Definition of Measured Hydraulic Conductivity Zones above a Longwall Panel, United Colliery

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Summary

This paper presents the results of a field investigation to determine zones of hydraulic conductivity above an extracted longwall panel at United Colliery in the Hunter Valley of NSW. The hydraulic conductivity zones were determined from targeted boreholes drilled into the subsided strata above the goaf of Longwall 10, an isolated panel with a supercritical width panel geometry. Five boreholes defined the edge of caving and characterised the hydraulic conductivity within and above the caved zone. The deepest hole in the centre of the goaf was drilled to 30m above the extracted seam, providing hydraulic conductivity data through most of the subsided overburden strata.

This drilling program successfully highlighted distinct hydraulic conductivity zones above a longwall panel. Hydraulic conductivity zones were defined in the goaf and outside the caved zone. These zones include:

1. Edge of Caving – very high conductivity high strain zone at the edge of caving
2. Goaf Centre – cyclic high and moderate conductivity zones
3. Outside Caved Zone – enhanced conductivity of rock outside the caved zone
4. Coal Seams – enhanced conductivity inside and outside the caved zone
5. Near Surface Zone – inferred low connectivity zone at surface

The results of this field measurement program were used for the applications of open cut/underground interaction and connectivity. These results also have application for improved definition of the hydraulic conductivity above a longwall panel in the area of groundwater modelling of mine inflows and surface connectivity.

1. Introduction

The hydraulic conductivity of the caved overburden above a longwall panel is an important characteristic in the determination of mine connectivity for both water and gas interaction hazards. This paper presents the results of a targeted goaf borehole drilling program that was designed to characterise the overburden and define the caved zone and hydraulic conductivity above a longwall panel.

The drilling program was conducted above Longwall 10 at United Colliery, a disused underground coal mine located in the Hunter Valley of New South Wales. The location of the mine is shown in Figure 1.

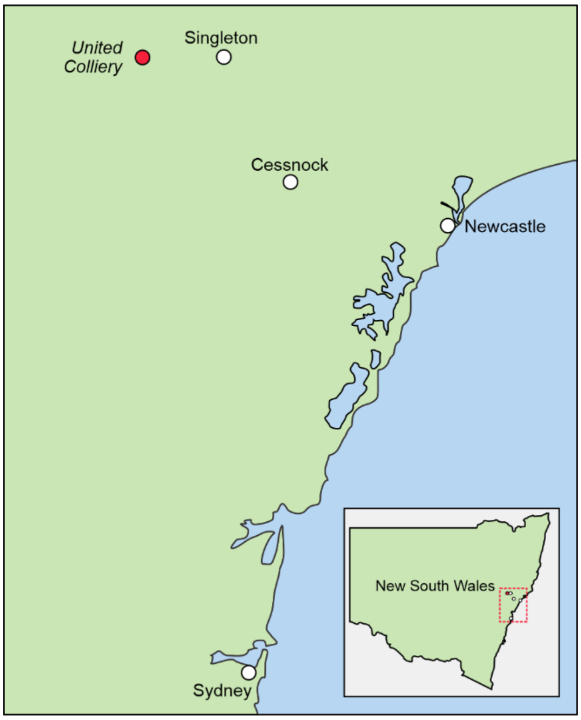

Figure 1 Location of United Colliery.

United Colliery was a longwall and pillar extraction mining operation in the Woodlands Hill Seam that is no longer operational. United Wambo Joint Venture implemented the drilling program to characterise the overburden above Longwall 10 panel to inform open cut hazard identification assessments.

United Longwall 10 is an isolated panel with a supercritical panel geometry at approximately 120m depth and 180m panel void width.

Five vertical boreholes were drilled above Longwall 10 to characterise the overburden above the longwall panel. The boreholes were geotechnically and geophysically logged and tested for hydraulic conductivity with Lugeon style packer testing. This paper presents outcomes of the drilling program relevant to definition of the hydraulic conductivity zones above the longwall panel.

2. Field Investigation

The borehole locations were designed to define the edge of the caved zone on the maingate and tailgate sides of the panel and to characterise the strata above and within the caved zone.

