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**EFFECT OF PUNCH LONGWALL RETREAT ON HIGHWALL STABILITY**

Luke Clarkson

*Abstract:* Punch longwall mining takes advantage of the final highwall exposure in an open cut coal mine, driving gateroads straight into the targeted coal seam then retreating the longwall back to just short of the highwall. A designed barrier pillar remains between the final longwall position and the highwall, which is subject to redistributed ground stresses. Material is strained to magnitudes unlike those typically measured in open-cut mining, and unlike typical longwall ground behaviour, the highwall was observed to strain in an opposite direction to the longwall caved and subsidence zone. Mine personnel and equipment may become exposed to the unstable highwall rockfall hazards, highlighting the importance of understanding the mechanism and implementing appropriate controls.

This paper describes the assessments undertaken through radar, survey prism and Light Detecting and Ranging (LiDAR) monitoring, as well as geotechnical inspection and analysis. Initial results show highwall movement is directly correlated with longwall goafing and any delayed ground movements are more related to the rate of retreat, the type of goafing behaviour and the influence of strata deteriorating in other locations along the face of the highwall. This paper also describes climatic conditions as the primary limitation with radar monitoring. In addition, diurnal steel mesh movement was measured with changing atmospheric temperature. Steel mesh is usually installed as ground support above portal entries to the underground workings. By filtering out any measured mesh movement, true trends of strata deformation in these areas can be identified. Recommendations are made for efficient and reliable radar data acquisition. Further recommendations are made to restrict people and plant access to a safe standoff from the highwall as the longwall approaches the final retreat position within the panel. Effective monitoring of highwall performance throughout the longwall retreat to establish stable trends will enable continued, safe access to these locations.

**INTRODUCTION**

Broadmeadow Coal Mine located in Central Queensland, Australia, operates the punch longwall underground mining method. Roadways are driven into the coal seam from previously excavated open cut operations. The open face of the final highwall can creep and strain in line with open cut geotechnical practice and analysis. In the punch longwall method, the complexity of geomechanical behaviour is heightened with longwall excavations undercutting the ground, at depth behind the highwall face. Typical overburden caving above the longwall usually reduces the competency of the major geological units, inducing ground stress redistribution and surcharging on the residual pillar immediately behind the highwall, as identified in Figure 1.

Although highwall stability is retained, the geomechanical behaviour related to longwall retreat can induce ground deformations much greater than those generally accepted in open cut stability assessments (Sullivan, 1993). As such, it is important that the mine operator understands the significance of these events to adequately manage the safety of personnel and equipment while ensuring productivity requirements.

Ground monitoring practice at Broadmeadow has now provided the opportunity to investigate trends, correlations and relationships of highwall and deep-seated deformation to mining practice and external factors. This paper presents a back-analysis of radar and survey monitoring data in order to gain a greater understanding of the behaviour at hand.

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MINING AND DATA CAPTURE

The barrier pillar width at Broadmeadow ranges from 95m to 225m, with an average of 142m. The mine plan and cross-sections of the region addressed in this paper is observed in Figure 1.

An SSR-XT radar was used for monitoring as the longwall neared the final stages of retreat. Data capture commenced when the longwall was, on average, 161m from the open face. This instrument has the capability to scan a distance of 30m to 3500m away from the radar setup, identifying failures to a resolution of 0.3m x 0.3m and 30.5m x 30.5m, respectively. At the reporting distance of 215m presented in this case, the integrated visual imaging system resolves a 2m x 2m pixel (Figure 2).

Figure 1: Mine Plan and Section View of Take-Off Face

Figure 2: Radar Scan Area of the LW9 Highwall with the portals indicated by the red areas, and the Goonyella Middle Seam in blue

Historically, geotechnical engineers and Explosion Risk Zone (ERZ) controllers routinely monitor to understand and manage the risk to personnel and equipment from isolated rock falls, failed rock bolts,
and inadequate drainage control on catch benches. These visual controls are established and implemented regardless of observed movement.

