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Piezometer interpretation: coal mine highwalls

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Abstract

The authors present the results and interpretation of the groundwater regimes from multi-tip vibrating wire piezometers (VWP) emplaced in coal mine highwalls. Four case studies are presented, with each case presenting a separate mining area. The data extents for each case vary: one case where there are 10 piezometers in the highwall over a strike length of 2.0 km to another case where 7 piezometers are available over a strike length of 2.8 km.

The interpretations have considered:

- *The depth to phreatic surface and variation in Hu (a Hu of 1.0 representing fully hydrostatic conditions and a Hu of 0.0 indicates unsaturated [dry] conditions) down the highwall (i.e. from crest to toe).*
- *Where faults crosscut the highwall, and between VWPs, the potential impact of compartmentalisation.*
- *The impact near end walls, corners in the highwall, potential aquitards in the highwall and depressurisation from progressive mining.*

This paper draws conclusions as to what groundwater regimes could be expected in coal mine highwalls.

Keywords: *coal mine highwall, vibrating wire piezometers, groundwater interpretation*

1 Introduction

With the exception of Simmons (2020), there is limited information in published literature as to the expectation on groundwater pressures in coal mine highwalls. Of note, in stability analyses is the use of the Hu parameter which effectively provides an estimate of groundwater pressures below the groundwater/phreatic surface – a Hu of 1.0 representing fully hydrostatic conditions and a Hu of 0.0 indicates unsaturated (dry) conditions.

In general coal mine highwalls are not established over significant heights and in the authors' experience there is a low potential for overall failure of the highwall through the rock mass. Where failures are observed there is a dominant influence by structure. For the coal mine in this study (the site), final heights of the highwalls may exceed 400 m. As such an understanding of key inputs are critical in assessing stability. Groundwater plays a key role in slope stability and for the range of Hu values stated by Simmons (2020) '0.70 to 0.95'. Analyses to date of the site have indicated that values towards the upper bound of the range place limits on the final highwall design. As such, at the site there has been progressive installation of multi-tip vibrating wire piezometers (VWP) as the highwalls have been developed.

Initial installation of VWPs is typically in the crest area and with progressive installation as the pit develops. Whilst interpretation of the crest VWPs provide initial insight into groundwater conditions, as noted in Simmons (2019), caution needs to be exercised in translating the initial interpretation to encompassing conditions over the final slope. Data over several years at the site has shed light on the range of groundwater

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scenarios that can be encountered in a highwall setting. Examples are provided below to place into context scenarios encountered and the implications for slope stability.

2 Site background

The site comprises a truck and shovel multi-seam coal mining operation with mining having been carried out in 10 pits over 40 years. Mining involves extraction from multiple seams, along a strike length of 45 km. Seam dips are commonly in the range of 10–20°, albeit there are some areas where seam dips exceed 40°.

The coal measures stratigraphy comprises a sequence of sandstones, siltstones, claystones and coal seams. Of critical note for stability of the footwall slopes is the presence of clay seams (inferred to be tuffs) and which are often encountered at the base of coal seams. Details of note for analysis of footwalls are provided in Cavers et al. (1986), Hawley et al. (1986), Stead & Eberhardt (1997) and Duran & Seedsman (2018).

For the highwall slopes, design checks indicated that where seam dips exceed 25° the critical failure mechanism comprised of a circular mechanism. For shallower seam dips, the mechanism transitions to a composite failure with the rear scarp comprising largely circular and the toe involving "up-dip sliding on a tuffaceous clay" (Simmons 2019). This latter mechanism is more adverse for stability and, owing to the typical seam dips at the site, is the critical highwall failure mechanism across much of the site. Studies to optimise the highwall at the site indicated groundwater would play a key role and has resulted in piezometer installation throughout the developing highwalls to better understand pore pressures in the pit slopes.

This paper presents examples of piezometer data through both cross-sectional interpretation and individual VWPs to allow an appreciation of groundwater concepts.

3 Examples

3.1 Textbook case

Figure 1 presents an interpretation on VWPs in cross-section through a coal mine highwall and wherein the total head of each piezometer tip has been shown. A key aspect evident at the crest is reducing head with depth for piezometer PZ01. Interpretation of the VWP data through a hydrograph (inset), indicates a Hu of nominally 0.70. However, near the current toe, piezometer PZ02 indicates hydrostatic conditions. This trend of increasing Hu progressively from crest to toe is the 'textbook case' – as noted by Beale et al. (2013), Beale (2018) and Simmons (2019) – and is often seen in pit slopes which are progressively being mined.

