at a location near the western edge of the overlap between each of the ULD Seam longwalls and the corresponding PG Seam longwall above.

**Multi-seam subsidence zones across the panel width**

Observations of the vertical subsidence profile show a number of distinct zones of ground behaviour through the interaction of the mining geometries of each seam. These zones include:

- subsidence outside the current panel but over previous goaf
- subsidence remote from chain and abutment pillars in both seams
- latent subsidence adjacent to overlying chain pillar
- subsidence above undermined chain pillar.

The individual components of the increment of subsidence are shown in Figure 7. Each of these components has different characteristics:

**Subsidence outside the current panel but over previous goaf**

Beyond the vertical subsidence profile for the first seam mining, the second seam mining causes only a small amount of additional subsidence due the undermining of the softer disturbed (modified) ground.

**Subsidence remote from chain and abutment pillars in both seams**

For the first seam of mining the vertical displacement is around 1.4 m or 55-60% of seam mining height. After the second seam is mined an increment of 1.8m or 70-75% of the second seam mining height is realised. The total cumulative vertical subsidence is 3.3 m or 65-70% of the combined seam mining heights.

**Latent subsidence adjacent to the overlying chain pillar**

Increases in the incremental vertical subsidence profile for the second seam of mining are seen adjacent to both sides of the overlying chain pillar. The second seam mining causes a maximum incremental vertical subsidence of 2.2 m. This subsidence represents 85-90% of the second seam mining height. However, this subsidence includes latent subsidence recovered from the upper seam that was previously restricted by the supporting effects of the nearby chain pillar. Latent subsidence is not a function of the mined seam height in the lower seam.

**Subsidence above undermined chain pillar**

For the first seam mining the vertical displacement is less than 0.1 m as expected for a supercritical geometry at shallow overburden depth. After the second seam is mined the increment of vertical subsidence is 1.4m or the same as the subsidence in the first seam in areas remote from the chain pillar or panel edges. A cycle of mining one longwall panel causes undisturbed ground to subsidence by a given amount of 50-60% of seam thickness whether it is the first seam mined under undisturbed ground or the second seam mined under undisturbed ground above a chain pillar in the first seam.

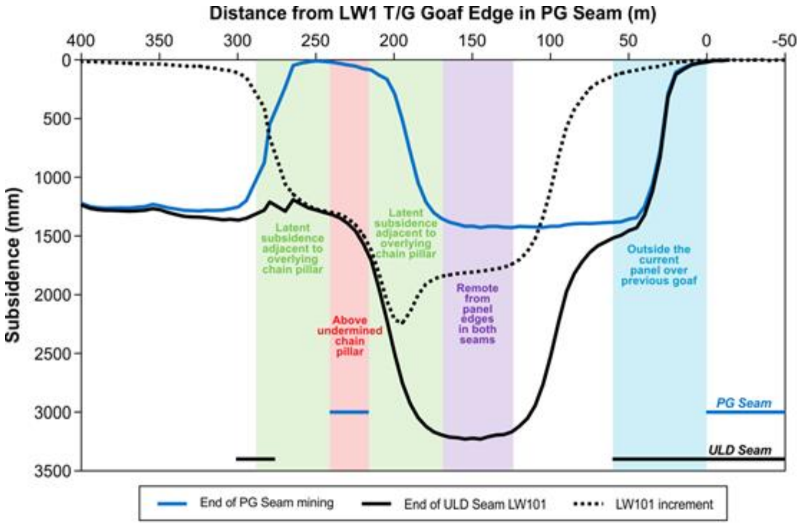


**Figure 7: Individual components of incremental subsidence profile.**

## MULTI-SEAM INCREMENTAL SUBSIDENCE OBSERVATIONS

The subsidence monitoring above Longwalls 101-104 (and the preliminary results from Longwall 105) indicates that for an offset mining geometry, the maximum subsidence can now be estimated with reasonable confidence in the multi-seam environment at the ACP site. The subsidence profile is also relatively predictable once the specific mechanics of the interaction of the two seams is recognised.