With any visual inspection, the requirement to capture early movement is based on the experience of the engineer or Statutory Official. BMA has supplemented these visual inspections with three different primary forms of survey monitoring, to differing resolutions. Each may be successfully used for monitoring if these resolution errors are accounted for. Firstly, prisms are embedded on the highwall for east-west movement. Secondly, stakes over the crest of the highwall identify vertical movement. Thirdly, airborne Light Detecting and Ranging (LiDAR) monitoring quantifies subsidence over the panel through laser survey of surface topography. Considerations to be made which may affect monitoring resolution through each method are seen:

Prism:
- Typical resolution of ± 3mm;
- Provides best measurement of movement out from wall;
- Relies on survey instrumentation;
- Limited sample compared to scan/ radar however accuracy is at the upper end of radar’s capability; and
- Limitation on time-based coverage and efficiency of technology in monitoring.

Stakes:
- Typical resolution of ± 10mm; and
- Relies on human eye and associated limitations.

Airborne Light Detecting and Ranging (LiDAR):
- Typical vertical resolution of ± 0.2mm;
- GPS to control position of airborne plane mounted with laser scanner;
- Inertial Navigation System (INS) unit in plane to correct tilt and roll;
- Methods can be employed to increase resolution to maximum ± 0.1mm; and

Acknowledging system capacity and existing limitations to allow a greater understanding of the strata behaviour is critical in stability assessments. Effective monitoring of highwall performance throughout the longwall retreat to establish stable trends will enable continued, safe access to these locations.

THEORISED MECHANISM

To understand the stress redistribution with the undercutting of the highwall block, a generalised model was developed in Phase 2. The model acts under the following conditions (Figure 3):

- Principal horizontal stress = 1.7 x vertical stress in plane and 1.3 x vertical stress out of plane everywhere aside from coal seam (1.0x).
- Assumption of continuous, homogeneous, plastic materials. Plastic conditions are inclusive of residual parameters.
Comparisons of stress distribution for different extents of staged caving are shown in Figure 4 and Figure 5.

Figure 4: Finite Element Analysis on Sigma YY (Normal Stress in Y direction, Vertical Stress)

Figure 5: Finite Element Analysis on Sigma XX (Normal Stress in X direction, Horizontal Stress)

Phase2 finite element modelling indicates maximum stress changes at the immediate highwall of -0.94MPa vertically, and -0.47MPa horizontally (compression positive notation). The inference here of a beam-like caving mechanism to the east of the longwall face is supported, where Sigma XX reflects stress trending with a maximum compression at the top of the beam, and tensional at the base, indicating sag of the sandstone unit. Once this mechanism is understood, one can interpret Sigma YY to exhibit the same behaviour, where tensile stresses nearer the excavation indicate caving into this area, and overburden stresses concentrated at the centre of the sagging units generate increased stress in the upper units. Sigma XX and Sigma YY demonstrate purely horizontal and vertical stresses, respectively, without the influence of stress orientation change post-excitation.
Lipping, identified as the differential lateral displacement between adjacent stratigraphic layers, was observed on the highwall and is thought to result from shearing between the layers. This is mainly supported by the smoothness of the exposed surfaces, suggesting shearing of the pre-existing asperities. This can occur when the shear stress between the layers exceeds the binding shear strength (Ritter, 2002). The magnitude of lipping is dependent on the extent of shear stress exceedance and the distribution across the layers (Figure 6).

Figure 6: Magnitude of Lipping for Different Stratigraphic Interfaces and Photo of Lipping between Stratigraphic Layers (P Seam)

As lipping occurs, greater strain is induced on the strata above the layer boundary, which induces the tendency for blocky failure and strain to be carried back into the strata.

Visual monitoring indicates an inversely proportional trend between strain magnitude induced on the highwall and distance between the longwall face and final longwall position \( \varepsilon = \frac{1}{d} \). Strain on the highwall face is measured as proportional to the height of the target area from the ground.

Longwall retreat through the coal seam (Figure 2) undercuts the overburden strata, altering the stress field and orientation as well as inducing a displacement of the overlying units relative to the excavation. One visible form of this is surface subsidence above the longwall panel. The remainder occurs within the strata units, which cave behind the longwall face and into the goaf (longwall goafing). Hydraulic supports (longwall shields) are utilised across the span of the longwall face in order to support the strata above the current shearer position, protecting both equipment and personnel as mining progresses and the longwall retreats toward the open face.

