MEASUREMENTS OF THE HEIGHT OF FRACTURING AND HEIGHT OF DEPRESSURISATION ABOVE A LONGWALL PANEL

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ABSTRACT: This paper presents the findings of a program of work to determine the height of mining induced fracturing and the height of groundwater depressurisation above a longwall panel. The program of work utilised two fully cored boreholes drilled from surface at Tahmoor Colliery, located southwest of Sydney in the Southern Coalfields in New South Wales. The boreholes were drilled adjacent to and over a subcritical longwall panel, one before and one after extraction of the longwall panel.

Field measurements of the geotechnical and hydrological ground conditions in the pre and post mining boreholes were compared. Three geomechanical zones were determined in the overburden above the extracted longwall panel which correlate with ground water and hydraulic conductivity measurements.

The results show that the determined height of caving and the start of a reduced pore pressure profile (from hydrostatic) coincide at the same height above the mining horizon. The reduction in pore pressure from hydrostatic to zero pore pressure is a gradual transition, meaning the height of depressurisation (zero pore pressure) and height of caving do not necessarily coincide.

This work program provides a comprehensive dataset of changes in pore pressure, conductivity and caving for the horizons within the overburden above a longwall panel at Tahmoor Colliery. The results from this program of work reinforce the results from a previous work program at Tahmoor Colliery detailing the height of caving and height of depressurisation.

The outcomes of this program are useful in providing an understanding for groundwater modelling above extracted longwall panels.

INTRODUCTION

Extraction of coal from a longwall panel leads to failure and collapse of the immediate overlying strata. This failure process causes additional failure and ground disturbances upwards into the overburden, propagating from above the extracted panel towards the surface, presenting as subsidence. Subsidence profiles at the surface are dependent on the mining geometry and geological characteristics.

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Complete understanding of the failure processes and associated changes to the groundwater is difficult due to the inherent variability of the overburden and limited data points that can be measured throughout the overburden. Monitoring both the caving and groundwater response over an active longwall also presents many challenges. This paper discusses comparative field measurements from pre and post mining boreholes as well as knowledge from other published studies that have defined the goaf caving behaviour using various field measurements.

A program of work to determine the impacts to the overburden from longwall mining was completed at Tahmoor Colliery in New South Wales. Two fully cored boreholes were drilled over Longwall West 2. Borehole HOFWD01 was drilled before extraction of Longwall West 2 and Borehole HOFWD02 was drilled approximately two years after extraction of the longwall panel. Field observations and measurements used to characterise the two boreholes consisted of geotechnical core logging, geophysical logging and imaging, borehole camera, Lugeon packer testing, and the installation of vibrating wire piezometers (VWP's).

SITE DESCRIPTION

Tahmoor Colliery is located on the western margin of the Sydney Basin, approximately 30 kilometres to the north-west of Wollongong. The mine extracts the Bulli Seam using a conventional retreating longwall method. The program of work was conducted over the Longwall West 2 Panel, part of the Western Domain Panels, located directly to the west of the town of Picton. The Longwall West 2 Panel void is 282 m wide, and depth of cover is approximately 526 m in the area of interest.

The surface topography is characterised by undulating farmland and native forest typical of the southern Sydney Basin. The full Narrabeen Group stratigraphic sequence is present across the area, with the Wianamatta Group (Ashfield Shale) overriding the Hawkesbury Sandstone in the Western Domain region. The depths of the stratigraphic units cored through in post mining Borehole HOFWD02 are shown in Table 1.

Table 1: Major stratigraphic units cored through in Post mining Borehole HOFWD02

Stratigraphic Unit	Depth from	Depth to	Interval
Ashfield Shale	3.0	66.5	63.5
Hawkesbury Sandstone	66.5	238.3	171.8
Newport Formation	238.3	255.2	16.9
Garie Formation	255.2	256.3	1.1
Bald Hill Claystone	256.3	264.9	8.6
Bulgo Sandstone	264.9	440.5	175.6

Borehole HOFWD01 was completed on 29 July 2020, during the mining of Longwall West 1 panel. HOFWD01 was drilled over a chain pillar in the Longwall West 1 Maingate (Longwall West 2 Tailgate), 80 m inbye the Longwall West 2 finish line. The borehole was drilled vertically to 410 m. The purpose of this borehole was to gain baseline information on the geotechnical and hydrological conditions in the overburden, unaffected by extraction of Longwall West 2.

Borehole HOFWD02 was completed on 29 March 2023, after extraction of all the Western Domain panels. HOFWD02 was drilled over the centre of Longwall West 2 Panel, 430 m inbye the Longwall West 2 finish line. The borehole was drilled vertically to 440 m. The purpose of this borehole was to gain information on the geotechnical and hydrological conditions in the overburden, after extraction of Longwall West 2 and to allow for a comparison to the pre mining borehole. The post mining Borehole HOFWD02 was drilled over the centre of the Longwall West 2 Panel to measure maximum effects of caving and depressurisation.

Figure 1 shows the location of the two boreholes in relation to the extracted longwall panels. The two boreholes were located 400 m apart. Ideally these boreholes would be closer together, however this was not possible at the time of drilling the pre mining borehole. Both boreholes were located away from any major geotechnical structures and were located within the same topography. The surface RL difference between the two boreholes was 5 m, and the major stratigraphic units were located at the same depths in each borehole, when accounting for the 5 m RL difference at the borehole collars.

