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Horizontal drain holes: a case study

A Duran *PSM, Australia*

Abstract

Horizontal depressurisation holes (drain holes) form one of many options that are available for the depressurisation of mine pit slopes to improve stability. Whilst horizontal drain holes have been employed for over 80 years (Royster 1980), the literature commonly indicates their benefit to slope stability through the causal relationship of slope movements decreasing after drain holes have been installed (Seegmiller 1979; Rahardjo et al. 2003; Tsao et al. 2005; Beale et al. 2013).

Clermont Coal mine is located in an atypical coal mine setting where a major thrust fault in the west wall results in Cambrian aged foliated metamorphics (basement) being thrust over Permian aged coal measures. Geotechnical studies have identified an area of the west wall where a significant exposure of foliated metamorphics will be exposed over most of a 200 m high slope with foliation dipping towards the east. Stability analyses have inferred the potential for unfavourable stability at the overall pit wall scale. Owing to existing infrastructure at the crest, a cutback or unloading were not considered as viable design alternatives whilst leaving a buttress of coal at the toe was considered economically less desirable. As such, a depressurisation program was considered, with horizontal drain holes put forward to depressurise the slope and improve stability.

This paper presents an overview of the results of the depressurisation program and with particular emphasis on the interpretation of pore pressures within the slope based on the combination of both vertical and horizontal multi-nested vibrating wire piezometers.

Keywords: *depressurisation, drain holes, horizontal piezometers, slope stability, open pit, coal mining*

1 Geological overview

The Clermont Coal mine and adjacent Blair Athol Coal mine were formed as sub-basins of early Permian aged coal measures in the Bowen Basin to the immediate east of the Anakie inlier (Figure 1).

The Clermont sub-basin is nominally aligned north–south, with dimensions of over 4 km in length and about 2 km in width. Smith & Miller (1995) provide the following overview of the geology at Blair Athol, and which is largely comparable at Clermont

> *"The Lower Coal Measures unconformably overlie a highly irregular basement surface (Anakie Metamorphics). The sequence comprises well indurated fluviatile conglomerates and coarse sandstone with minor carbonaceous shale and stony coal lenses. Its maximum thickness is estimated as 130 to 150 m around the basin centre. The upper boundary of the sequence has been arbitrarily fixed at the floor of the lowest most coal seam."*
>
> *"The Upper Coal Measures comprise fine to medium grained sandstones and siltstones with four major coal seams and lesser mudstones and granule to pebble conglomerate."*

At Clermont the *Upper Coal Measures* form the key economic target and with mining of the Gowrie, Prospect and Wolfang coal seams, the latter being the key target and thickest seam (up to 35 m in places). Open pit mining at Clermont comprises a truck and shovel terrace operation, advancing to the south and with in-pit backfilling of waste in the northern part of the pit. Clermont Mine Planning use the term 'pushback' to denote each progressive terrace being developed.

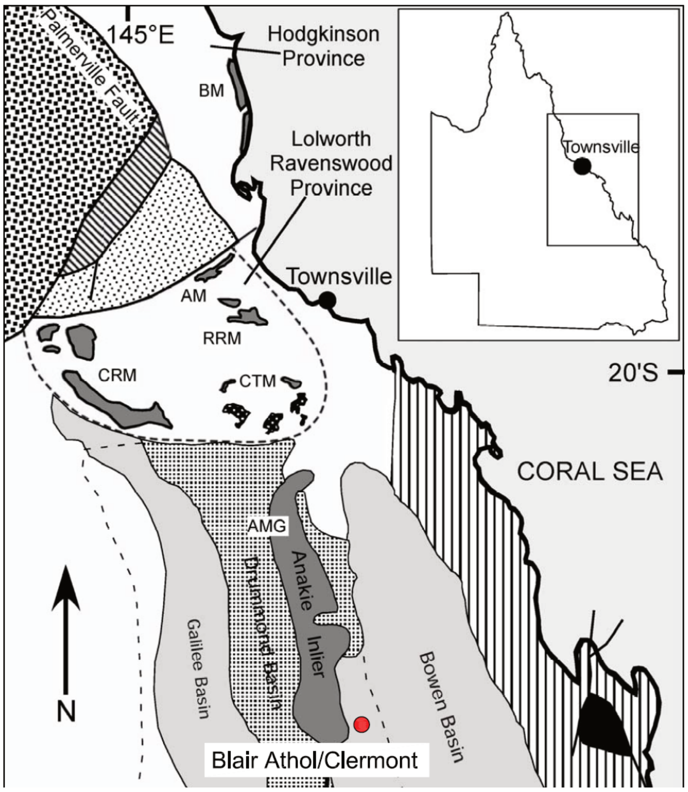


Figure 1 Regional geology and location of Clermont Coal mine

Of note at Clermont is the presence of a major thrust fault which truncates the northern half of the western edge of the sub-basin and places basement Anakie Metamorphics adjacent to Permian coal measures. Foliation within the Anakie Metamorphics dip towards the east. Early open pit mining encountered stability issues in the west wall owing to the pit-wards (i.e. east) dipping foliation.

2 Geotechnical overview

Ongoing geotechnical studies have involved cored geotechnical drilling with Acoustic Televiewer (ATV) interpretation, structural domain interpretation, kinematic stability analyses at the bench scale and limit equilibrium stability analyses to aid in assessing multi-bench and overall pit wall designs.

The geology in the west wall is complex. In several pushbacks this has resulted in the following exposed in the west wall:

- Wolfang coal occurring towards the toe of the west wall and varying from moderately to sub-vertically dipping.
- Conglomerate, varying from moderately to sub-vertically dipping and comprising large portions of the west wall in several pushbacks.
- A 'Sediment Package' beneath the conglomerate and forming the contact with the basement in exposures to date. The Sediment Package is typified by thinly bedded, highly jointed, fine grained Permian sediments.
- The latter two units form part of the *Lower Coal Measures* (Smith & Miller 1995).
- There were indications from the geotechnical drilling of a brecciated metamorphic unit beneath the Sediment Package. The brecciated metamorphic unit was inferred to be discontinuous as there were negligible indications of its presence from other boreholes which intersected the contact. Subsequent exposures indicate a lack of structure compared to the underlying foliated and jointed metamorphics (see Figure 2), and that it forms a mappable unit in the area discussed herein.