The location of the boreholes relative to Longwall 10 is presented in Figure 2. Four of the five boreholes form a cross section across the panel. The fifth borehole is located on the centreline further along the panel.

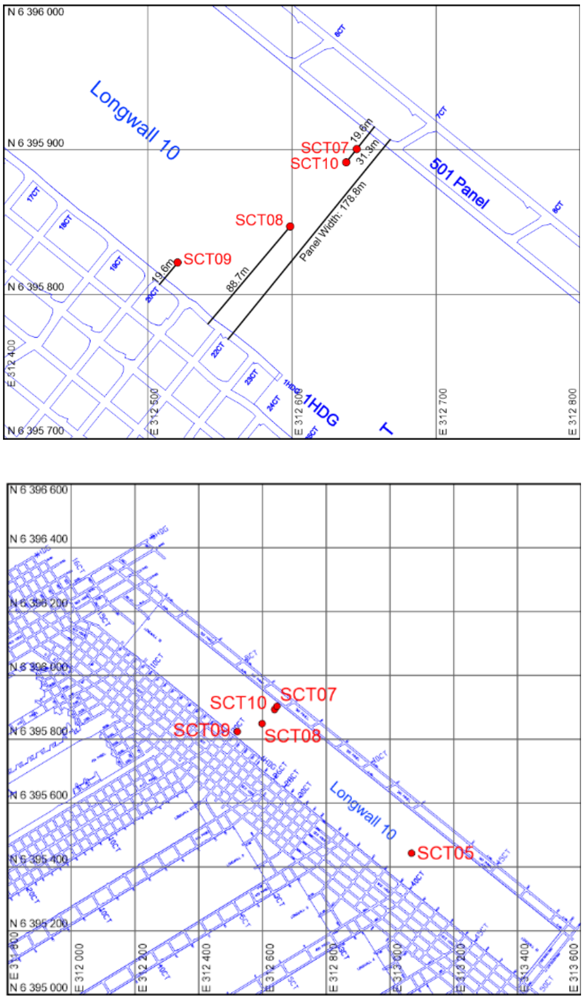

Figure 2 Location of boreholes over Longwall 10.

Boreholes SCT07 and SCT10 were located on the north-eastern side of the panel, Borehole SCT09 was located on the south-western side of the panel, and Borehole SCT08 was located in the centre of the panel. Borehole SCT05 was also located in the panel centre, approximately 600m southeast of the main cross section to investigate variability above the middle of the panel.

All boreholes were vertical HQ cored boreholes. The first 20m of each borehole was not cored due to weaker ground and installation of casing.

The inherent issues of drilling into a goaf including water loss and gas connectivity, meant that boreholes could only be drilled until total water loss was encountered. The panel edge boreholes and one of the centre boreholes were drilled until total water loss. The other centre goaf borehole was drilled to 30m above the seam and was terminated to avoid connecting directly to the goaf.

All core was geotechnically logged. Geophysics were logged where water return was made possible by either a competent borehole, or by a Van Ruth plug inserted at the base of the hole to re-establish water returns. Where geophysics were run, the geophysical tools consisted of gamma, density, caliper, Acoustic Televiewer and Optical Televiewer. A borehole camera survey was conducted where possible.

Presentation of the drilling results, core logging and fracture characterisation for this program of work is discussed in an earlier paper on the definition of the caved zone above a longwall panel (Heritage *et al.* 2022).

Characteristics relating to identification of the caved zone and hydraulic conductivity zones are presented in this paper. Pre-mining comparison of overburden hydraulic conductivity was not included in this study.

3. Caved Zone Definition

A summary of the caved zone definition, detailed in the earlier paper by Heritage *et al.* (2022), is included in this section. The identification of the caved zone is important in defining the hydraulic conductivity zones above the longwall panel.

The three panel edge definition holes were drilled until total water loss occurred. The total water loss coincided with gas make and a high angled fracture. The gas make indicated connection with the goaf. This location was interpreted as the high strain zone at the edge of the caved zone.