Retreating at a faster rate has two primary influences; both related to the time-dependent deterioration of overburden strata. Firstly, it reduces the detrimental impact of load build-up on shields, their serviceability and any potential of becoming iron-bound ('buried' after excessive convergence). The second influence is whereby behaviour of the overburden strata is emphasised, and self-spanning competency of units can cause hang-up of the strata, leading to larger magnitude falls as opposed to periodic caving behaviour. The influence on the longwall supports in this case is minimized where the supports, with adequate retreat rate, progress past the fracture point ahead of the face before extensive time-dependent strata influence will be transferred. It is because of these two factors that speed of longwall progression is not only favourable for production, but also in limiting the detrimental influence of strata on longwall shields. This is stated with no other external considerations on retreat rate present, such as hydraulic fracturing at optimal times. The practicality of this concept is discussed in Deformation vs Shears.

LiDAR analysis, with output observed in Figure 7, showed the last 100m of strata, measured east from the open face exhibited no vertical displacement. This indicates that known displacement of the strata was purely horizontal. Voids in this plot relate predominantly to surface works which distort the real data.

Modelled total displacement vectors in Figure 8 show a distinct trend of strata movement fanning out from the subsidence and caving zone into horizontal movement, directed toward the open face of the highwall. The direction of deformation is greater inclined to the open face proportionally with distance to the west. The blue curve indicates the first trend of strata deformation which is directed beyond the excavated void and into the barrier pillar, commencing 67m east of the highwall toe on the surface.
Modelled vertical and horizontal displacements were also generated in Phase2 (Figure 9). The intention of reporting the deformation model is to determine the behaviour, rather than absolute values. In introducing residual values through the assumption of plastic behaviour, the finite element model for this scenario has heavily over exaggerated the magnitude of deformation in the caving zone compared to that known, and realistic in the actual environment. Cooler colours represent lower values, hotter represent greater. Zero values are red for vertical displacement and green for horizontal displacement, and are consistent across the highwall prior to excavating underneath. The contour plot highlights that predominantly negative values are applied to the deforming strata for vertical displacement.

The horizontal displacement plot shows a tendency for the strata to move outward at the location of the exposed face. The theoretical angle of draw, taken from the vertical displacement plot ahead of the longwall face equates to 13.5°, significantly less than site approximations of 28°. An exploded view of the horizontal deformation theorised to occur on the immediate highwall face is shown in Figure 10.
Figure 10: Exploded Horizontal Deformation on the Immediate Highwall Face

Figure 10 shows a trend of heightened deformation of the massive sandstone unit out from the wall, and movement into the wall nearer the crest of the highwall. Any horizontal movement along the stratigraphic boundary is anticipated to reflect lipping behaviour. The behaviour observed only approximates that modelled, as seen when comparing this data to Figure 6, where the boundary between coal and massive sandstone reflects the coal layer lipping beyond the sandstone. The data in Figure 10 is complemented by analysis of the deformation vectors, seen in Figure 8, where there is a defined ‘zero-line’ whereby the influence of the goaf no longer draws on the strata to the west.

DEFORMATION vs SHEARS

There is measured correlation between highwall movement out from the wall and the rate of retreat on the longwall. The data in this section is based on averaged readings over the mid-longwall face region highlighted in Figure 11.

Figure 11: Highwall Scan Area to be Analysed (Green Shade)

An investigation into the rate of retreat against the rate of highwall movement is discussed in this section. Two primary regions of trending data are defined. Section (a) of Figure 12 is a region of higher retreat rate and coincident with higher highwall deformation rates. Section (b) is a region of a steady rate of retreat and a near-linear deformation trend.

Figure 12: Chart Showing Shearer Position vs Deformation over Time
An average was taken over Section (b) in order to distinguish the total movement per longwall shear, and over a longer average time. The average over a 24 hour segment was taken. Interpreted rates are calculated as 2.28mm of movement per shear, and 3.36mm of movement per day. Direct comparison between these two rates indicates that movement predominantly occurs as a result of retreat, which emphasises the influence of the underground longwall excavation with movement of the highwall.

Section (a) must also be analysed to determine the relationship between increased shearer speed and the associated deformation. A focus on deformations and velocities throughout this section is provided in Figure 13.

The sandstone unit, when unbroken, is of greater length and hence volume as strata competency (self-spanning capacity) combines with heightened rates of retreat to extend the void underneath. Eventual fracturing induces stress redistribution to overburden layers and consequent gradual deterioration of these units, with the effects observed primarily through subsidence and stress redistribution of adjacent units is in line with Newton’s third law. This behaviour is not instantaneous, but rather observed through delayed deformation, where magnitude of deformation and delay time are dependent on strata characteristics. It is suggested that the fracturing of the self-spanning sandstone units is the primary cause for increased movement rates (Figure 13). An analysis of a greater number of events would further validate this theory.