Lower rock mass strengths are assigned to the Sediment Package, owing to its very block nature, and the brecciated metamorphics.

Figure 2 Nature of brecciated metamorphic unit with evidence of occasional sub-vertical shear

During evolution of the large-scale structural interpretation of the west wall, it was recognised that there was a sinistral offset in the major thrust fault of nominally 400 m horizontally. This offset was initially interpreted, based on borehole data and sectional interpretations, to potentially comprise a transfer fault. However, as the exposures were developed there was difficulty in observing such a transfer fault. It was therefore proposed the thrust fault may have 'curved' to accommodate the offset. Ongoing development of exposures and structural studies resulted in Silwa (2019) proposing that the thrust fault was absent between 7 486 100 and 7 487 000 mN. Moreover, instead of a continuous thrust fault, the updated interpretation comprised two separate thrust fault segments to the north and south linked by a syncline/anticline fold pair between the thrust segments. Figure 3 presents the broad geology in plan and with the northern thrust fault segment out of view.

As a result of the geometry and folds in the Wolfang coal seam, Mine Planning had indicated a complex pit geometry whereby the west wall would form a concave indent to gain access to coal around the fold pair. This would result in a large portion of the west wall exposing Anakie Metamorphics with anticipated foliation dips in the order of 35 to 45° to the east. Figure 3 presents the pit in plan, location of geotechnical boreholes in the area of interest, folds in Permian and key lithologies in west wall.

Figure 4 presents cross-section 30R through the west wall and largely orthogonal to foliation in the metamorphics and bedding in the Permian. Of note in Figure 4 are (A) the adopted base case phreatic surface for stability analyses, (B) the conceptually required phreatic surface to achieve adequate Factor of Safety and (C) the critical failure surface for analyses utilising the base case phreatic surface. The base case phreatic surface had been formulated from review of piezometers installed at the crest of the west wall and with the phreatic surface slope between crest and toe inferred. Subsequent in-pit open hole piezometers installed progressively as the west wall had been developed indicated the base case phreatic surface was largely appropriate where the slope was predominantly comprised of conglomerate. Also shown in Figure 4 are the: base of weathering and interpreted structural domains, largely subdivided by changes in foliation or bedding dip. Of note is that in domains FP, P and T the bedding in the Permian is dipping to the east and near sub-vertical whilst domains L1 and K comprise metamorphics with foliation dipping at 35–45° to the east.