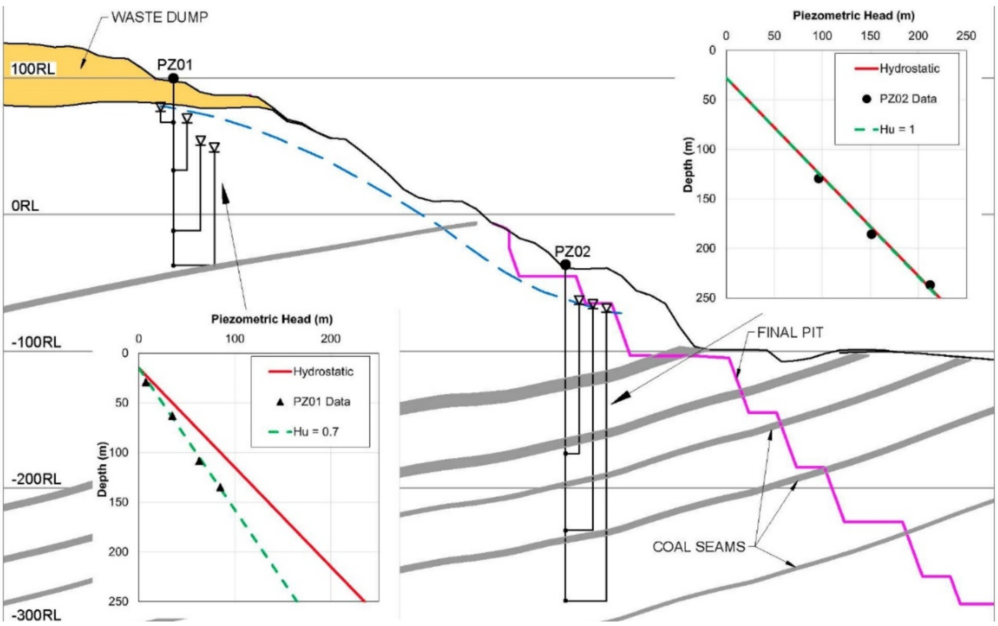


Figure 1 Increasing Hu towards of toe of slope – 'textbook case'

3.2 Consistent Hu

Figure 2 presents an interpretation on VWPs in cross-section of a different pit area, where future mining is planned and with piezometers placed well in advance of mining. In this case whilst the data in piezometer PZ04 infers a Hu of nominally 0.85 piezometers PZ03 and PZ05 indicate a Hu near unity (hydrostatic). Of note is that whilst active mining is occurring in an adjacent pit, along strike, the distance is such that it is only marginally impacting one piezometer in this cross-section. The interpretation is essentially indicating hydrostatic conditions and would be conceptually expected where the groundwater regime is not being stressed through mining.