A direct analysis of goaf behaviour can be taken by assessing Longwall Visual Analysis data, which records and documents a number of loading parameters through sensors on the hydraulic roof supports (longwall shields) positioned along the face (Figure 14).
Based on site experience, the periodic increase in time weighted average pressure is a function of the geometry and spanning capacity of the overburden cantilevering into the goaf. Once this cantilever fractures and joins the goaf, the shields reflect a decrease in pressure which builds again as the next cantilevering unit is supported. In some cases this can cause more significant longwall weighting events as was experienced between 28th July and 29th July.

A direct correlation between longwall caving behaviour and highwall deformation is suggested. Measured increased deformation on the tertiary layers above the immediate highwall face supports this theory, where deformation occurs in line, albeit delayed deformation, with shields being removed from the final longwall position. This occurs from north to south, parallel to the highwall face (Figure 15).

Figure 15: Rate of deformation vs time for tertiary layer as shields are removed

Figure 15 shows that any increase in rate of movement occurs at the same time for each set of shields, no matter the position along the face. It is the magnitude of the rate of movement during these increased periods which is worthy of noting. It is assumed that each increase in rate of movement is reflective of a goaf convergence event where the removed shields once stood. The amount of rock falling into the goaf is anticipated to be proportional to the magnitude of rate of movement in Figure 15. Dependent on proximity to the fall area, either primary abutment loading or secondary effects on deformation are measured on the highwall face an average of two and a half days after the associated goaf has fallen. This aligns with the proposed relationship between cave behaviour and highwall deformation as discussed in Figure 13.

It is suggested that the abutment support of the pillar and unmined longwall panel to the south causes shields nearer the tailgate end of the face to experience both a lower rate, and a lower total magnitude of deformation when compared against the response of other shield locations across the face.

In consideration of the variability of strata geomechanics and characteristics, the recommended operational control is to restrict people and equipment access to outside a safe standoff zone while the longwall is cutting, with close monitoring during, and until trends stabilise afterward. The best estimate on controlling accelerated highwall deterioration at this stage is applied where movement trigger rates of 1.5 mm/2 hours and 2.0 mm/2 hours over two radar scans are implemented above the portal and sump, respectively. The two hour period allows greater responsiveness to operational changes, yet includes enough data points to eliminate noise (such as diurnal, and atmospherics). It is important to note that alarm settings used should be based on trigger points that would suggest the slope movement has changed from a steady state to a state of accelerated movement, potentially heading to failure. The triggered alarm settings that are quoted are the upper limit of what is currently accepted as steady state movement of the slope at Broadmeadow. The forward influence of goafing on abutment load, stress,
and strain promotes the recommendation for radar monitoring to be implemented when the longwall is within 200m of the zero line.

**DIURNAL MOVEMENT**

Diurnal movement relates to the deformation in radar monitoring from thermal expansion and contraction of steel mesh over the highwall. At Broadmeadow, heavily galvanised mild carbon steel mesh is installed above the portal entrances to control and redirect any fall of surface rock into catch drains.

As common with most material properties, mild carbon steel expands with increasing temperature. The theoretical magnitude of linear change is quantified through the coefficient of thermal expansion.

Characteristic properties of mild carbon steel give the coefficient of linear thermal expansion in the range of $11$ to $13 \times 10^{-6} \left[ m/(m \cdot K) \right]$ at $20^\circ C$. Working under the given assumptions, a relationship between change in temperature and the mesh behaviour can be defined (Thermal Expansion 2002).

**Assumption:**
- Coefficient of expansion does not change with temperature increase

$$\frac{\Delta L}{L} = \alpha_L \Delta T$$  \hspace{1cm} (1)

$$\frac{\Delta L}{L} = 12 \times 10^{-6} \Delta T$$  \hspace{1cm} (2)

where:

$$\alpha_L = \text{linear coefficient of expansion as a function of temperature } T$$

$$\frac{\Delta L}{L} = \text{fractional change in length}$$

$$\Delta T = \text{change in temperature (}^\circ C \text{ or } K)$$

In solving for actual strata against mesh deformation, consideration is made for the change in length of the mesh and effect of the length of mesh provided per metre on the highwall. This calculation would require the assumption that the mesh experiences this deformation averaged over the scanned metre, as displayed in Figure 16. Measured behaviour shows that with an increase in climatic temperature, the mesh will sag into the wall. On cooling, it retracts.