The location of the boreholes in relation to the Woodlands Hill Seam, longwall panel edges and surface topography is presented in Figure 3. Figure 3 shows that these high strain water loss zones form an arc shape consistent with industry understanding of the caved zone shape of approximately 1 x panel width (Mills, 2011).

The caving angle from the panel edge to 50-60m above the seam is 19-21° from vertical. The caving angle increased to 25° from vertical between 50-75m above the seam, indicating the arc shape of the caved zone. Considering the 2.5° seam dip, the caving angle perpendicular to the seam horizon is also 19-21.5° but on the opposite side of the panel.

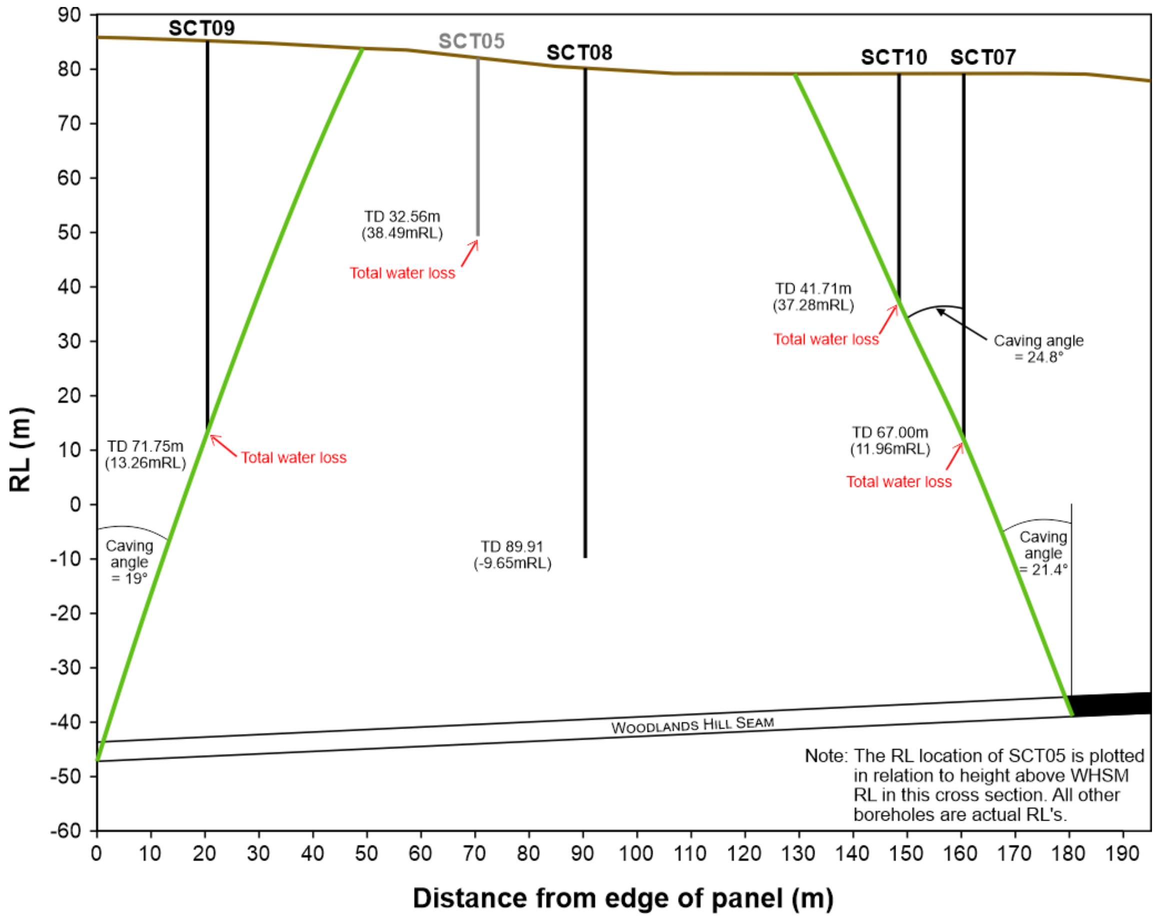

Figure 3 Inferred edge of caved zone from drilling results.