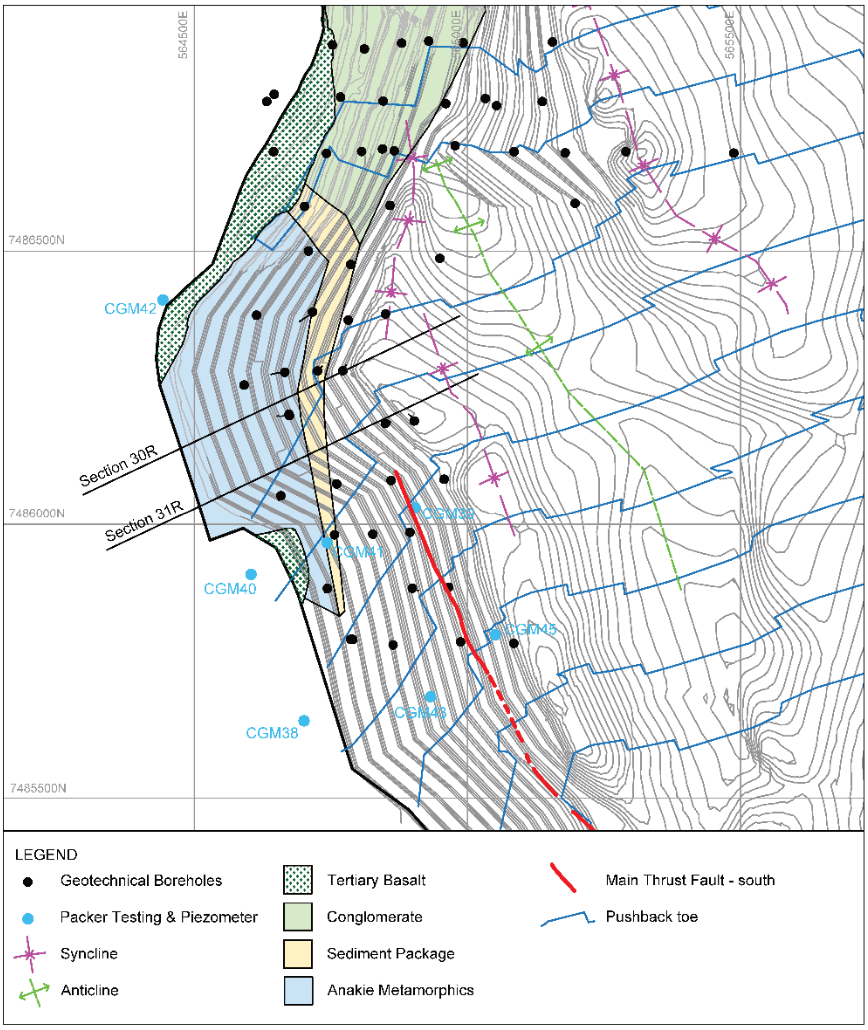


Figure 3 Plan view of western half of pit with key lithologies shaded

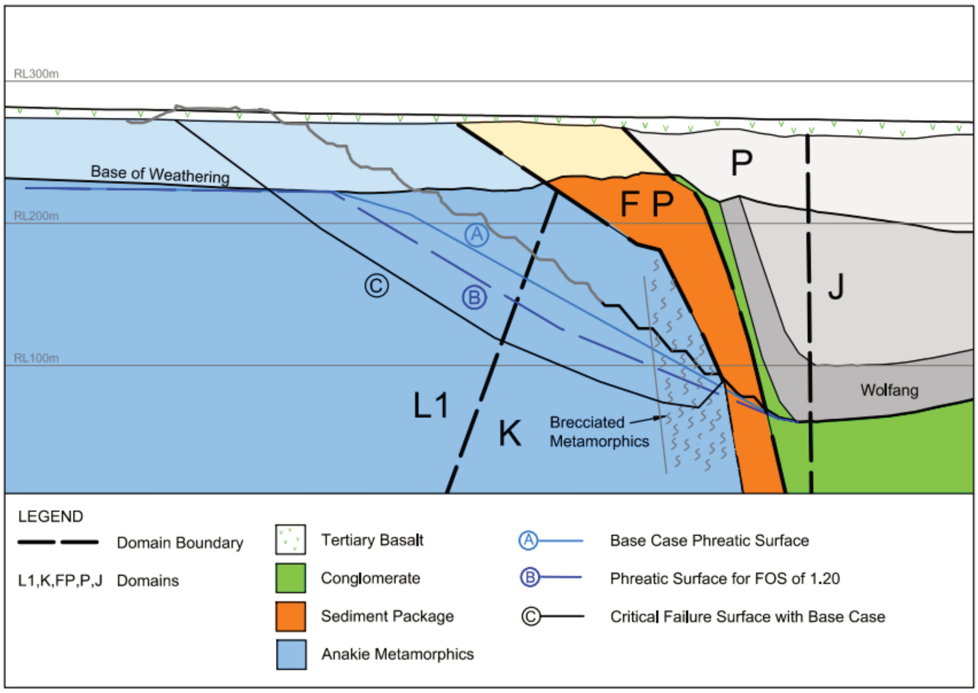


Figure 4 Cross-section 30R through west wall

3 Hydrogeological investigations

Hydrogeological investigations were carried out to confirm hydrogeological conditions within the key rock types and to allow an initial assessment of depressurisation measures which could be considered. A drilling program of seven cored boreholes and single packer testing was carried out (Australasian Groundwater and Environmental Consultants Pty Ltd 2018). At completion of drilling multi-nested vibrating wire piezometers (VWPs) were installed in all seven boreholes (Figure 3).

Table 1 presents the results of the packer testing grouped based on lithology within each packer interval. The rock mass hydraulic parameters determined from the packer tests confirmed that the use of conventional vertical production bores to assist in depressurising the west wall were unlikely to be effective owing to very low likely yields (as a result of the low transmissivity).

Table 1 Result of Packer Testing

Geology	No. tests	Geomean transmissivity (m^2/day)	Geomean hydraulic conductivity (m/day)
Weathered metamorphic	4	2.0×10^{-2}	8.8×10^{-4}
Fresh metamorphic	12	2.5×10^{-2}	1.4×10^{-3}
Sheared and foliated metamorphic	11	1.7×10^{-2}	8.3×10^{-4}
Sediment Package/conglomerate	6	4.1×10^{-2}	2.1×10^{-3}
Sediment Package/metamorphic	2	8.0×10^{-4}	4.2×10^{-5}
Conglomerate	5	2.1×10^{-2}	9.4×10^{-4}

Horizontal drain holes were the preferred depressurisation approach and initial drain hole design was derived using a combination of FEFLOW modelling and empirical design, Wu & Chieng (1991). Preliminary designs indicated a requirement for drains at approximately 30 m horizontal spacing and 100 m in length.

4 Depressurisation program

4.1 Overview

Figure 5 presents an overview of the depressurisation program and key aspects of note include:

- Several inactive piezometers. Many of those in the south, installed as part of the hydrogeological study, were lost because of the progression of pushback mining. Although reconnection was considered, the VWP cables could not be found following mining of each bench. The inactive piezometers in the west wall crest (CGM32, CGM33 and CGM34) were lost prior to the hydrogeological study and because of surface mining activities.
- Drain holes were drilled in campaigns as exposures in the west wall allowed.
- It had been initially planned to install vertical in-pit VWPs. However, it was later decided to install horizontal VWPs as the slope was developed. Horizontal VWPs were installed and focusing on the critical area of stability on cross-sections 30R and 31R. The horizontal VWPs typically comprised 150 m long holes, nominally inclined downwards 5° (to ensure appropriate grouting encapsulation) and with six VW tips installed in each hole. Hole selection was often based on drains producing limited flows.

- A row of vertical VWPs was installed at the west wall crest (CGM46 to CGM42) and in selected in-pit locations (CGM52 and CGM54) to assist in interpreting the effectiveness of the depressurisation drilling.

4.2 Initial program

An initial drain hole program of six drain holes was carried out, northernmost holes in Figure 5, and 'fanned' towards piezometers CGM21 and CGM46. There was limited response noted in the four vertical VWPs at the pit crest, CGM22, CGM46, CGM21 and CGM47, to the initial program of drain hole drilling.