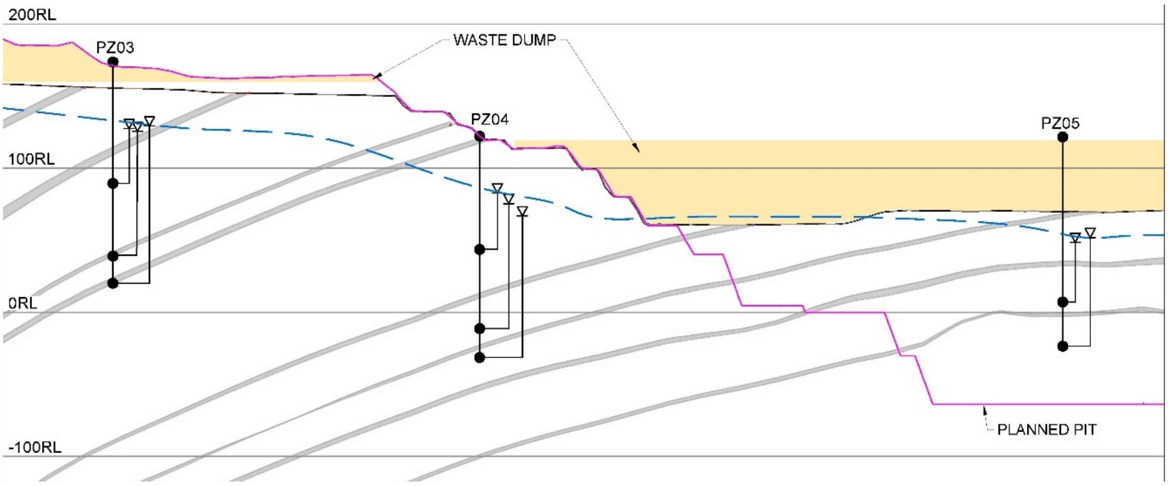


Figure 2 Consistent Hu throughout slope

3.3 Variations in Hu within individual piezometers

Figure 3 presents data from one VWP plotted on a hydrograph. Accepting a consistent Hu with depth, a near linear fit through the data can be utilised to infer the location of the phreatic surface below the piezometer collar (12 m). A Hu of nominally 0.65 is interpreted (i.e. pore pressures at any point below the phreatic surface are 65% of hydrostatic).

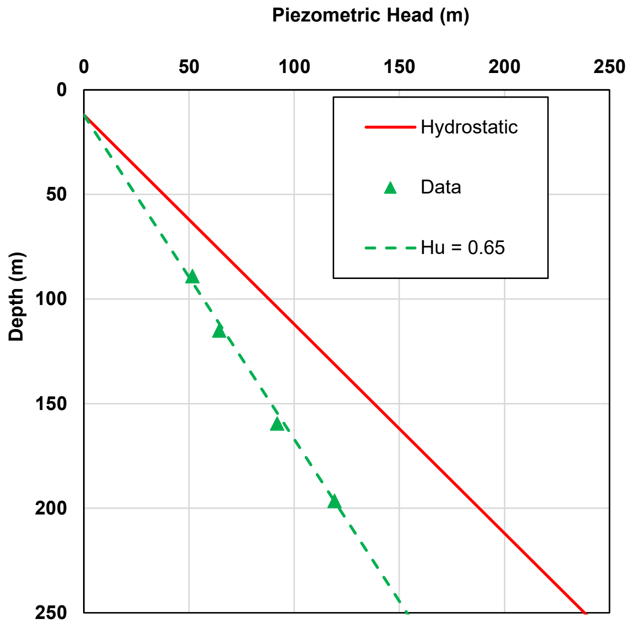
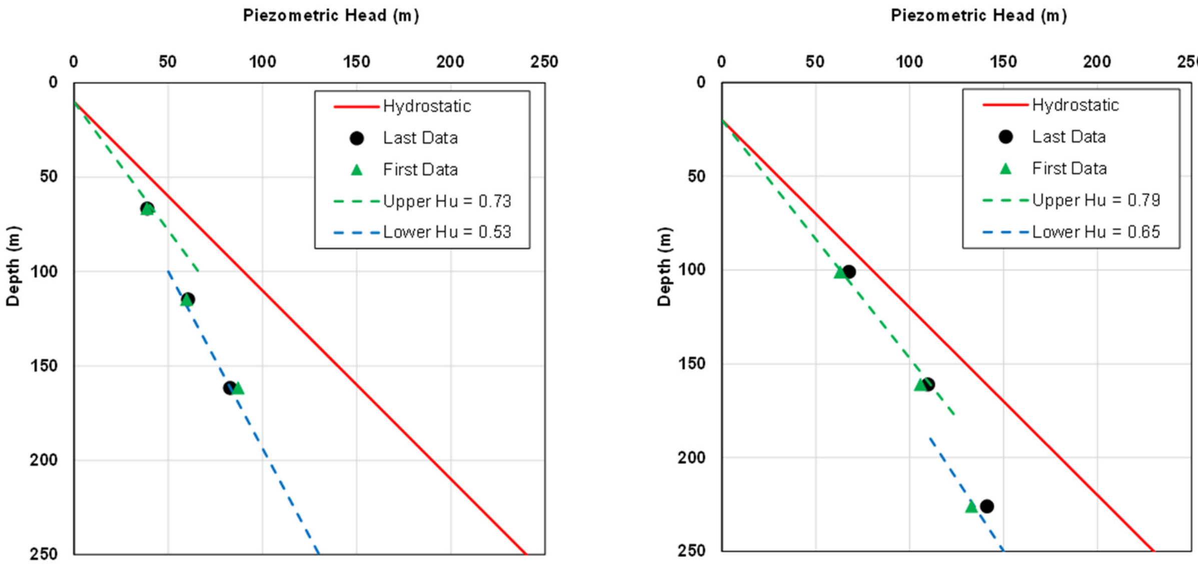