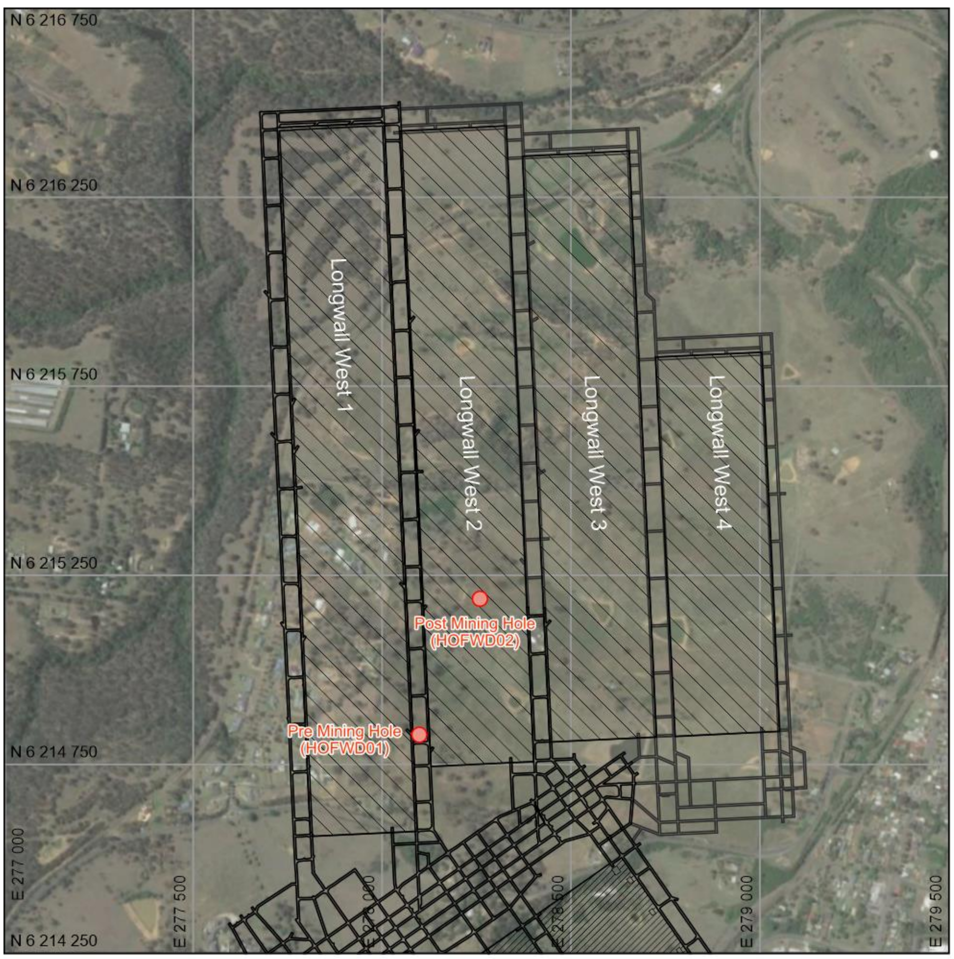


Figure 1: Site location showing Tahmoor's Western Domain mine plan.

FINDINGS

Based on the field measurement comparisons between the pre and post mining boreholes, three geomechanical zones have been determined above the Longwall West 2. The height of these zones aligns well with zones depicted by Mills (2012), in relation to panel width to height above mining horizon ratios. Over Longwall West 2, the following geomechanical zones have been derived:

- The <u>zone of elastic relaxation</u> extends from the surface to 76 m below the surface (450 m above the mining horizon). This equates to a height above the mining horizon of 1.60 times the panel width.

- The <u>zone of bedding plane separation</u> extends from 76 m to 200 m below the surface (450 m to 326 m above the mining horizon). This equates to a height above the mining horizon of 1.60 to 1.16 times the panel width. This zone shows an increase in horizontal hydraulic conductivity.

- The <u>zone of large downwards movement</u> extends from 200 m below the surface (326 m above the mining horizon) to the top of the mining horizon. This equates to a height above the mining horizon of 1.16 times the panel width. This zone is considered the main caving zone and the top of this zone is referred to as the height of caving in this paper. This zone shows reduced pore pressure profile and an increase in vertical and horizontal hydraulic conductivity.

The pore pressure data indicates that the near surface groundwater level has not been significantly affected by the mining of the Western Domain Panels. This is due to a zone from the top of the water table down to approximately 200 m below surface (326 m above the mining horizon) maintaining a hydrostatic gradient. Below this there is a gradual reduction in pore pressure down to the measured height of depressurisation located between 330 m and 356 m below surface (196 m and 170 m above the mining horizon).

The geomechanical and hydrological zones have been determined by comparing the pre and post mining borehole data, presented in this paper.

The analysis and interpretation of the dataset from this program of work is consistent with that from the similar work program over Longwall 10A approximately 8.5 km to the south presented in Mills and Blacka (2017).

Mills and Blacka (2017) found a zone of large downward movement extending to 0.94 x panel width, changes in the piezometric profile (from hydrostatic) starting at the top of the zone of large downward movement and reducing to complete depressurisation at a point consistent with an estimate using the Tammetta (2012) approach.

BOREHOLE DEFECT COMPARISON

Both the pre mining Borehole HOFWD01 and the post mining Borehole HOFWD02 were fully cored. Geotechnical core logging of the two boreholes allowed for a comparison of the defects in each borehole. Borehole camera surveys were also conducted at the completion of drilling to gain information on defect separation and any potential water flow rate and direction. Figure 2 shows a composite log of the defect data, comparing the two boreholes.