Figure 8 shows the incremental vertical displacements and cross panel horizontal movements for the five ULD Seam longwalls (Longwalls101-105) mined to date. The profiles are overlaid relative to each ULD Seam panel edge. The subsidence behaviour observed indicates:

- a regular, repeatable form, with a general smoothing and reduction in peak values with increasing overburden depth
- the maximum vertical and horizontal movements occur substantially within the footprint of the active panel
- movements over the previous panel are insignificant for all practical purposes
- the influence of the recovered latent subsidence from the PG Seam extends over the softer, disturbed ground of the next panel due to the location of pillars in this offset panel geometry.

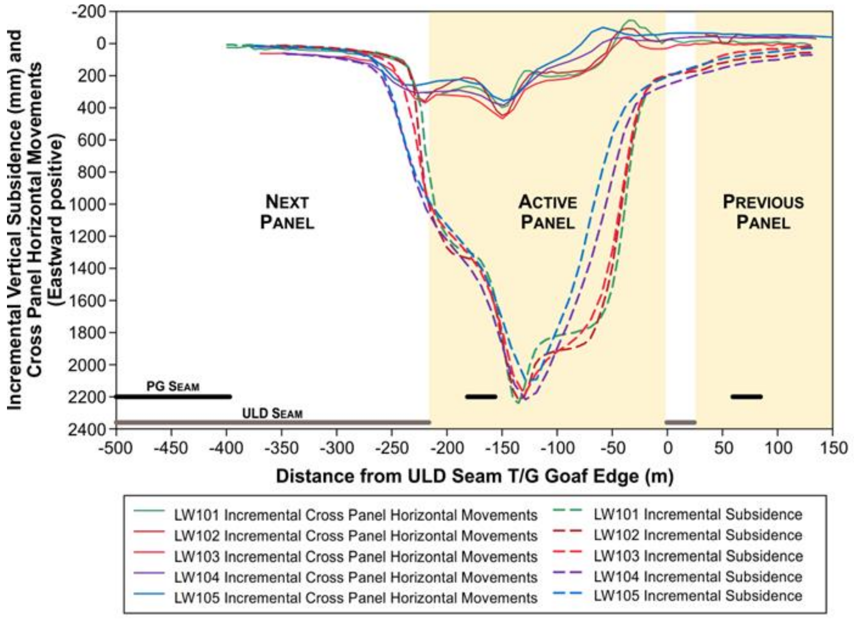


**Figure 8: Incremental Vertical Subsidence and Cross Panel Horizontal Movements and for LW101, LW102, LW103, LW104 and LW105.**

## IMPLICATIONS FOR SUBSIDENCE PREDICTIONS

It is clear from this data that multi-seam subsidence presents a number of challenges for describing the subsidence behaviour. In a single seam mining environment, the subsidence behaviour is consistent with and largely controlled by the mining geometry in the seam that is mined. In a multi-seam mining environment, the presence of previous mining in an overlying seam means that the subsidence behaviour is no longer simply a geometrical function of the seam being mined, but rather a sometimes complex interaction of the geometries in both seams. Furthermore impact assessments need to recognise the effects of earlier mining.

At some locations, the incremental subsidence may be a higher proportion of the seam thickness in the second seam mined when subsidence associated with mining in the first seam is recovered. This recovering of latent subsidence is particularly evident around the edges of the first seam panels where the overburden strata was supported on the chain pillars and abutments following mining in the first seam. When the second seam mines under the chain pillars and other abutment edges, the strata above the first seam chain pillar and abutment edges is disturbed and the supporting effect around the edges is lost. The ground above the edge of the first seam chain pillar and other abutments subsides by an increased amount that includes subsidence that did not occur during mining in the first seam. This latent subsidence increment has both vertical and horizontal components.

An understanding of both the magnitude and distribution of this latent incremental subsidence is useful for estimating the likely cumulative subsidence profile for any future mining. The maximum subsidence is not simply the addition of all the maximum increments, but rather the addition of the individual incremental profiles for each seam including the areas of latent subsidence.
Figure 9 shows the latent vertical subsidence sections (adjacent to the overlying chain pillar edges) in the ULD Seam incremental vertical subsidence profile across all longwall panels.