Figure 3 Interpretation of phreatic surface and Hu for a highwall piezometer at the site

The value of Hu is often utilised in stability analyses. Where Hu is consistent with depth and across the slope the use of Hu in stability analyses is appropriate. Whilst it is not unusual to observe near consistent Hu values within a given piezometer, Figure 3, the following provides examples where the interpretation is more complex, and a unique value of Hu does not always match the observations within a VWP. The implication is compartmentalisation of the groundwater regime and this may be either because of faults or potentially stratigraphically controlled aquitards. Such complex scenarios, and where Hu values also change across the slope profile, require appropriate consideration in developing stability analysis models.

Figure 4 presents 2 cases, both in one pit, where stratigraphically controlled aquitards have been interpreted. Based on the site geology the authors infer such aquitards are associated with the clay/tuff seams. In both examples the VWP data includes the initial readings at time of installation (triangles) and latest data (circles). Of note is that in both cases a lower Hu value is inferred below the aquitard.



(a) (b)

Figure 4 Examples of compartmentalisation in vibrating wire piezometers data and with inference of lower Hu values below inferred stratigraphically controlled aquitards

For the examples in Figure 4, there was minor pit development at the toe which is better reflected in Figure 4b, with minor depressurisation occurring in the lowest tip over time.

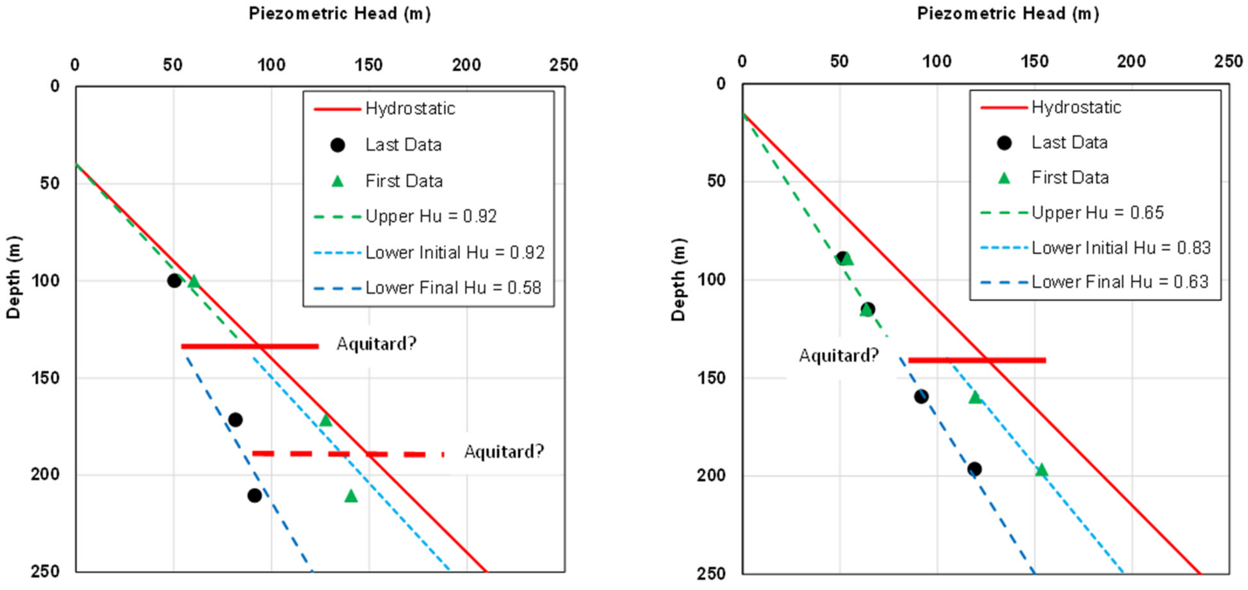
Figure 5 also presents cases where stratigraphically controlled aquitards have been interpreted. However, in both examples there is clear evidence of depressurisation of the lower strata in response to mining development. In the Figure 5a the Hu of the lower strata was initially similar in value to the upper strata but subsequently decreased over time. Whilst in Figure 5b the lower strata had initially a higher interpreted Hu and over time reduced to a similar value to that of the upper strata. Of note in Figure 5a is that conceptually an additional aquitard could be inferred, which has been ignored to simplify the interpretation of Hu value of the lower strata.