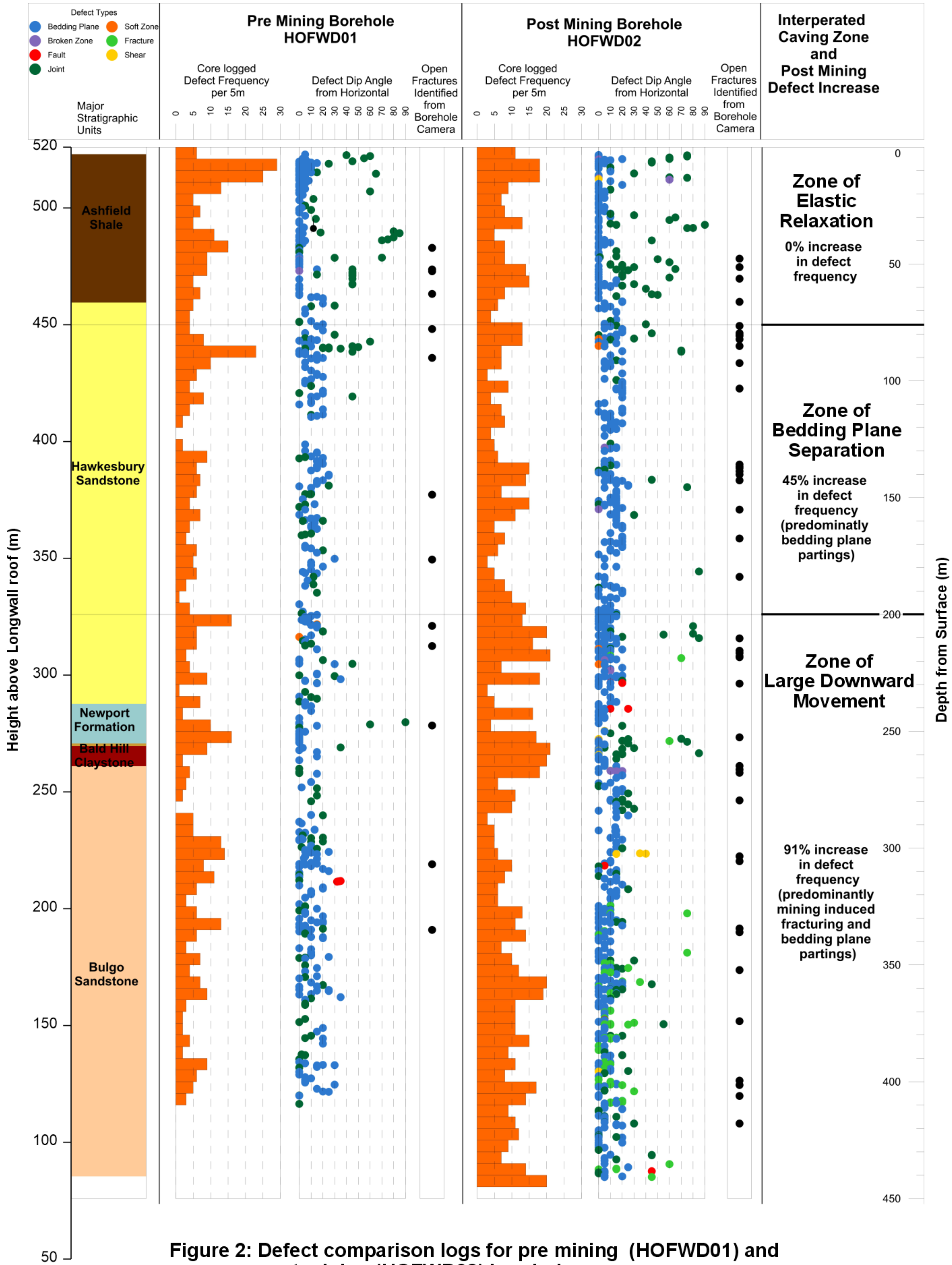


Figure 2: Defect comparison logs for pre mining (HOFWD01) and post mining (HOFWD02) boreholes.

CORE DATA

Geotechnical core logging of the pre and post mining boreholes show similar defect data in the top 76 m of both boreholes, with an average of 2.0 defects per metre. This section of the overburden is predominantly made up of the Ashfield Shale (top 66 m), which contains a high amount of mid/high angle jointing due to proximity to the surface, undulating topography and nature of the Ashfield Shale. These joints are naturally occurring and unrelated to mining.

From 76 m to 200 m there was a 45% increase in logged defects in the post mining borehole compared to the pre mining borehole. Majority of these additional defects were bedding plane partings.

Below 200 m from surface there was a 91% increase in defect frequency in both low and high angle defects. Many of these additional defects have been logged as mining induced, generally identified as freshly formed with a jagged fracture surface. Figure 3 shows an example of an angled mining induced fracture logged in the post mining Borehole HOFWD02, located at 436 m below surface.

Figure 3: Mining induced fracture identified in core at 426m.

Table 2 shows a comparison of the pre mining and post mining defect frequencies for the interoperated geomechanical zones.

Table 2: Pre mining and post mining defect frequency comparison

Depth from surface		Defects logged per m		Interpreted caving zone	Defect percentage increase
From	To	HOFWD01 (Pre Mining)	HOFWD02 (Post Mining)		
0	76	2.0	2.0	Elastic relaxation	0
76	200	1.1	1.6	Bedding plane separation	45
200	410	1.2	2.3	Large downward movement	91

BOREHOLE CAMERA

At the completion of drilling each borehole, a borehole camera was lowered into the holes on an electric winch with real time video of the boreholes displayed at the surface. The camera can be remotely controlled and rotated about a horizontal and vertical axis to allow inspection of open fractures and other features in the borehole. The borehole camera can identify features that cannot be picked up from the core. Some of these features include water flow (and direction), borehole breakout, open fractures and standing water level.