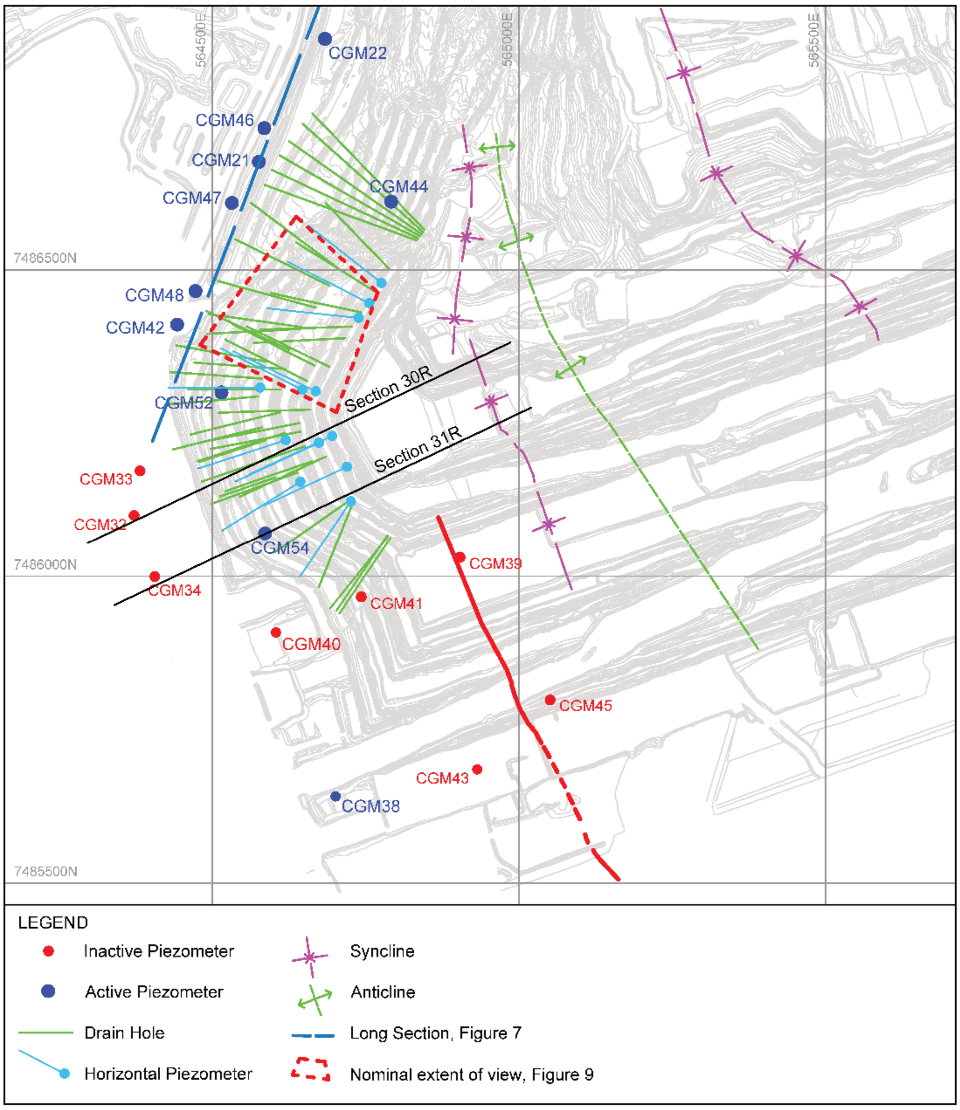


Figure 5 Plan of depressurisation program overlying pit

4.3 Subsequent programs

There was more favourable piezometric response to subsequent drain holes. Figure 6 presents the results from CGM42, with both an initial rapid downward response and continued falls in total head (and pore pressures). A similar response was also noted in nearby CGM48. Falls of near 15 m of total head are evident up to one year after drain hole installation in Figure 6. Whilst such responses are favourable at the pit crest, the key area of interest for slope stability is between lines (A) and (C) in Figure 4 and hence emphasises the requirement for in-pit monitoring.

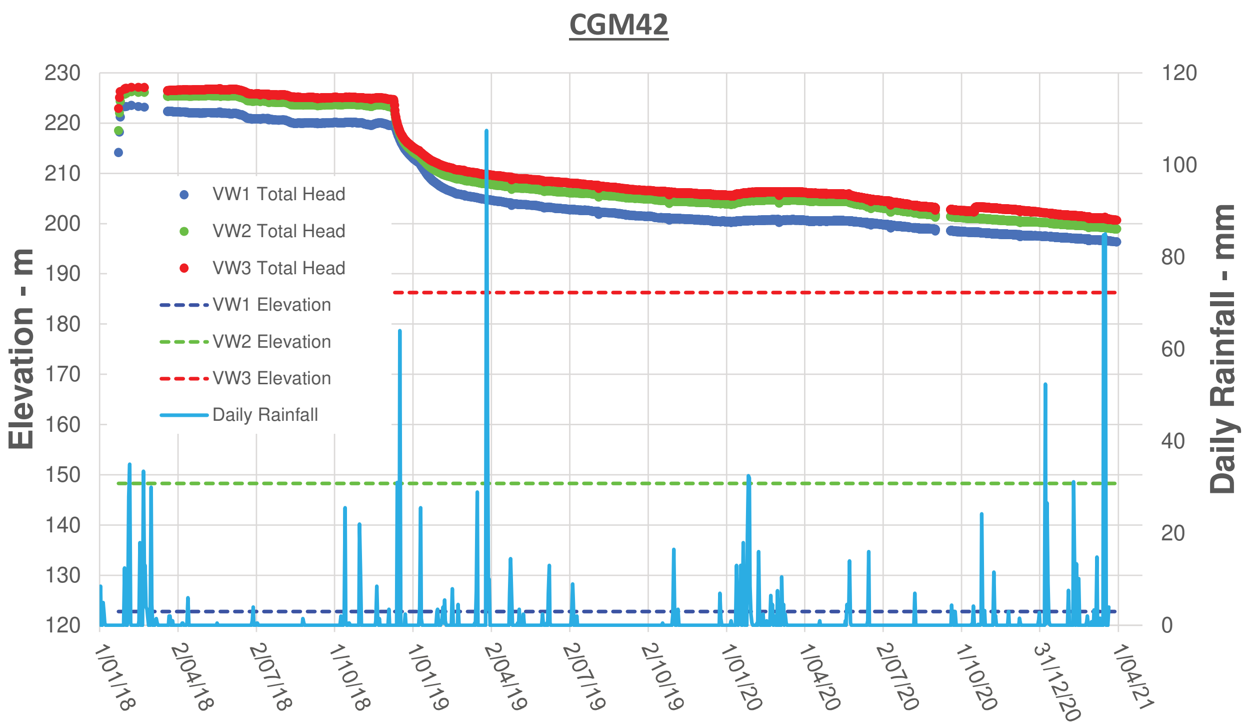


Figure 6 Response in CGM42 to drain hole drilling

Ongoing mapping of the exposures focused on the following aspects as these played key components in the stability analysis outcomes:

- Extent of Sediment Package and brecciated metamorphics as these lower strength units occur towards the toe of the slope.
- Foliation dip in Anakie Metamorphics.
- Structural domains.

5 Interpretation of depressurisation

5.1 Long section

An interpretation of total head response in long section along the west wall crest (see Figure 5 for long section location), was carried out to assess variability of the groundwater conditions. Figure 7 presents an interpretation part way through the depressurisation program and with foliation dipping toward the viewer (i.e. section is looking west).