The reduction in Hu value of the lower strata ranges from 0.20–0.34 and occurred over timeframes of nominally 2 and 5 years respectively for the 2 cases presented in Figure 5.

Interestingly in all 4 examples, whilst different Hu values can be inferred throughout the strata the phreatic surface in each case has not changed.

Of note are the Hu values in Figure 3 and of the upper strata in Figures 4 and 5. A range in Hu of 0.65–0.92 is indicated and in keeping with the range indicated by Simmons (2020).

All 4 cases relate to 2 pits where historic dumps perched near the pit crest have impinged on the ability to emplace ‘good’ surface water management practices. As such, whilst some depressurisation of the lower stratigraphy has been observed in some cases, Figure 5, the combination of the uppermost aquitard and infiltration of surface water into the rock mass has negated any depressurisation of the upper strata. This highlights that reliance on crest piezometers alone can be misleading in inferring appropriate groundwater conditions over the entire slope. As such, in-pit piezometers (i.e. lower down in the slope) are warranted to ensure an overall understanding is developed.



(a) (b)

Figure 5 Examples of compartmentalisation in vibrating wire piezometers data and with inference of lower Hu values below inferred stratigraphically controlled aquitards and depressurisation of lower strata

Figure 6 presents an example of where a known fault transects a piezometer, resulting in significantly different Hu assumptions either side of the fault. Some depressurisation of the lower strata is evident, albeit the data also suggests the aquifer above the fault has been somewhat 'drained' relative to the lower aquifer.

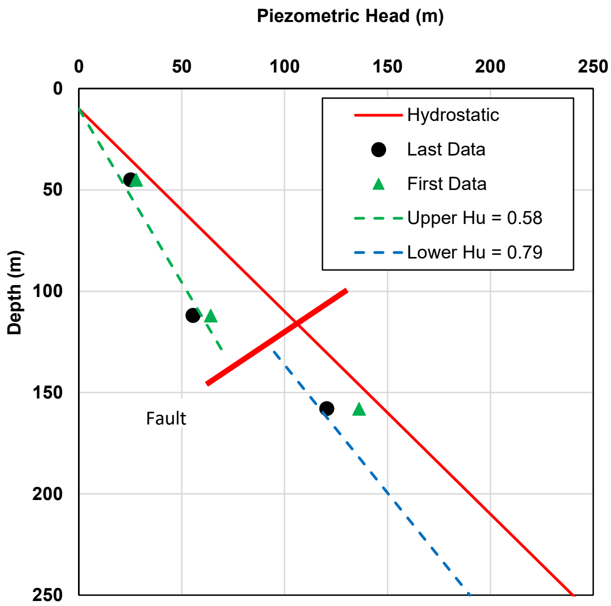


Figure 6 Example of compartmentalisation in vibrating wire piezometers data and with inference of higher Hu values below known fault

Figure 7 presents a case where a piezometer had been located near the crest on an internal corner between an advancing highwall and a temporary endwall (with endwall to be excavated as part of the next highwall progression). Significant depressurisation is evident and assigned to the strata being progressively exposed in the endwall and the proximity of the piezometer to the endwall. Whilst the extent of depressurisation is extensive, care needs to be exercised in considering the results as representing depressurisation of the adjacent highwall.