A total of 43 open fractures were identified in Borehole HOFWD02 using the borehole camera. In comparison, 13 open fractures were identified in Borehole HOFWD01. The shallowest significant open fracture in HOFWD02 was at 76 m below surface and coincided with the first occurrence of complete water loss while drilling. No zones of water loss were identified in Borehole HOFWD01. Below 76 m open fracture frequency significantly increases in HOFWD02 compared to HOFWD01. Figure 4 shows some borehole camera screen capture examples of mining induced fracturing and bedding plane separation in Borehole HOFWD02.

GROUNDWATER

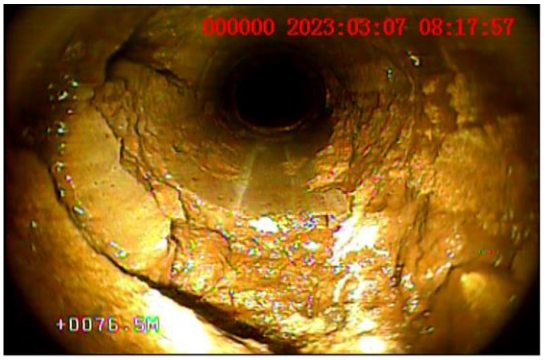
Hydraulic Conductivity Comparison

Lugeon style packer testing was completed in Boreholes HOFWD01 and HOFWD02 at 6 m intervals to gain hydraulic conductivity measurements throughout the overburden. Figure 5 shows the hydraulic conductivity measurements from both boreholes, plotted relative to depth from surface and height above the mining horizon.

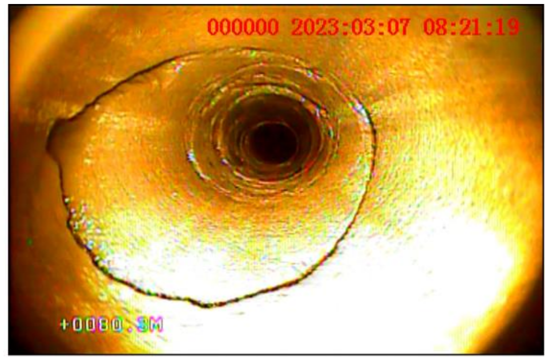
The pre mining Borehole HOFWD01 shows a general trend of decreasing hydraulic conductivity with increasing depth. The reduction in conductivity with depth is due to an increase in confining pressure. This is a typical hydraulic conductivity profile of the overburden above the Illawarra coal measures, when unaffected by mining. In general, the post mining Borehole HOFWD02 shows an increased hydraulic conductivity compared to HOFWD01, particularly evident with increasing depth.

For post mining Borehole HOFWD02 in the centre of Longwall West 2:

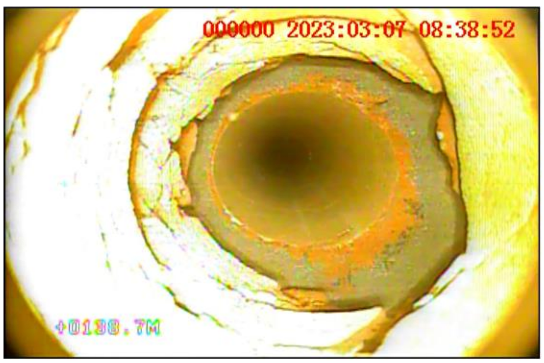
In the upper 76 m, interpreted as the zone of elastic deformation, there is a large variation in hydraulic conductivity in both pre and post mining boreholes. The variation in hydraulic conductivity in this zone occurs due to a combination of a fine grained/low porosity nature of the Ashfield Shale, topography and the high level of natural jointing associated with the unit. In general, there is a slight increase in hydraulic conductivity in the post mining borehole.



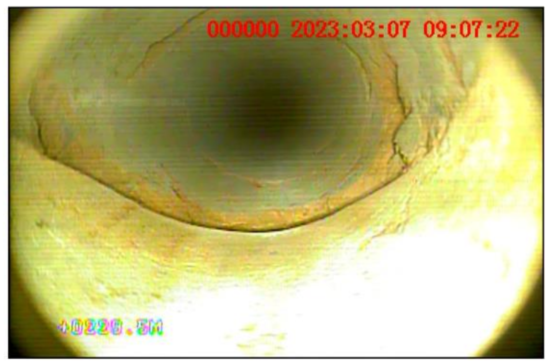
a) Uppermost mining induced fracture, water loss zone



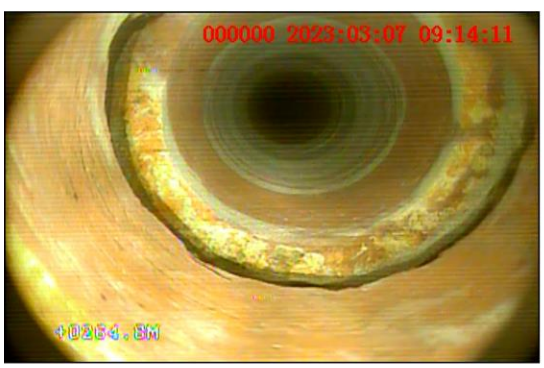
b) Angled open fracture in Hawkesbury Sandstone



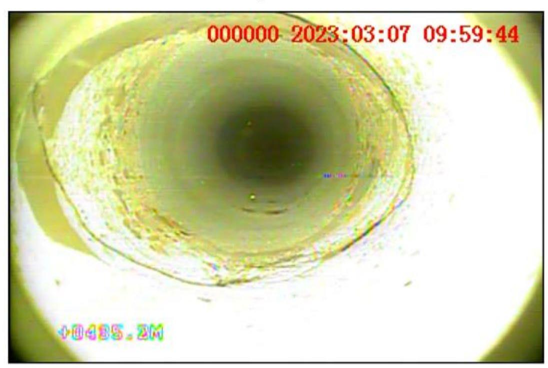
c) Open fracture in Hawkesbury Sandstone



d) Angled open fracture in Hawkesbury Sandstone



e) Open fracture in Bald Hill Claystone



f) Angled fracture in Bulgo Sandstone

Figure 4: Mining induced fractures identified in post mining borehole (HOFWD02).