4. Hydraulic Conductivity

Hydraulic conductivity testing was conducted in all boreholes using Lugeon style straddle packer testing at 6m intervals. The hydraulic conductivity test results and water loss zones observed whilst monitoring drilling returns are presented in Figure 4.

Hydraulic conductivity for the caving delineation holes (SCT07, SCT09 and SCT10) ranged $1x10^{-10}$m/s to $1x10^{-7}$m/s. Hydraulic conductivity increased to $1x10^{-6}$m/s in some intervals that included coal seam horizons.

At the total water loss horizons, hydraulic conductivity was estimated to be more than $1x10^{-4}$m/s based on the maximum pump rate of 100L/min and assuming 10m of water head in the drill string.

The two central boreholes (SCT08 and SCT05) showed significantly different outcomes. Borehole SCT05 experienced total water loss at 30-32m from surface. Borehole SCT08 was able to be drilled to 90m depth, 30m above the extracted Woodlands Hill Seam, without total water loss occurring. Hydraulic conductivity in Borehole SCT08 ranged $1x10^{-8}$m/s to $1x10^{-6}$m/s.

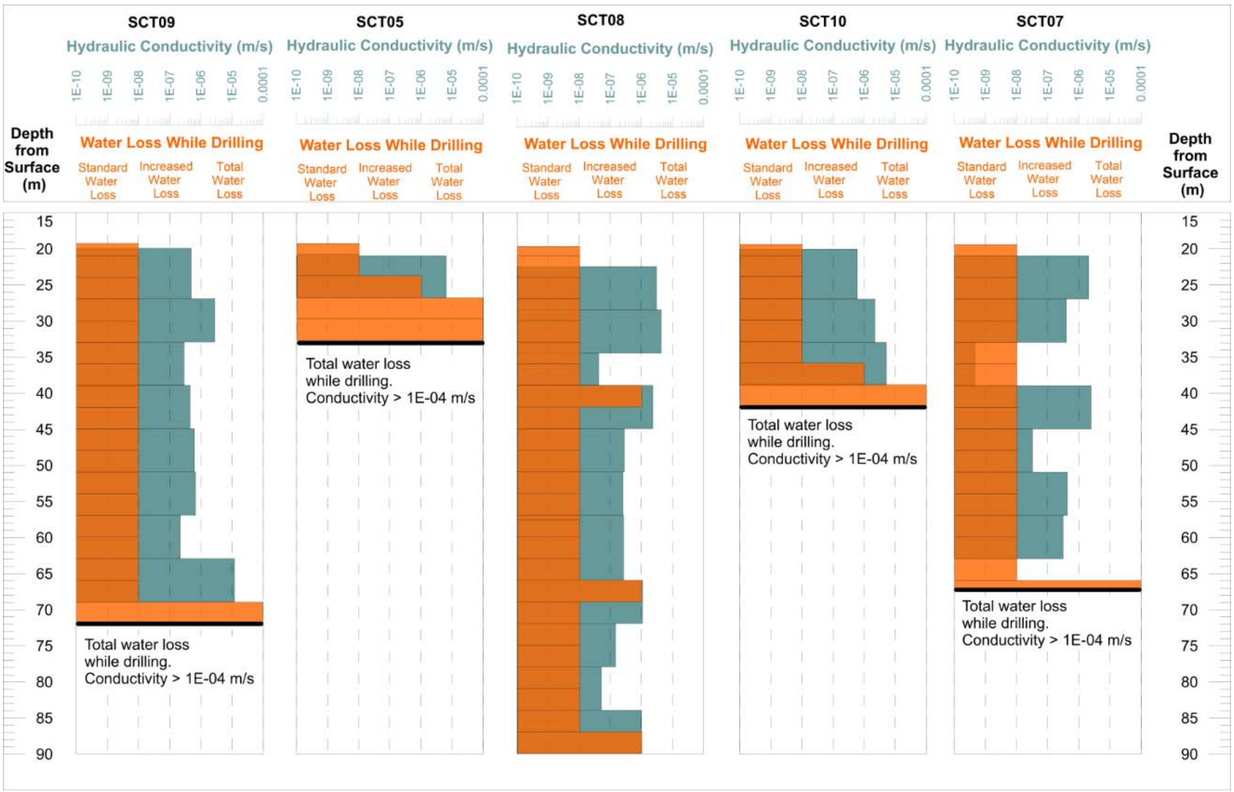

Figure 4 Hydraulic conductivity results and water loss zones over Longwall 10.