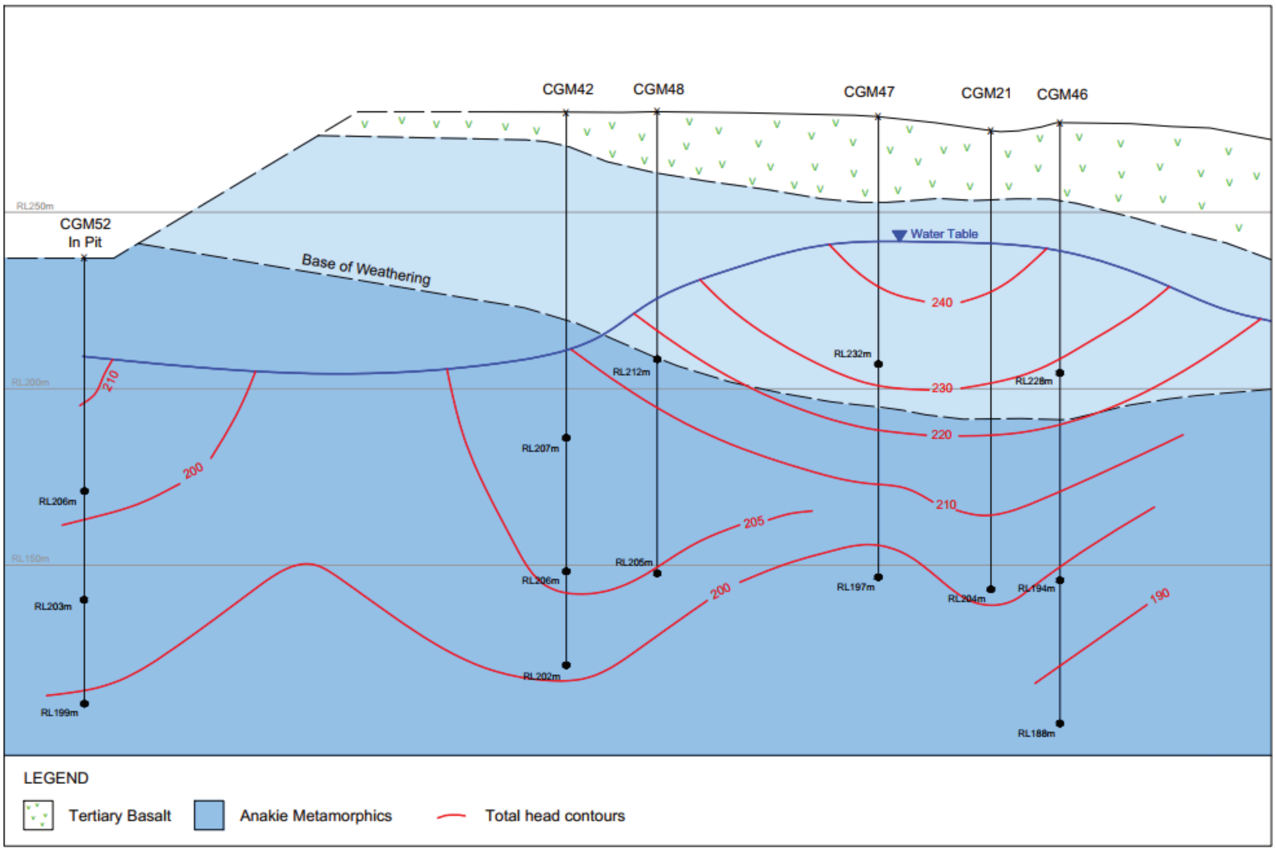


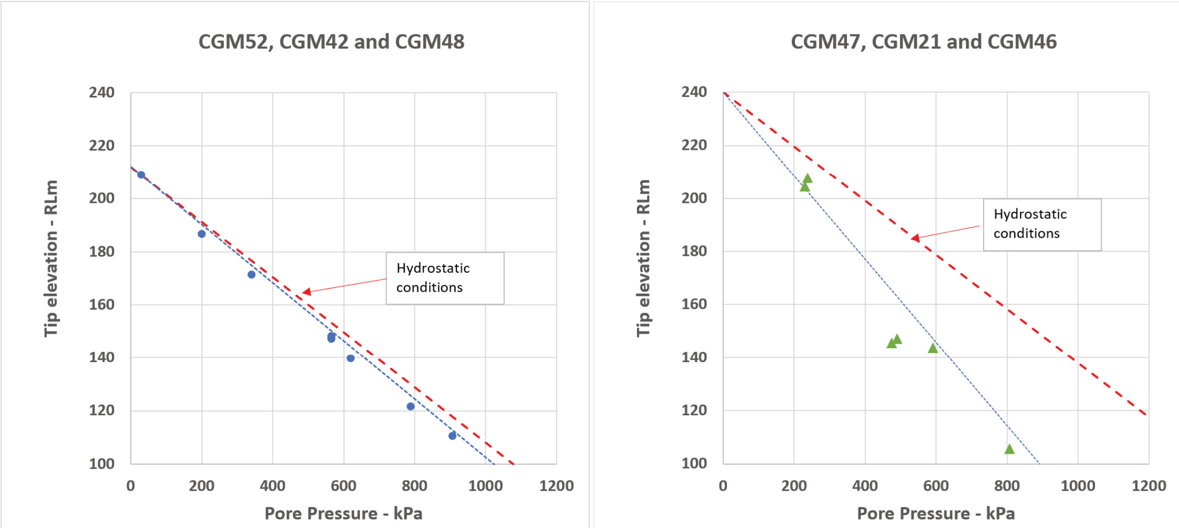
Figure 7 Long section interpretation of total head contours within metamorphics

Key aspects of the interpretation at the time included:

- Persistent elevated total heads and water table centred near CGM47 with flow occurring radially from this setting. The evidence suggests the elevated total heads are sustained by a perennial/consistent recharge source which may comprise either: catchment-scale flow in unconformity zones on Tertiary basalt contact or infiltration from a surface water dam some 250 m northwest of CGM47. This recharge may also explain the limited piezometer response to the initial drains installed in the north.
- The elevated groundwater heads in proximity to CGM47 are atypical based on other piezometers at the west wall crest.
- The elevated groundwater heads in CGM47 have not decayed in response to adjacent mining or drain holes.
- However, depressurisation is evident further south and where water table elevations show drawdown up to 15 m and total heads show reductions of up to 25 m from drain hole drilling.
- Sustained discharge from initial drain holes, despite comparatively high elevation of installation, indicate interception of persistent recharge.