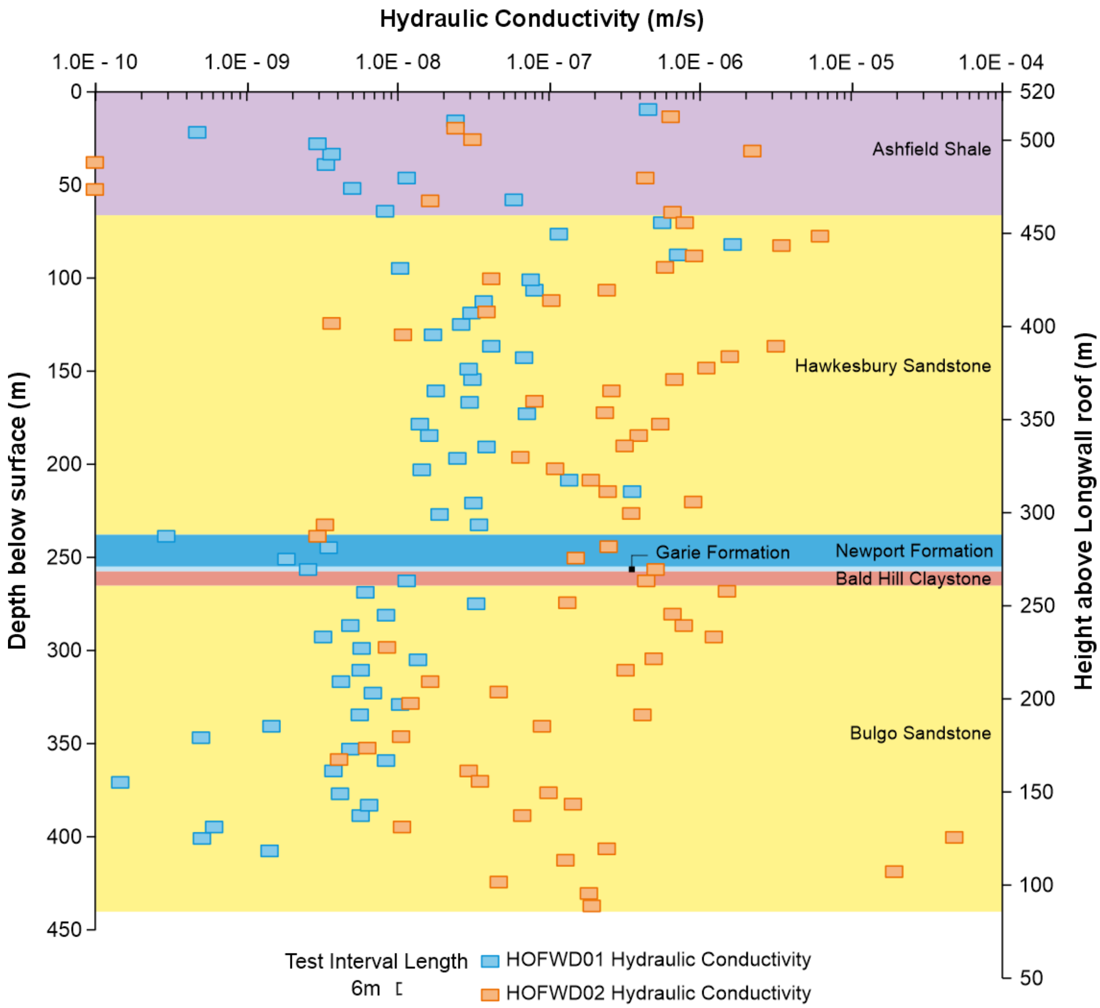


Figure 5: Hydraulic conductivity comparison for pre mining (HOFWD01) and post mining (HOFWD02) boreholes.

From 76 m to 200 m, interpreted as the zone of bedding plane separation, there is a general increase in hydraulic conductivity of approximately one order of magnitude. This increase in hydraulic conductivity is primarily due to bedding plane separation caused by Longwall West 2 caving process, causing an increase in horizontal hydraulic conductivity. The increase in hydraulic conductivity does not occur in every test interval, as the bedding plane separations are not always intersected in the 6 m packer test intervals.

Below 200 m, interpreted as the zone of large downward movement, there is a general increase in hydraulic conductivity of approximately two orders of magnitude. In this zone, there is an increase in both horizontal and vertical hydraulic conductivity due to the intersecting fracture network caused by the Longwall West 2 goaf formation. The increase in vertical hydraulic conductivity is interpreted from a decrease in the pore pressure profile (from VWP results) and an increase in angled fractures. The increase in hydraulic conductivity does not occur in every test interval, as the fracture network does not always intersect each 6 m packer test interval.

Pore Pressure Measurements

Eight fully grouted vibrating wire piezometers were installed into the two boreholes to gain pore pressure profiles before and after extraction of Longwall West 2. The piezometric profiles of Boreholes HOFWD01 (prior to shearing) and HOFWD02 are shown in Figure 6 in relation to depth from surface and height above the mining horizon. The graph shows the pore pressure measured on each VWP converted to head pressure in metres.