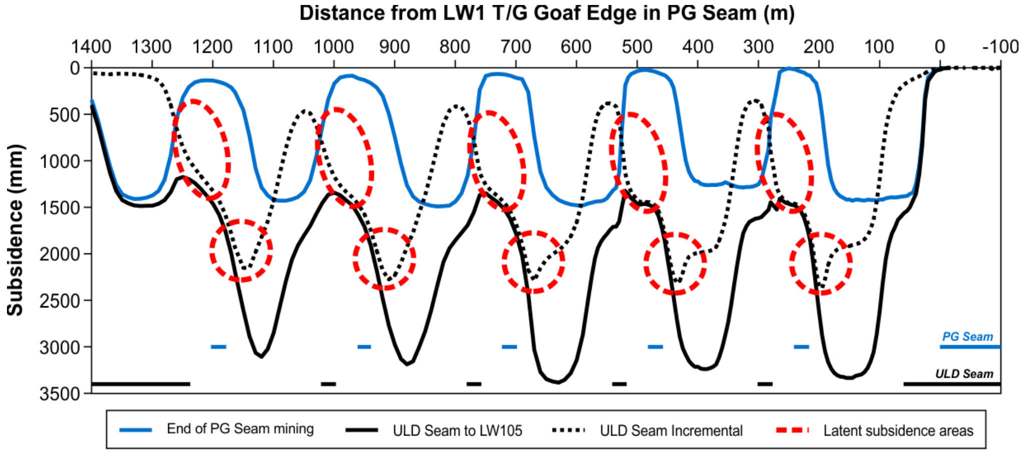


**Figure 9: XL5 monitoring line subsidence - Latent vertical subsidence sections (adjacent to overlying chain pillar) in ULD Seam incremental subsidence profile.**

Figures 10 and 11 show examples of the latent vertical subsidence recovered at goaf edges from monitoring along the panels, including a temporary stacked goaf edges near the northern end of the panels.

The concept of an angle of draw determined purely as a function of overburden depth becomes somewhat less meaningful in a multi-seam mining environment because of the influence of previous mining and the interaction of overlying geometries. Beyond the solid goaf edge in the outermost seam, angles of draw appear to have a similar magnitude to those in a single seam mining environment. Where there is an existing goaf, the concept of an angle of draw becomes less meaningful not only because of the previous subsidence that has occurred but also because of the influence of latent subsidence.

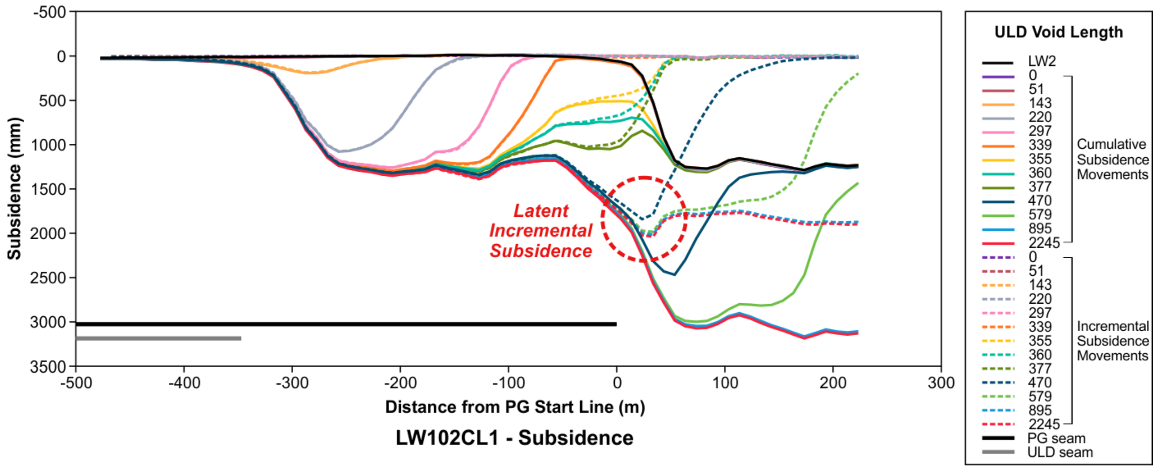


**Figure 10: Subsidence movements observed on Line LW102CL1 during mining of Longwall 102.**

## IMPROVED PREDICTION METHODOLOGY

The method used to predict subsidence for the ULD Seam longwalls was originally based on 85% of the combined seam mining thickness (after Li *et al* 2010). The guidelines presented by Holla (1991) for the Western Coalfields were used to estimate tilts and strains. These approaches appear to still be valid based on the comparison of past predictions with subsequent measurements, but there is clearly room for refinement now that more multi-seam subsidence monitoring data is available.