Hydrographs of piezometers grouped south and north show clear differences in response (see Figure 8). Whilst the group to the north (piezometers near the groundwater high) indicates a higher groundwater level, the piezometers indicate nominally 65% of hydrostatic conditions. In comparison the group to the south has a lower groundwater level but the piezometers indicate nominally 95% of hydrostatic conditions.

The author assigns the large difference in behaviour of the north and south groups because of the location of the piezometers relative to the area where east dipping foliation planes crosscut the northern wall of the indent (see Figure 5). Owing to the foliation planes daylighting in the wall (see Figure 9), this has allowed depressurisation of the rock mass to the immediate north of the dashed area in Figure 5. Whilst for the south group the foliation planes are parallel to, and dip into the slope, therefore allowing limited natural depressurisation to occur and hence nearly hydrostatic conditions observed in the piezometers.



(a) (b)

Figure 8 Hydrographs of west wall crest piezometers. (a) South group; (b) North group

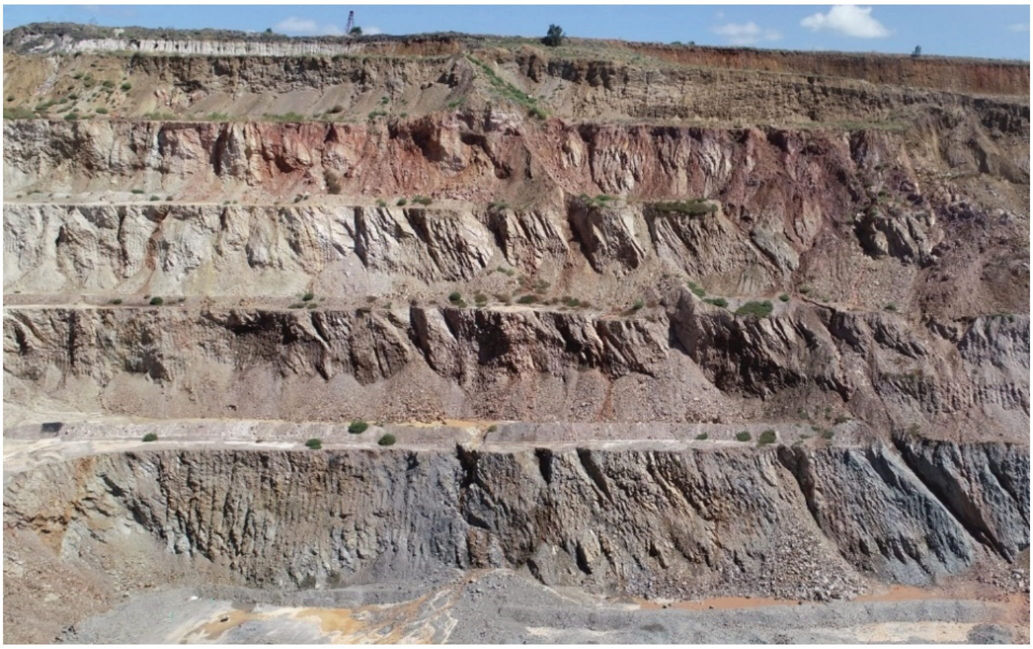


Figure 9 Overview of northern wall where foliation planes crosscut and are fully exposed over height of wall, see Figure 5 for location

5.2 Interpretation of depressurisation from drain holes

Figure 10 presents cross-section 30R, pore pressures within the VWP tips and interpreted total head contours. Similar responses were noted in cross-section 31R (see Figure 11) and indicate the behaviour was widespread and in response to the horizontal drains. However, there are some fundamental differences between the two interpretations, and which are assigned to the difference in geology across the two sections.

The presence of the brecciated metamorphics towards the middle of the slope (Figure 11) as opposed to occurring at the toe (Figure 10) is considered of primary significance.

Figures 10 and 11 suggest a broadly isotropic rock mass and with very localised depressurisation in response to the drain holes. Of interest is the occurrence of a near horizontal lobe of lower total heads. In Figure 10 this is indicated to occur directly aligned with CGM66, largely driven by a comparatively very low total head in the deepest VW tip and suggesting locally enhanced depressurisation near this VW tip. However, in Figure 11 this lobe appears to occur between levels of drain holes. The interpretation in Figure 11 may be an artifice of the horizontal piezometer locations as CGM60 and CGM70 are 50 m north of the cross-section.

Of note in Figures 10 and 11 are the 'boxed' piezometer tips which were not utilised in interpreting the total head contours. In Figure 10 the significantly higher head in the far tip of CGM59, total head of RL269 m, is out of character with all other piezometers at the west wall crest. This tip is interpreted to potentially be influenced by seepage along a foliation plane intersecting the base of the Tertiary basalt (which forms a perched aquifer at Clermont). In Figure 11 the lowest tip in CGM54 was ignored from the interpretation as the total head of RL128 m is at odds with surrounding measurements. Inspection of the piezometer response indicated an initial total head of about RL190 m (which is somewhat in keeping with the interpretation in Figure 11) and thereafter erratic behaviour over a period of six months.