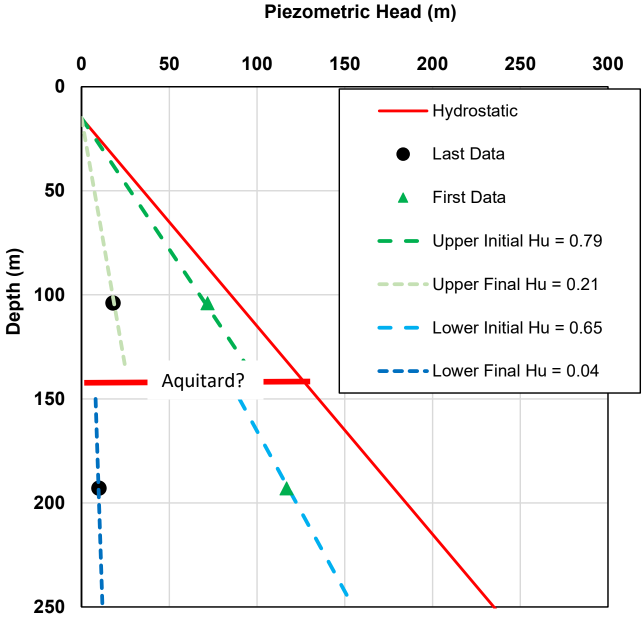


Figure 7 Extensive depressurisation of piezometer near an endwall

An aspect of note within the Figure 7 data is the progression of the depressurisation having occurred over a 4-year-period for the data presented. For the upper tip, the progression occurred in a relatively steady manner whilst the lower tip occurred a matter of months after piezometer installation. This raises the issue of confidence of VWP data. Whilst in general VWPs provide reliable data there are cases where there is either one VWP tip with 'suspect' data or, on occasions, the entire VWP installation is assigned as suspect owing to poor book-keeping practices. The former case requires multiple VWPs with observable trends (such as that evident in Figures 4 and 5 and discussed above) to ensure appropriate interpretation, whereas out of character data noted in a singular tip within one VWP would be commonly assigned as suspect data. Based on over 120 piezometer tips in the site highwalls, there is a trend of less suspect data over time. The causes for such suspect data can include, poor grouting, impact of gas pressures, poor booking-keeping on installation depths, erroneous connection and errors in application of calibration formulas. As such, interpretations in pit areas that rely on very limited VWP installation need to exercise caution where isolated tips suggest differences that might not be present.

Based on the interpretations presented in Figures 4–6, the following sub-sections presents additional interpretation scenarios on cross-sections.

3.4 Complex Hu

Figure 8 presents an interpretation on VWPs in cross-section in a pit area where there are 3 inferred stratigraphically controlled aquitards, and which provide a complex groundwater scenario. Four compartments are present, and from crest down to the pit toe are comprised of:

- Package 1 in crest area where a Hu of 0.80 is interpreted and where a phreatic surface labelled as PS1 is appropriate.

- Package 2 in upper slope, where a Hu of 0.80 is interpreted but where a phreatic surface labelled as PS2 is appropriate (note PS2 is appreciably lower than PS1).
- PZ06 is transected by packages 1 and 2 (note the significant head difference in the lowest tip of PZ06).
- Fault separates packages 2 and 3.
- Package 3, where a Hu of 0.70 is interpreted. A phreatic surface labelled as PS3 is appropriate assigned PS3 albeit the difference between PS2 and PS3 near fault is unknown.
- Package 4, covering pit floor. In this case mining to the south is deeper and hence the reducing heads in package 4.
- PZ08 is transected by packages 3 and 4 (note the VWP for PZ08 also shows the initial heads and the presence of the lowest aquitard is based on the initial interpretation of data). Data for PZ08 is shown in Figure 5b.