The total water loss in Boreholes SCT07, SCT09 and SCT10 indicate intersection with the high strain zone associated with the edge of the cave zone. The water loss trends in Borehole SCT05 suggest the borehole intersected a cyclic high strain zone that forms during the dynamic longwall retreat process.

The increase in water loss in the drill run above the total water loss zone in Borehole SCT05 is comparable to the experience in Borehole SCT10 above the water loss zone of the caving arc. The low conductivity in Borehole SCT08 suggests that it may not have intersected a high strain cyclic caving zone, or if it did, it may have been at depth and the aperture reduced by goaf loading and confinement.

The hydraulic conductivity of fractures above the high strain zone are in the range of $1x10^{-10}$m/s to $1x10^{-7}$m/s. This observation indicates that mining induced fractures that may occur above the high strain zone, are less conductive than fractures in the high strain zone.

The hydraulic conductivity in relation to the longwall panel and caved zone is presented in Figure 5. The fracture frequency count presented in Figure 5 shows that the fracture frequency doubles within the caved zone. The average fracture frequency above the caved zone is 2.61/m compared with 5.04/m within the caved zone.

The fracture frequency in the goaf centre holes is lower above the D Seam. This reduction in fracturing is consistent with the apparent lack of connectivity between the mine and the surface indicated by barometric pressure observed in the goaf.