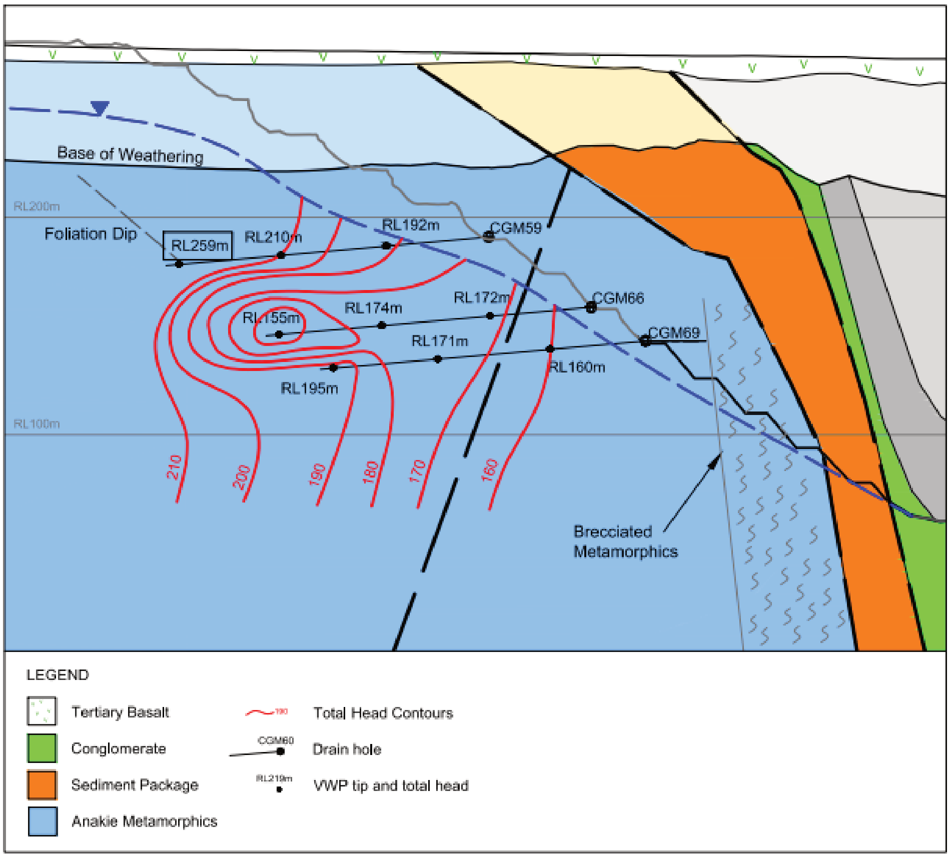


Figure 10 Interpreted total head contours on cross-section 30R

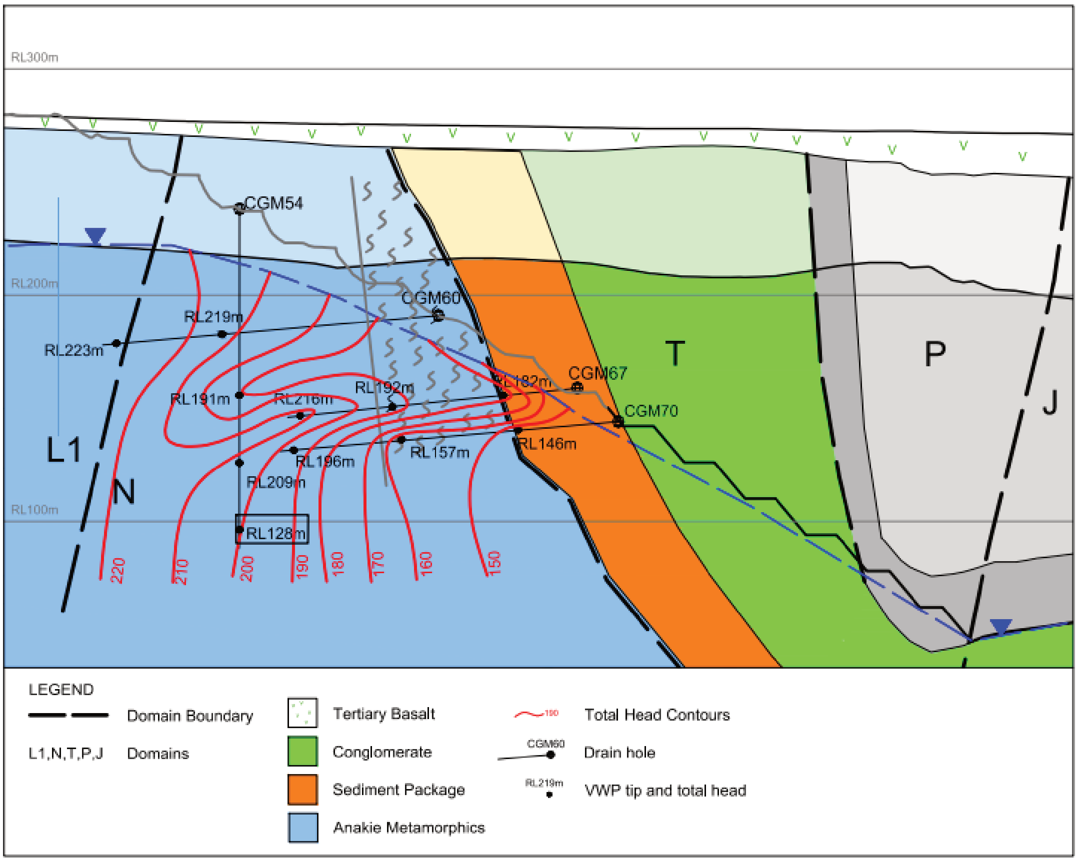


Figure 11 Interpreted total head contours on cross-section 31R

6 Discussion

The Clermont data from the vertical and horizontal piezometers indicates a complex hydrogeological setting and complex response to the horizontal drains.

The presence of foliation in the metamorphics would suggest the potential for anisotropic behaviour such that total head contours as shown by Brawner et al. (1971) under anisotropic conditions (see Figure 12b) could be expected. Whilst lateral and down-dip anisotropy is inferred in the behaviour from the grouping of piezometers in the crest area (see Figure 8 and relevant discussion thereof), the interpreted total head contours in Figure 7 and broader interpretation of total head contours in Figures 10 and 11, away from the immediate influence of the horizontal drains, indicates largely isotropic conditions (see Figure 12a).