![Figure 16: Mesh deformation, (a) undeformed mesh (b) real deformation (c) assumed deformation](image)

Using the linear coefficient of expansion of $12 \times 10^{-6} \left[ m/(m \cdot K) \right]$ the expression is given:
\[
\frac{\Delta L}{L} = \alpha L \Delta T
\]

\[
L = 12 \times 10^{-6} \times \Delta T
\]  

(3)

As this extension is averaged over a metre length of mesh, it is assumed that \( \Delta L \) is also the equivalent of the lateral movement of the mesh.

By plotting the two variables against the actual deformation charts, the difference between actual and theoretical deformation can be observed. Actual deformation takes an average of the masked area between two vertical bolts. This is seen in Figure 17.

**Figure 17: Chart Showing Change of Temperature on Heating and Cooling Extremes against Change in Deformation in Individual Scans**

The sign convention of theoretical deformation has been reversed in order to represent thermal expansion of the mesh as a negative reading, aligning with what is known as real and described in Figure 16. The theoretical data is derived from the same periods of heating and cooling as defined for unstable conditions. It is observed that the rate of deformation in unstable conditions is approximately 3.7 times the theoretical rate for heating, and 17 times the rate for cooling. Limitations of the theoretical method in calculating mesh movement are identified where, in theory, this movement would be equal to the real, stable data. Theory also states that any strata instability would be identified through the difference between the rate and magnitude of deformation in the real values. The scatter of data and consequent coefficient of determination (\( R^2 \)) values in the real, stable data deem it unreliable to compare against. Further, logarithmic and polynomial data trend lines presented a correlation more aligned than linear, yet still inaccurate in representing diurnal mesh influence. As such, the best estimate for strata deformation with diurnal variation is through isolating temperature cycles, with consideration of theoretical mesh deformation as plotted in Figure 18.

**Figure 18: Chart showing difference in actual vs theoretical mesh deformation over time**

It is the difference between the actual cooling and heating that defines the strata behaviour, as physical highwall deformation is applied regardless of the temperature cycle. This difference is dependent on the
change in temperature and its influence on diurnal mesh movement, an independent variable. If actual cooling is greater than actual heating, there is an outward movement of the wall and vice versa. The magnitude of difference gives an indication of strata movement (Figure 18). Within the stable zone, near-equal deformation is expected and the remainder of deformation spikes represent real movement.

WET WEATHER

A coherence event occurs on comparison between the change in range and amplitude of signal waves between one scan and the next. Two spikes are identified in the data presented in Figure 19. These spikes are a reflection of the external, unpredicted presence of rain on the highwall face, which distorts the data for a single scan.

![Rainfall Event](image)

Figure 19: Coherence event and influence on deformation trend with spikes on 30 August and 12 September

Once identified, the trending data can still be monitored in order to assess deteriorating conditions, albeit at a rougher accuracy while the presence of rain remains. If onset of instability were to be induced during the initial stages of a rainfall event, it is anticipated that the trend prior to the spike in data would be upward and alarming. As such, geotechnical monitoring of the highwall face can still be deemed effective with analysis of the trends either side of the spike in data.

CONCLUSION

Punch longwall retreat redistributes ground stresses toward the open face as a result of undercutting the material body. The highwall was observed to strain away from the longwall caved and subsidence zone, inducing a displacement of material outward up to 200m on the immediate highwall face. The following controls are recommended to protect personnel, plant, and operational safety:

- Radar monitoring when longwall is within 200m of the final position;
- Respective movement trigger rates of 1.5mm/2 hours and 2.0mm/2 hours over two radar scans above the portal and sump, dependent on designated steady state movement limits; and
- Recognition and consideration of monitoring limitations including wet weather and radar’s initial correction source.

Consideration of structure, seam and stratigraphic dip, as well as barrier pillar and highwall design is recommended when referring to different longwall panel retreats. The influence these parameters have on both caving behaviour and strata response is highly variable and generally unknown based on the number of case studies available.
Through knowledge and understanding of the interaction mechanism between underground and open cut workings, considerations can be applied in mine design to ensure safe access to underground workings, without interruption to operational activities.

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