The measurements from Longwalls 101-105 indicate that the maximum cumulative vertical subsidence was less than 75% of the combined seams extraction heights. The maximum incremental vertical displacement due to the recovery of latent subsidence adjacent to abutment or pillar edges was higher than 85% of the ULD Seam mining thickness but this latent subsidence is subsidence that did not occur during mining in the first seam. Latent subsidence effects need to be determined separately from the general body subsidence.

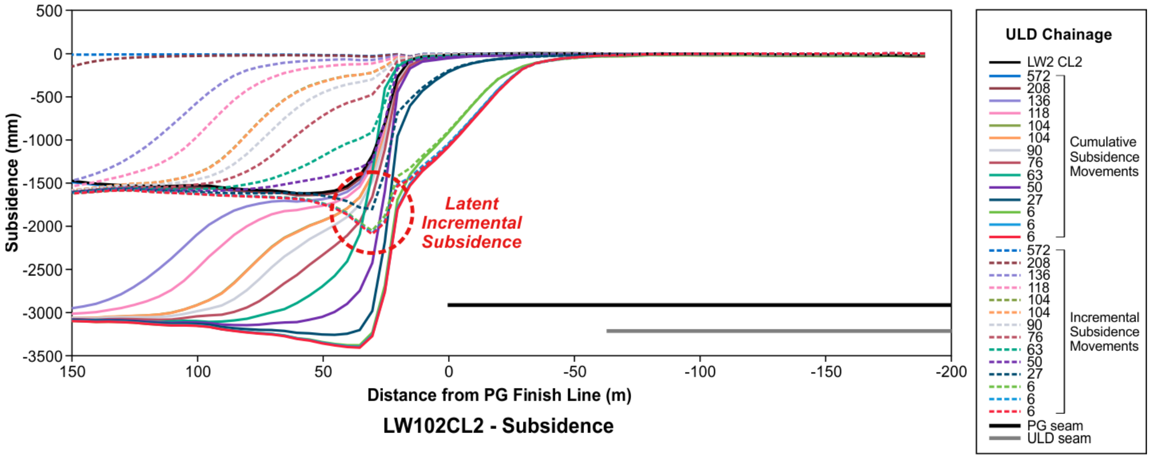


**Figure 11: Subsidence movements observed on Line LW102CL2 during mining of Longwall 102.**

The monitoring data from Longwalls 101-105 indicates that the use of 85% of the combined seam mining heights is a reasonably conservative approach to estimating maximum cumulative subsidence. A refinement to this estimating method is used to predict the total subsidence profile for the proposed ULLD Seam mining. This method estimates the incremental subsidence profile i.e. the subsidence associated with mining in the ULLD Seam, additional to the actual cumulative subsidence that previously occurred due to mining in the PG and ULD Seams, rather than a percentage of the combined seams mining heights, as the cumulative subsidence from the PG and ULD seams is known.

A conservative approach has been adopted for estimating the incremental subsidence for the proposed ULLD Seam longwalls as this will be the first occasion in Australia where longwall mining extracts three coal seams in a multi-seam operation.

The estimated incremental subsidence profile for Longwalls 201-204 is based on 85% of the planned mining height of this seam plus an allowance for the amount of latent subsidence to be recovered from around pillar and abutment edges in the overlying seam (or seams). The allowance for latent subsidence is somewhat interpretative but is consistent with the site parameters (similar seam mining heights) and improved understandings of multi-seam subsidence gained from the monitoring conducted to date. A small additional allowance is then applied for any remaining uncertainties around the extent of the multi-seam interactions as overburden depth increases and for any other variations in mining heights and depth of cover along the length of the panels.