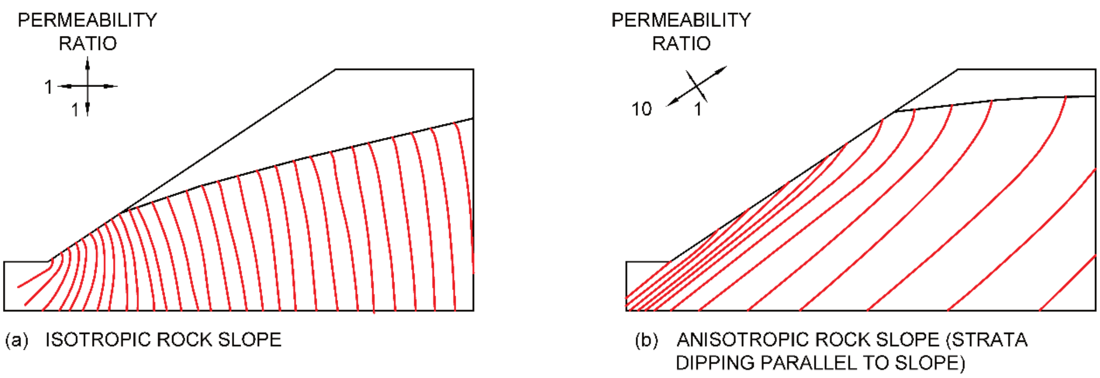


Figure 12 Conceptual elevation head contours (Brawner et al., 1971) for (a) isotropic and (b) anisotropic settings

Whilst Clermont VWP data indicates a high phreatic surface, there are appreciable areas within the slope where there are reductions in pore pressures (see Figures 10 and 11) as evident in the near horizontal lobes of lower total heads. This complexity is not captured in the conceptual idealisation presented in Figure 4, i.e. assuming installation of horizontal drains reduces phreatic surface from (A) to (B), or as presented by Seegmiller (1979), Rahardjo et al. (2003), Tsao et al. (2005) or Beale et al. (2013). In fact, without the intensity of both in-pit vertical and horizontal VWPs emplaced at Clermont these lobes of lower total heads would not have been evident.

Key findings of the study have comprised:

- In complex geological settings, pore pressures and head responses to both natural pit slope drainage and depressurisation drilling can be significantly at variance to conceptual idealisations.
- It is not uncommon, and variable depressurisation responses should be expected from drain holes.
- Caution needs to be utilised with conceptualised depressurisation responses both in terms of the character of the response and assuming that an even response will be achieved throughout the area where depressurisation is carried out.
- A conceptual depressurisation profile is useful as a presentation tool but can provide optimistic expectations of achievable depressurisation.
- A good distribution of VWPs is required to capture the achieved depressurisation rather than relying on limited data and inferring typical 'text book' pore pressure profiles elsewhere.
- Plan for additional piezometers in complex environments and with ongoing tailoring of the depressurisation program to achieve adequate stability outcomes.
- Horizontal VWPs provide an alternative to vertical VWPs and offer an advantage in better capturing groundwater conditions within the slope and crucially in the vicinity of where critical failure surfaces are anticipated (compare surface (C) in Figure 4 with interpretation of total heads in Figure 10).

7 Implications for stability analyses

For Clermont, the total head contours in Figures 10 and 11 were respectively utilised in creating a pore pressure grid for each of cross-sections 30R and 31R. Stability analyses with the pore pressures grids coupled with updated geological interpretation and foliation dips from mapping resulted in acceptable Factors of Safety for the final proposed design in this area.

8 Conclusions

In complex geological settings, pore pressure and head responses to both natural pit slope drainage and depressurisation drilling can be significantly at variance to the conceptual idealisations as presented by Seegmiller (1979), Rahardjo et al. (2003), Tsao et al. (2005) or Beale et al. (2013). Caution needs to be utilised with conceptualised depressurisation responses in terms of: the character of the response, assuming that an even response will be achieved and optimistic expectations of achievable depressurisation.

It is not uncommon, and variable depressurisation responses should be expected from drain holes. As such, a good distribution of VWPs is required to better understand the achieved depressurisation rather than relying on limited data and inferring typical 'text book' pore pressure profiles elsewhere.

Plan for additional piezometers in complex environments and with ongoing tailoring of the depressurisation program to achieve adequate stability outcomes. Fundamentally, in-pit monitoring is critical, as data from piezometers at the pit crest alone does not provide an adequate appreciation of depressurisation achieved in the critical area for overall pit scale stability. Multiple nested, horizontal VWPs provide a significant benefit in understanding the depressurisation in the critical area and where potential failure surfaces may be anticipated.

Adequate redundancy for piezometers should be allowed as they are commonly impacted by mining operations. Although reconnection is sometimes possible it should not be relied upon as it often has a low chance of success.

Acknowledgement

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References

Australasian Groundwater and Environmental Consultants Pty Ltd 2018, *Clermont Coal Mine Packer Testing*, report G1888.

Beale, G, De Sousa, J, Smith, R & St Louis, B, 2013, 'Implementation of Slope Depressurisation Systems', in G Beale & J Read (eds), *Guidelines for Evaluating Water in Pit Slope Stability*, CSIRO Publishing, Collingwood.

Brawner, CO, Pentz, DL & Sharp, JC 1971, 'Stability Studies of a Footwall Slope in Layered Coal Deposit', *Proceedings of the 13th US Symposium on Rock Mechanics*, American Rock Mechanics Association, Alexandria, pp. 329–365.

Rahardjo, H, Hritzuk, KJ, Leong, EC & Rezaur, RB 2003, 'Effectiveness of horizontal drains for slope stability', *Engineering Geology*, vol. 69, pp. 295–308.

Royster, DL 1980, 'Horizontal drains and horizontal drilling: an overview', *Transportation Research Record*, vol. 783, pp. 16–20.

Seegmiller, BL 1979, Horizontal drains - their use in open pit mine dewatering, *Drainage Control for Surface Mines*, Miller Freeman Publications, Inc., San Francisco.

Smith, RDC & Miller, DE 1995, 'The Blair Athol Coal Mine', *Proceedings of the Bowen Basin Symposium 1995: 150 Years On*, Geological Society of Australia, Coal Geology Group 1v, Mackay, pp. 265–270.

Silwa, R 2019, *Clermont thrust Fault Interpretation, January 2019 Update*, Integrated Geoscience Pty Ltd report to Clermont Open Cut.

Tsao, TM, Wang, MK, Chen, MC, Takeuchi, Y, Matsuura, S & Ochiai, H 2005, 'A case study of the pore water pressure fluctuation on the slip surface using horizontal borehole works on drainage well', *Engineering Geology*, vol. 78, pp. 105–118.

Wu, G & Chieng, ST 1991, 'A Convenient Drain Spacing Formula for Layered Soils', *Canadian Agricultural Engineering*, vol. 33, pp. 239–243.