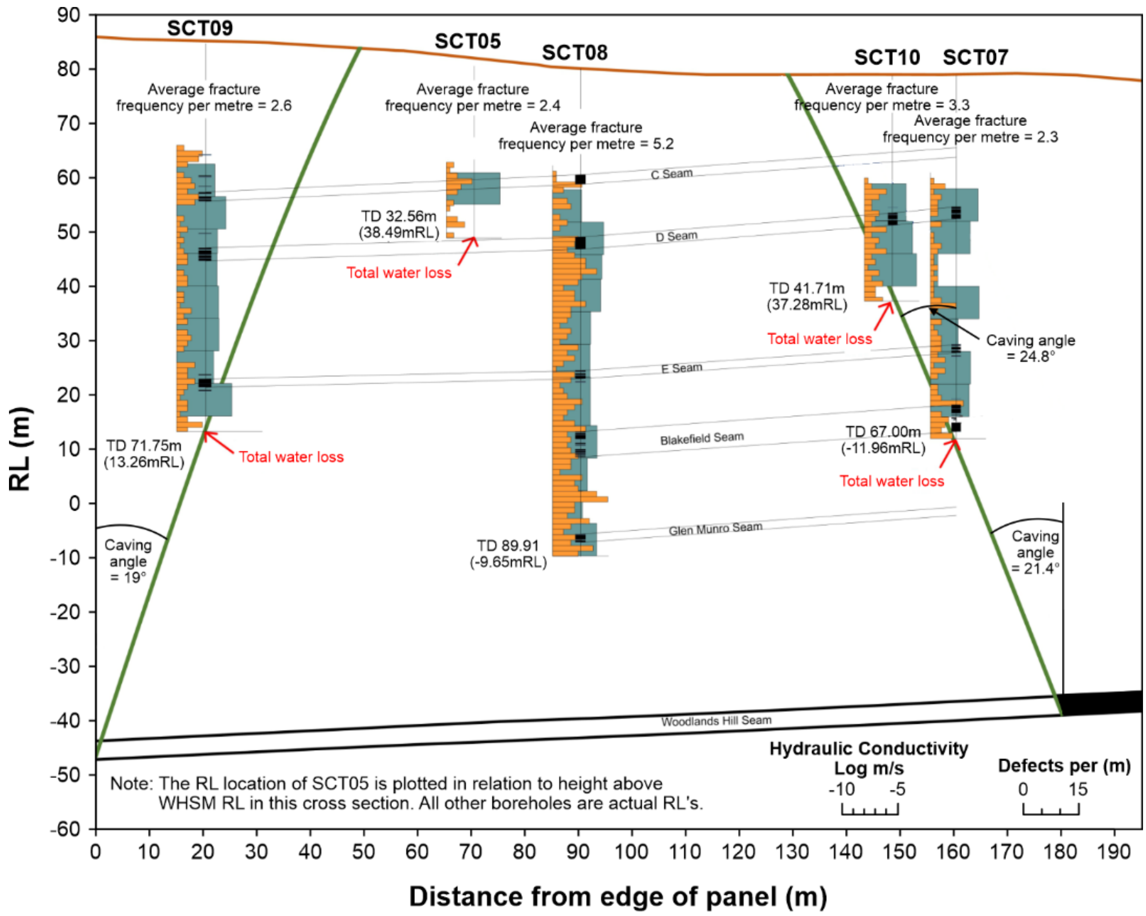

Figure 5 Drilling and hydraulic conductivity results in relation to caved zone.

It is understood that the barometric pressure underground does not reflect the surface air pressure changes, indicating the near surface strata provides a low permeability layer restricting the connectivity from the surface to the caved zone. This low permeability layer could be due to weathered strata, ingress of fines into fractures, or mining-induced fractures focussing horizontally on the weak bedding planes of the interbedded near surface strata, rather than creating distinct subvertical fractures to the surface.

5. Hydraulic Conductivity Zones

Characterisation of the hydraulic conductivity within the subsided strata above a longwall panel provides a basis to define zones of hydraulic conductivity above the longwall panel. The identification of the edge of the caved zone was an important factor in the hydraulic conductivity zone definition as it not only provides a zone boundary, but the very high conductivity of this zone means the edge of caving is a zone in itself.

Five zones were identified from the hydraulic conductivity results of the packer testing, and the observations of total water loss and borehole gas make.

The five hydraulic conductivity zones are presented in Figure 6. These zones are:

1. Edge of Caving – a very high conductivity zone on the edge of the caved zone.
2. Goaf Centre – moderate to high conductivity with cyclic very high conductivity associated with cyclic caving fracture zones.
3. Outside Caved zone – in situ fracture network possibly enhanced conductivity from low confinement and horizontal shearing of bedding.
4. Coal Seams – enhanced coal seam conductivity due to horizontal shearing, reduction in confinement and gas drainage.
5. Near Surface Zone – apparent lower conductivity zone from weathered strata, fewer subvertical fractures and/or surface subsidence compression.

The location of the boundaries between the goaf centre zone and adjacent zones are less defined due to various limitations of the drilling program. The zone boundaries were estimated from drilling limits and surveyed surface subsidence

The conductivity ranges for each hydraulic conductivity zone based on the drilling and packer testing results are summarised in Table 1. These conductivity values are estimated for both vertical and horizontal conductivities unless specified, as for instance in the coal seams.

The hydraulic conductivity zones and zone boundaries are described in more detail in the following sections.