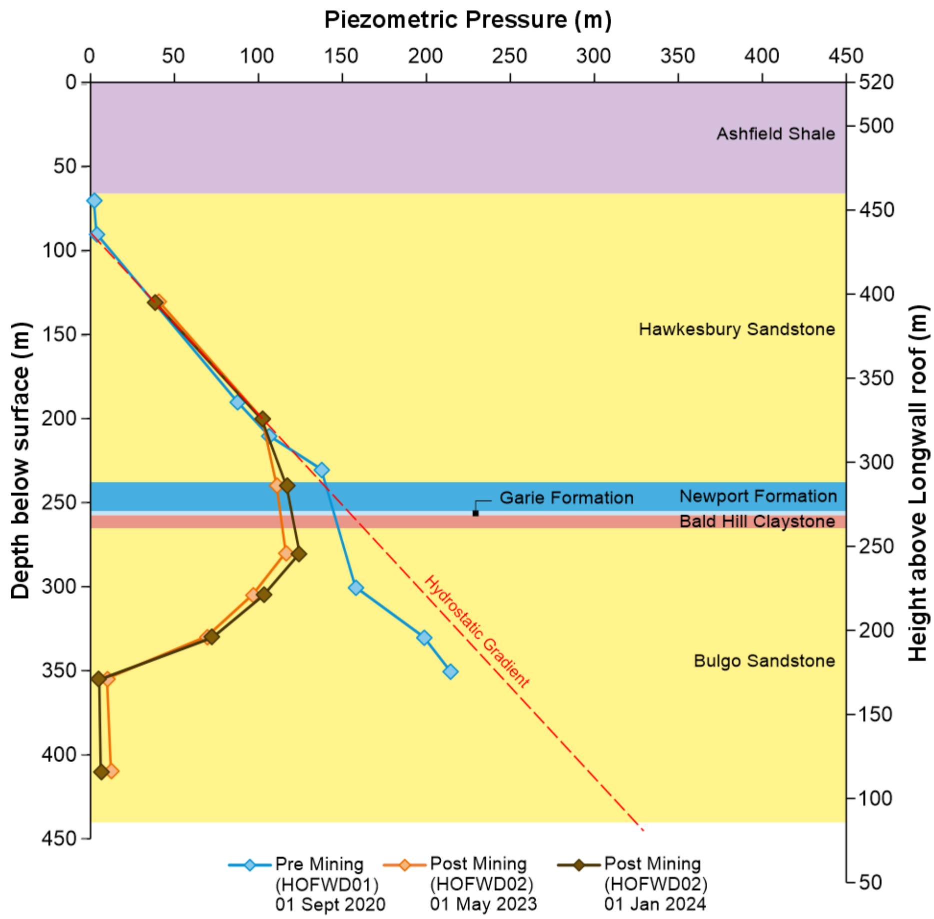


Figure 6: Piezometric profile comparison for pre mining (HOFWD01) and post mining (HOFWD02) boreholes.

In the pre mining Borehole HOFWD01, the top five VWP's down to the Newport Formation/Bald Hill Claystone, indicate a hydrostatic pressure profile consistent with a groundwater level at 85 m below surface. The lower three VWP's installed below the Bald Hill Claystone indicate a hydrostatic pressure profile consistent with a slightly reduced hydrostatic head. This slight reduction in pore pressure is potentially from regional drawdown due the approaching Longwall West 1 face and/or previous longwalls in the nearby Tahmoor North longwall domain. The lowest five VWP's in Borehole HOFWD01 (190 m to 350 m below surface) showed a reduction in pore pressure as Longwall 1 retreated towards the borehole. These VWP's were then severed due to longwall shear ahead of the face. This first occurred in the lowermost VWP when Longwall West 1 was approximately 70 m inbye of the borehole. The shearing of the VWP's progressed upwards as the longwall continued to retreat towards the borehole. The upper two VWP's (70 m and 90 m below surface) were not severed by shear movements.

In the post mining Borehole HOFWD02, the top two VWP's down to 200 m below surface indicate a hydrostatic pressure profile consistent with a groundwater level at 85 m below surface. A continual decline in pore pressure is evident in the underlying VWP's due to the extraction of Longwall West 2. The VWP's located below 200 m, show a clear drop in pressure from the hydraulic gradient. The bottom two VWP's located at 355 m and 410 m below surface show depressurisation. Pore pressure readings eight months apart are shown on Figure 6, indicating there was minimal change over this time period.

Table 3 shows the pore pressure readings converted to metres head for Borehole HOFWD02.

Table 3: VWP installation locations and pore pressure readings in the post mining Borehole HOFWD02 converted to metres head.

VWP Number	Stratigraphic Unit	VWP Install Depth Below Surface (m)	VWP Install Height Above Mining Horizon (m)	Pore Pressure in metres head 01/01/2024	Comment
1	Hawkesbury Sandstone	130	396	39.9	Hydraulic gradient (85m water level)
2	Hawkesbury Sandstone	200	326	103.8	Hydraulic gradient (85m water level)
3	Newport Formation	240	286	118.1	Reduction in pore pressure from hydraulic gradient
4	Bulgo Sandstone	280	246	125.7	Reduction in pore pressure from hydraulic gradient
5	Bulgo Sandstone	305	221	104.6	Reduction in pore pressure from hydraulic gradient
6	Bulgo Sandstone	330	196	73.7	Reduction in pore pressure from hydraulic gradient
7	Bulgo Sandstone	355	171	6.8	Depressurised
8	Bulgo Sandstone	410	116	8.2	Depressurised

Height of Depressurisation

In the context of this paper the term height of depressurisation is taken to mean the height above the longwall mining horizon where pore pressure is zero and downward flow can proceed under the action of gravity alone. The concept of a zero-pressure zone is helpful for conceptualising groundwater impacts but should not be seen as the extent or limit of the impact of longwall mining. A reduction in pressure occurs above the zone of depressurisation (zero pressure) calculated using the approach described in Tammetta (2012) and extends upward until the pre-mining hydrostatic gradient has been reached.