Maximum strains and tilts are sometimes of interest on an incremental basis, and sometimes on a cumulative basis. The monitoring data from Longwalls 101 to 104 indicates that strains and tilts for general background conditions in an offset geometry are quite different to, and much less than, the strains and tilts observed at stacked goaf edges. Maximum strains and tilts therefore need to be estimated for six different conditions; incremental and cumulative for general background, disturbed or modified ground locations, and at stacked goaf edges or undercut stacked goaf edges.

To estimate maximum strains and tilts, the Holla approach captures the key drivers and allows the differences between the levels of background offset geometries and stacked geometries to be accommodated by varying the constant of proportionality K values.

K values derived from analysis of the subsidence database for Longwalls 101-104 appear suitable to use with the Holla approach to provide a reasonable and conservative estimate of the measured strains and tilts for the six combinations of incremental and cumulative subsidence in general background (disturbed or modified ground) locations, or at stacked goaf edges and/or undercut stacked goaf edges.

Using these K values, estimates for the maximum values for tilts and strains expected at the stacked goaf edge locations can be calculated. The appropriate K values to use at any given location depend on consideration of the direction of mining and how closely the geometry represents a variant of a stacked goaf edge.

The challenge for the proposed ULLD Seam mining subsidence predictions remains in accurately estimating the profile of incremental subsidence and the tilt and strain values from the various components that are now recognised to contribute to the total subsidence movements. Additional factors not significant in single seam mining such as direction of mining relative to existing goafs, separation between existing goafs and latent subsidence effects have a significant influence on estimation of the subsidence profile and maximum tilt and strain levels in a multi-seam operation. Despite these challenges there is substantial confidence that the current predictions contain sufficient conservatism to inform environmental assessment processes.

## CONCLUSION

The monitoring data from Ashton allows significant advances in the understanding of multi-seam subsidence behaviour. The characteristics identified indicate that multi-seam subsidence behaviour, although more complex than single seam, is nevertheless regular and reasonably predictable.

The effects of multi-seam mining in modifying the behaviour of overburden strata is highlighted in the magnitude of maximum incremental vertical subsidence as a percentage of the second seam mining height, the magnitude of tilts and strains remote from pillar and goaf edges and in the magnitude of vertical subsidence above the lower seam chain pillars. Other observed effects of multi-seam mining include the difference in behaviour of the overburden strata in response to different mining directions when undermining solid coal/ goaf edges.

The magnitude of vertical subsidence resulting from multi-seam mining has a number of components. A key component in the cumulative subsidence profile is the magnitude and distribution of incremental latent subsidence recovered from the overlying seam.

In areas away from panel and pillar edges, tilt and strain levels from multi-seam mining are likely to be similar to single seam values despite the greater levels of vertical subsidence.

At locations where stacked goaf edges are formed, elevated tilts and strains can be expected. The maximum levels of these parameters is likely to be sensitive to the relative panel geometries in each seam, the dynamics of the mining including mining direction and final mining geometry at these locations.

There is a strong similarity in the characteristics and distribution of horizontal subsidence movements measured above the first four longwalls in the ULD Seam indicating a consistent mechanism driving the horizontal movements and a strong influence of strata dilation in this process.

The magnitude, direction, and form of the horizontal movement for the ULD Seam mining are consistent with horizontal movements observed during mining of the PG Seam longwalls. However subtle differences are seen in the pattern of horizontal movements for the ULD Seam mining, highlighting the influence of the offset geometry and latent subsidence recovered from the PG Seam.

The single seam concepts of angle of draw and subcritical-supercritical width are likely to be less meaningful for multi-seam mining due to the subsequent behaviour of the disturbed (or modified) ground beyond the first episode of mining.

Latent subsidence is a key contributor to the subsidence outcomes. The contribution is seen in all subsidence parameters. Further research is required to better quantify the drivers of the magnitude and extent of latent subsidence effects for each seam particularly in regard to the effect on horizontal subsidence movements. The understanding of latent subsidence effects should also be considered in the design of future subsidence monitoring programs to ensure the maximum subsidence movements are captured.

## ACKNOWLEDGEMENTS

The authors wish to thank Yancoal Australia Ltd - Ashton Coal Operations Pty Ltd for permission to present this data.

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