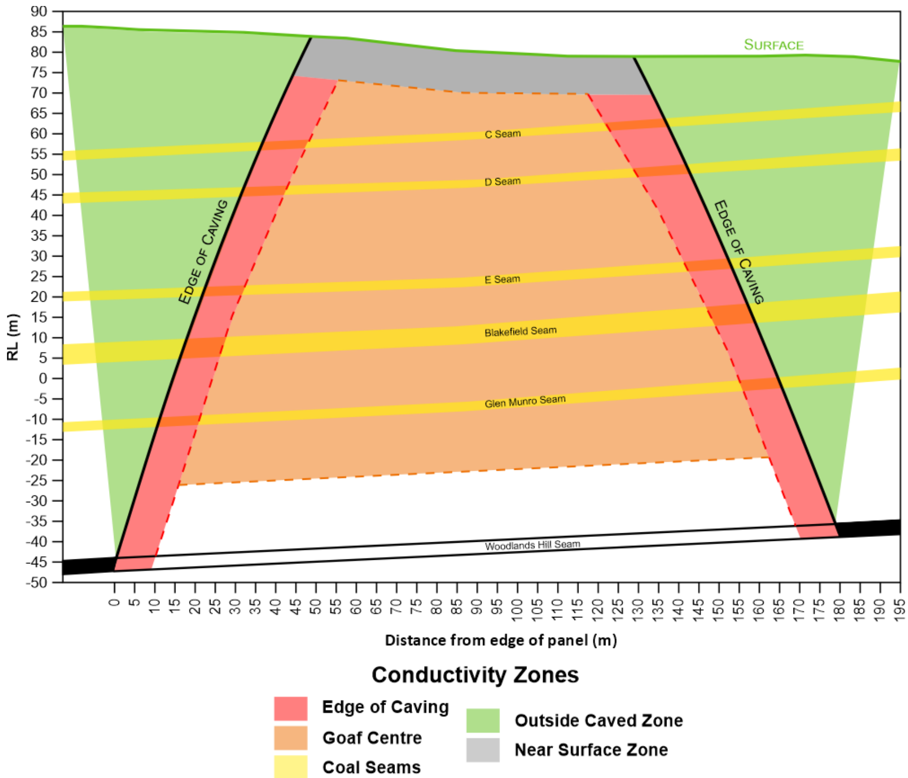

Figure 6 Hydraulic conductivity zones above Longwall 10.

Table 1: Hydraulic Conductivity Zones based on the LW10 drilling program

Zone No.	Conductivity Zone	Relative Conductivity	Conductivity (m/s)
1	Edge of Caving	Very high	>$1x10^{-4}$m/s (up to $1x10^{-3}$m/s to $1x10^{-1}$m/s*)
2	Goaf Centre	Very high to moderate	Cyclic: >$1x10^{-4}$m/s (up to $1x10^{-3}$m/s to $1x10^{-1}$m/s*) Background: $1x10^{-7}$m/s to $1x10^{-6}$m/s
3	Outside Caved Zone	Moderate to low	$1x10^{-9}$m/s to $1x10^{-6}$m/s
4	Coal Seams	High	$1x10^{-6}$m/s to $1x10^{-5}$m/s horizontal conductivity
5	Near Surface Zone	Low	Estimated <$1x10^{-8}$m/s

** The conductivity of the high strain zones has the potential to be up to $1x10^{-3}$m/s to $1x10^{-1}$m/s based on ACARP research (Heritage and Gale, 2009; Gale, 2020)*

5.1 Edge of Caving

The zone at the edge of caving was determined from the three panel-edge boreholes. These boreholes experienced total water loss and gas make form the goaf when this high strain zone was intersected. High angled fractures were also intersected in this zone.

Hydraulic conductivity of this zone was the highest of all the zones. Packer testing could not be conducted because total water loss prevented a water head being maintained to surface.

The hydraulic conductivity of this zone is determined to be greater than $1x10^{-4}$m/s based on the water flow pumped into the borehole in an attempt to sustain a water head. It is possible that hydraulic conductivity could be up to $1x10^{-3}$m/s to $1x10^{-1}$m/s based on ACARP research projects measuring overburden connectivity (Heritage and Gale, 2009; Gale, 2020).

The boundary between the edge of caving zone and goaf centre zone is estimated based on surveyed surface subsidence data where the subsidence trough flattens. The width of this zone is estimated to be approximately 5-10m from the edge of caving.

5.2 Goaf Centre

The goaf centre zone was determined from the two boreholes drilled in the panel centre. These holes showed variable hydraulic conductivity results. One borehole was drilled to 30m above the mined seam without experiencing total water loss. The other hole was drilled to only 30m below surface and 95m above the seam. Total water loss and gas make was experienced at 25m to 30m whilst drilling.

The variable range in hydraulic conductivity observed is consistent with the understanding of cyclic caving that occurs in the overburden during longwall extraction. A generic rock failure model is presented in Figure 7, where the caving cycles cause fractures to form in the overburden at 15-30m spacing.