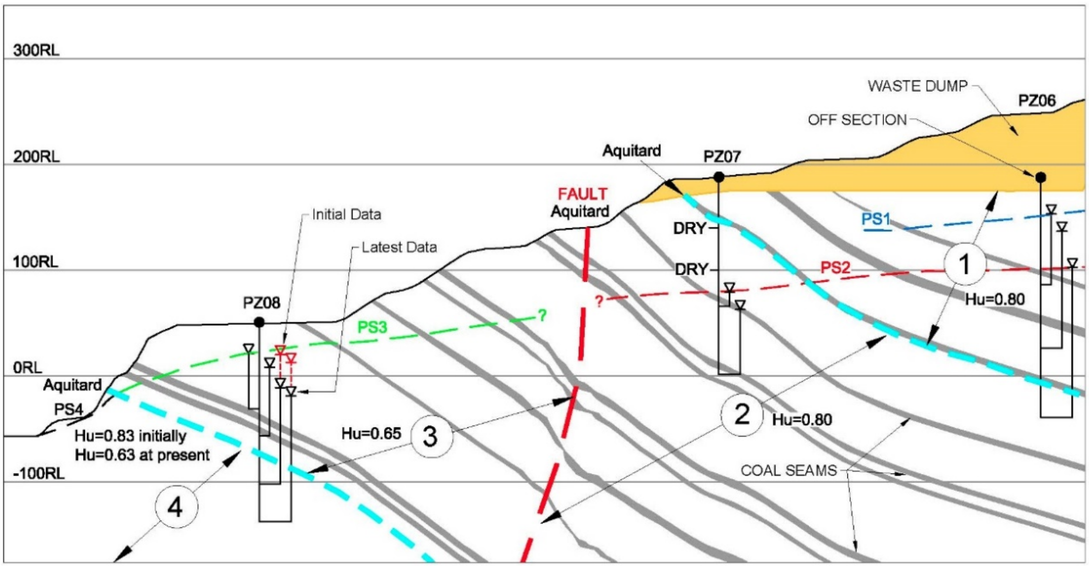


Figure 8 Compartmentalisation and complex Hu in a highwall slope

3.5 Hu – highwall and endwall

Figure 9 presents an interpretation on VWPs in cross-section which occurs at the extreme end of a highwall and in vicinity of an endwall. In this case the strata are 'quasi-confined' with strata partially connected to saturated alluvials above the endwall. Three compartments are present, and from crest to pit toe are comprised of:

- Package 1 in crest area where a Hu of 0.70 is interpreted.
- Package 2 in mid slope, where a Hu of 1.0 is interpreted (hydrostatic).
- Fault transects PZ10 and separates packages 1 and 2. The VWP data for PZ10 being the example presented in Figure 6.
- Package 3 below current toe and where marginally artesian conditions (Hu of 1.15) are inferred based on trend in both lowest tips of PZ11/PZ12.

Whilst PZ11/PZ12 is shown as one VWP, the installed upper tip of PZ11 indicated suspect data with abnormally high pore pressure (not presented in Figure 9). An adjacent piezometer PZ12 was drilled nearby and with one tip installed to a similar depth to the suspect tip in PZ11 (shown in Figure 9). This highlights the comment above where isolated tips can show suspect data. In appropriate scenarios redrilling of additional holes and replacement VWP tips is warranted.