This work program (and others) show that the height of depressurisation and height of the main caving zone (zone of large downward movement) do not necessarily coincide. There is a reduction in pore pressure, below the hydrostatic profile, that starts at the top of the main caving zone due the fracturing network within this caving zone but depressurisation (zero pressure) is not reached until a point below the top of this zone.

Measured Height of Depressurisation

Prior to mining of a longwall there is typically a hydrostatic pore pressure profile in which water head pressure (m) increases with depth (m) at a ratio of 1 to 1, below the standing water level.

After longwall mining, a drainage path is created whereby water will be drawn down towards the goaf. The pore pressure at the mining horizon is zero. The height of depressurisation is at the top of the zero pressure zone.

As the lower two VWP's in HOFWD02 have been reduced to close to zero pore pressure (zero pressure for all practical purposes) these locations have been depressurised by the underground longwall workings, therefore the height of depressurisation is somewhere between the second and third lowest VWP sensors. The measured height of depressurisation is located in the Bulgo Sandstone, between 196 m and 171 m above the mining horizon (330 m and 355 m below the surface).

Due to the high density of the VWP's installed, the transition from the hydrostatic piezometric profile to the height of depressurisation is measured. The pore pressure data shows a gradual transition between these two stages. In Borehole HOFWD02, this transition occurs from 326 m above the mining horizon (200 m below surface) down to the measured height of depressurisation. This transitional section of the ground shows a reduction in pore pressure from a hydrostatic gradient, meaning downward flow is occurring in this section of the overburden, however this zone is not depressurised.

Theoretical Height of Depressurisation

A method for estimating the height of depressurisation above a longwall has been produced by Tammetta (2012), based on an extensive world-wide database available in the public domain, giving the following empirical equation:

$$H = 1438 \ln(4.315 \times 10^{-5} u + 0.9818) + 26$$

where $u = wt^{1.4} d^{0.2}$

H = Height of depressurisation above the mining horizon (m)
u = Tammetta Factor
w = Panel Width (m)
t = Mining Height (m)
d = Mining Depth (m)

The theoretical height of depressurisation for Borehole HOFWD02 is calculated as 176 m above the mining horizon and 350 m below surface, which lies within the measured height of depressurisation zone. These calculations are based on a panel width of 282 m, mining height of 2.2 m and mining depth of 526 m, using the Tammetta (2012) empirical equation.

SYNTHESIS OF RESULTS

A synthesis of the field measurements and observations from the pre and post mining boreholes have been compiled in Figure 7 to show the interpreted geomechanical and hydrological behaviour in the overburden above the extracted Longwall West 2 Panel.

The arch shaped zones depicted in Figure 7 is based on previous field measurements from a number of sites. Mills and O'Grady (1998) measured the arch shape using overburden extensometers in a series of boreholes over two adjacent longwall panels. Mills and Blacka (2017) measured the arch shape in a single borehole drilled over the centre of a longwall. Heritage and Blacka (2021) measured the arch shape via a series of cored boreholes drilled in a cross section over a mined out longwall panel.