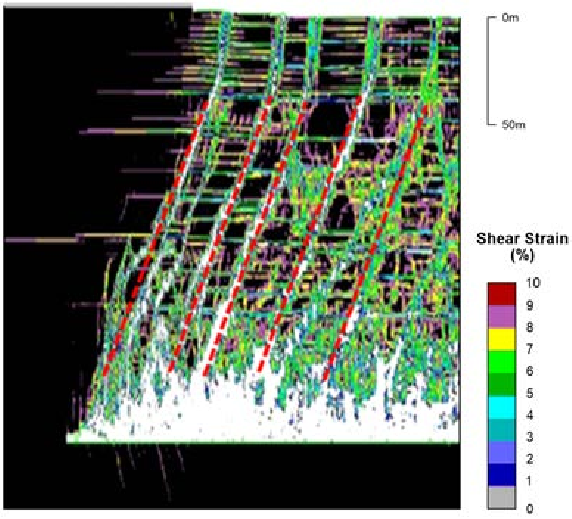

Figure 7 Generic numerical model of longwall caving showing cyclic overburden caving fractures.

The hydraulic conductivity of the goaf zone was determined to be cyclic, with background hydraulic conductivity measured from packer testing at 1x10^{-7}m/s to 1x10^{-6}m/s, and cyclic very high conductivity zones of greater than 1x10^{-4}m/s and possibly up to 1x10^{-3}m/s to 1x10^{-1}m/s.

The immediate goaf zone above the mined seam was not measured in this study due to drilling stopping 30m above the mining horizon. It is anticipated that the immediate goaf zone would have very high hydraulic conductivity and be highly connected. The location of the boundary between the immediate goaf zone and the measured goaf zone was not able to be determined from this study and is therefore located within 30m above the mined seam.

5.3 Outside Caved Zone

The hydraulic conductivity of the strata above the caved zone was measured from packer testing to range in the order of 1x10^{-9}m/s to 1x10^{-6}m/s. These levels of hydraulic conductivity may be slightly enhanced from in situ hydraulic conductivity due to horizontal ground movements and stress reduction associated with longwall extraction.

Fracture data suggests that some mining induced subvertical fractures may be present in this zone within the panel edges, however these fractures were not measured to have a high connection to the goaf (Heritage, 2022). Horizontal movement on bedding planes is likely within this zone.

5.4 Coal Seams

Coal seams in the overburden strata above the longwall panel were measured to have hydraulic conductivity of the order of 1x10^{-6}m/s. The coal seam zone extends outside the caved zone to beyond the longwall panel edge.

The coal seams have been highlighted as a separate zone as the seam conductivities are at the upper bound of general overburden conductivity (other than the high strain zones). It is expected that horizontal shearing along the coal seams occurs both within and outside the panel edges. The coal seams are a high conductivity zone with potential for goaf connectivity to well outside the panel edges.

5.5 Near Surface

The near surface is highlighted as a separate zone in this case study due to the apparent separation of mine and surface barometric pressures.

This lower conductivity zone may be due to weathered strata, self-healing of fractures due to ingress of fines, compressive surface subsidence, horizontally focussed bedding fractures, or a combination of some or all of these factors.

The location of the boundary between the near surface and goaf conductivity zones is estimated to be between the D Seam and the surface. There was no core or testing within this 20m horizon to further define the boundary location.

This zone may not be present in other mining environments because its existence may rely on site-specific lithology, weathering or low strength bedding.

6. Conclusions

Hydraulic conductivity zones within the overburden strata above an extracted longwall panel are characterised based on the field drilling program conducted at United Colliery.

The edge of the caved zone is the most conductive zone with indications this zone is connected to the mining horizon. The panel centre contains cyclic zones of high conductivity that are also likely to connect to the mining horizon.

Coal seams provide a conduit of enhanced hydraulic conductivity that have the potential for water, air or gas to connect with the mining horizon.

These results have application for improved definition of the hydraulic conductivity above a longwall panel for assessments of groundwater inflow to underground mines, surface connectivity, and multi-seam and open cut interactions.

7. Acknowledgements

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Thank you to all other personnel who were also involved in the project, including Ken Mills, Stuart MacGregor, Rick Lee, Adrian Rippon, and Michael Holland.

8. References

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