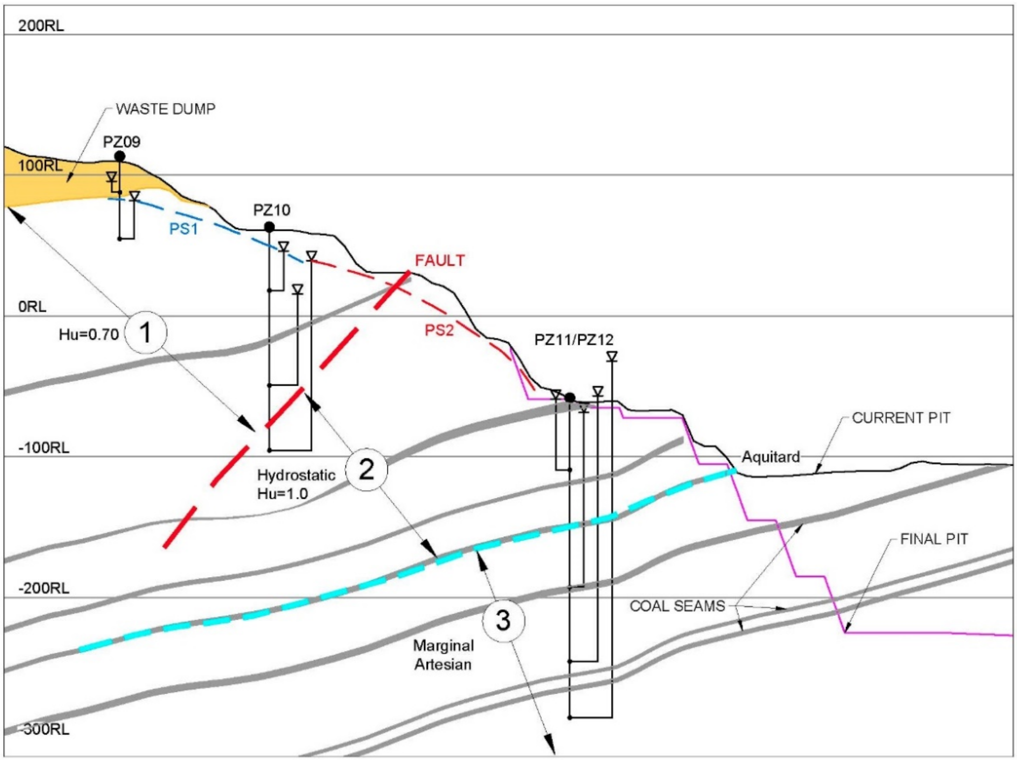


Figure 9 Hu in a highwall immediately near an endwall slope

In complex cases, application of various Hu values in cross-section will result in stability analysis models with creation of appropriate boundaries and materials (with differing Hu values). Whilst use of numerical hydrology models can be considered, one must weigh the complexity of the observations and how these can be conceptually captured in numerical modelling. One must also appreciate that results of numerical modelling based on limited VWP placed near pit crest may infer pore pressures in areas which are critical to stability, but which may not have VWP data to corroborate the interpretation as appropriate. This will also be the case in using a Hu approach and emphasises that piezometer placement needs to recognise the critical failure mechanism with appropriate placement of the VWP tips. Furthermore, this also highlights the need for uncertainty analysis in either approach and to cover a range of possible head conditions where there is no data.

3.6 Summary

In terms of an overview, the cases in relation to highwalls (and ignoring the example presented in Figure 2), the groundwater regime is not consistent across the site and can range from:

- textbook case of increasing Hu towards the toe
- compartmentalised packages, with higher Hu in the upper part of the slope, with a trend of reducing Hu towards the toe, often with depressurisation over time evident in the lower part of the slope.

4 Conclusion

Based on VWP interpretation at the site, the presence of clay/tuff seams has been inferred to provide stratigraphically controlled aquitards. These aquitards in a coal mine highwall setting emplace a groundwater regime that does not align with the 'textbook case' of increasing Hu progressively from crest to toe. In some cases, a higher Hu is observed in the upper part of the slope with a trend of reducing Hu towards the toe, often with depressurisation over time evident in the lower part of the slope.

The 4 cases presented relate to pits where historic dumps perched near the pit crest have impinged on the ability to emplace ‘good’ surface water management practices. As such, whilst some depressurisation of the lower stratigraphy has been observed in 2 cases, the combination of the uppermost aquitard and infiltration of surface water into the rock mass has negated any depressurisation of the upper strata. This highlights that reliance on crest piezometers alone can be misleading in inferring appropriate groundwater conditions over the entire slope. As such, in-pit piezometers (i.e. lower down in the slope) are warranted to ensure an overall understanding is developed. This latter statement can also be expressed as in-pit piezometers are not just warranted; they are critical to reliable pore pressure monitoring.

A range in Hu of 0.65–0.92 is indicated for the highwall piezometers presented and these Hu values are in keeping with the range indicated by Simmons (2020) of 0.70–0.95.

In a case where significant depressurisation was evident, the geological setting and piezometer placement in proximity to the developed pit wall was considered not to be representative depressurisation of the highwall.

Whilst in general VWPs provide reliable data there are cases where there is either one VWP tip with suspect data or, on occasions, where an entire VWP installation is assigned as suspect; generally owing to poor book-keeping practices. There is a noted trend of less suspect data with time. In appropriate scenarios, redrilling of additional holes and replacement of VWP tips is warranted.

An alternative to the Hu approach is to adopt hydrogeological numerical modelling. One must appreciate that results of numerical modelling, based on limited VWP data in the crest area, may infer pore pressures in areas which are critical to stability, but which may not have VWP data to corroborate the interpretation as appropriate. This will also be the case in using a Hu approach and emphasises that piezometer placement needs to recognise the critical failure mechanism with appropriate placement of the VWP tips in key areas. This also highlights the need for uncertainty analysis/assessment where there is limited or no data. This doesn’t need to be a detailed probabilistic uncertainty analysis (which is being increasingly adopted in numerical modelling) but could be simply considering a range of ‘realistically’ possible heads where you don’t have hard data.

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