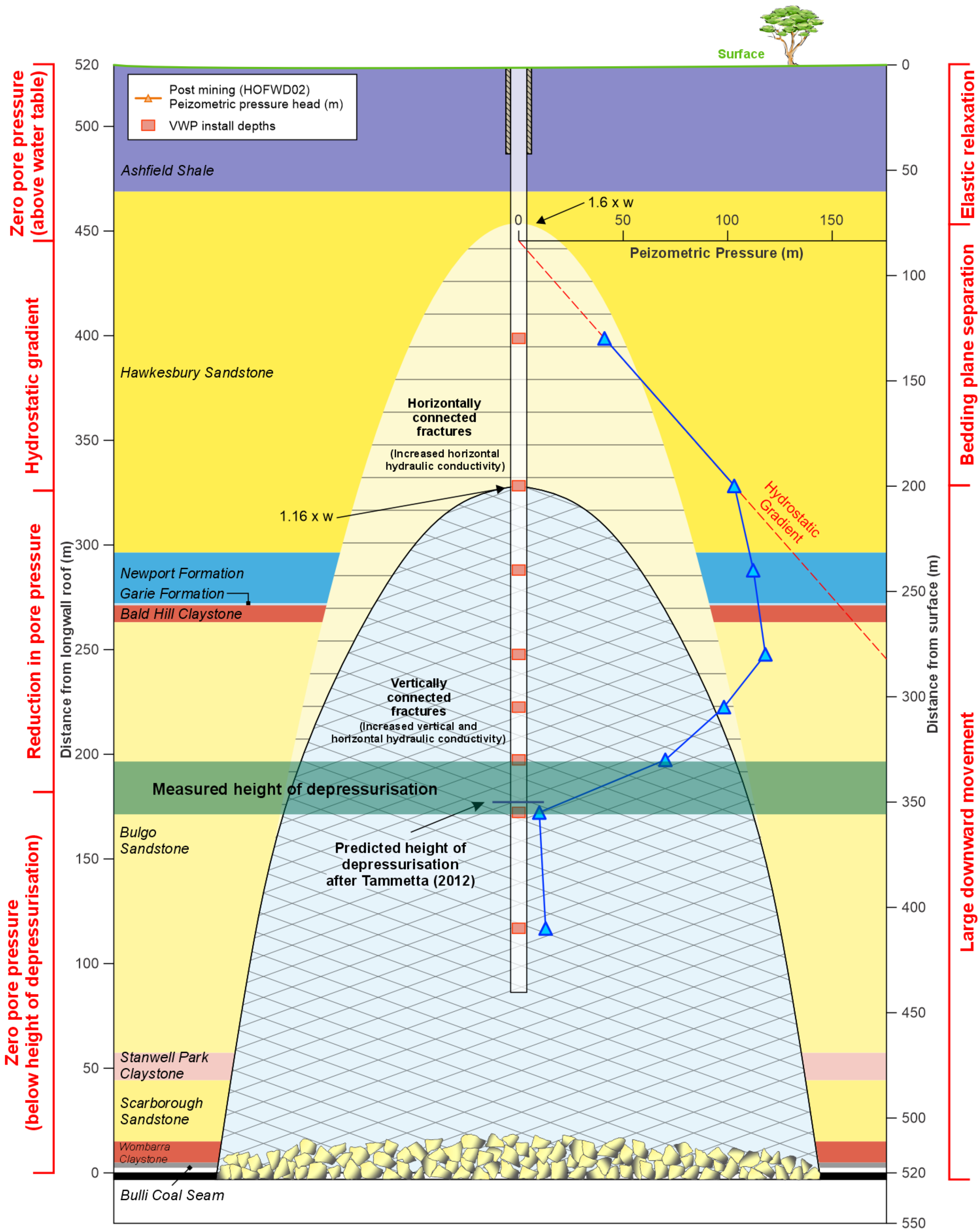


Figure 7: Caving zones, height of depressurisation and piezometric profile over Longwall West 2.

The geomechanical behaviour above an extracted longwall panel is depicted by Mills (2012). The height of the caved zones are determined by ratios of the longwall panel width. These zones are based on field measurements from Australian longwall operations using a range of different techniques. The three major zones are classified by Mills (2012) as:

- Zone of elastic relaxation - A zone of small ground movements from 1.6 to 3 times panel width above the mining horizon.

- Zone of bedding plane separation - A zone of bedding plane separation from about 1.0 to 1.6 times panel width above the mining horizon.

- Zone of large downward movement - A zone of large downward movement from seam level to a height above the mining horizon approximately equal to the panel width.

The measurements and observations completed in the pre and post mining boreholes over Longwall West 2 at Tahmoor show a reasonable correlation with the Mills 2012 caving model. These zones have been refined to correspond with the site specific geotechnical and hydrological comparisons of the pre and post mining boreholes over Longwall West 2.

Zone of Bedding Plane Separation

The zone of bedding plane separation over Longwall West 2 is interpreted to extend from 450 m to 326 m above the mining horizon (76 m to 200 m below surface). This equates to a height above the mining horizon of 1.60 to 1.16 times the panel width.

The top of this zone was indicated by the uppermost location of water loss while drilling and the uppermost significant open fracture.

There is an increase in core logged defect frequency of 45 percent in the post mining borehole compared to the pre mining borehole in this zone, with the increase occurring in bedding plane partings. The borehole camera survey identified significant bedding plane separation below 76 m in the post mining borehole compared to the pre mining borehole.

Hydraulic conductivity in this zone has a large variation, with a generally increase of one order of magnitude in the post mining borehole. The increase in hydraulic conductivity in this zone is likely due fracture flow through bedding plane separations.

Pore pressure data shows a hydrostatic gradient in this zone, indicating the increase in hydraulic conductivity in this zone is horizontal and has minimal vertical connectivity.

Zone of Large Downward Movement

The zone of large downwards movement over Longwall West 2 is interpreted to extend from 326 m above the mining horizon (200 m below the surface) to the top of the mining horizon. This equates to a height above the mining horizon of 1.16 times the panel width.

There is an increase in core logged defect frequency of 91 percent in the post mining borehole compared to the pre mining borehole in this zone, predominantly angled fractures and bedding plane partings. The increase in angled fractures is indicative of mining induced fracturing of intact rock. These fractures form behind the longwall face as the overburden strata fails behind the supports and are generally cyclic in nature.

Hydraulic conductivity in this zone is variable and generally increased by two orders of magnitude in the post mining borehole compared to the pre mining borehole. The increase in hydraulic conductivity is horizontal and vertical due to the interconnected fracture network.

There is a reduction in pore pressure from a hydrostatic gradient commencing at the top of this zone, which continues to decrease until pore pressure reduces to close to zero, indicating the height of depressurisation, measured between 196 m and 171 m above the mining horizon (330 m and 355 m below the surface). The reduction in pore pressure in this zone suggests downward flow, supporting the evidence of an interconnected fracture network and increased vertical hydraulic conductivity.

CONCLUSION

Pre and post mining cored boreholes over Longwall West 2 at Tahmoor have allowed for a direct comparison to determine the geomechanical and hydrological changes due to longwall mining and the interrelationship between the two. The field measurements and observations in these boreholes show there are multiple zones above the extracted longwall panel that correlate well the zones described by Mills (2012).

At this site, the determined height of caving and the start of a reduced pore pressure profile (from hydrostatic) coincide at the same height above the mining horizon. The reduction in pore pressure from hydrostatic to zero pore pressure is a gradual transition, meaning the height of depressurisation (zero pore pressure) and height of caving do not necessarily coincide.

ACKNOWLEDGEMENTS

The authors wish to thank SIMEC Mining and Tahmoor Mine for the opportunity to undertake these measurements and to present the results in this paper. The views expressed are entirely those of the authors and are not necessarily those of SIMEC or Tahmoor Mine.

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