13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)

Implications of groundwater pressure models for slope stability assessment

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ABSTRACT: Two case histories are described where strings of vibrating-wire piezometers were installed in mine slopes with the intention of providing information that was critical for stability. Data interpretation highlighted uncertainties in the impact of groundwater pressure models on Factor of Safety outcomes. Piezometer data were backanalysed using anisotropic permeability parameters. The impacts of the backanalysed pressures on computed Factor of Safety were greater than expected, emphasising that greater attention should be paid to the role of groundwater model uncertainty in slope instability risk management.

1 INTRODUCTION

1.1 *Context*

Slope stability analysis requires information on geometry, shear strength, and groundwater pressure. While geometric information may be complex and three-dimensional, it is usually possible to model slope and material geometry with an acceptable understanding about geometric uncertainty. Models for shear strength always involve uncertainty, but guidelines and procedures for modelling variability are readily available.

Models for groundwater pressure, on the other hand, are invariably simplified, usually based on meagre data, and the impacts of model uncertainty on outputs are often ignored or misunderstood.

1.2 *Background: Groundwater Pressure Modelling*

The principle of effective stress is fundamental to our understanding of how shear strength is mobilized. Information is required on groundwater pressure throughout the region of analysis. This depends on groundwater boundary conditions and on some model for determining groundwater pressures within those boundaries.

The simplest model is a phreatic surface for unconfined flow, from which the groundwater pressure should be derived from an associated equipotential line. Too-frequently, this is approximated by calculating the groundwater pressure from the vertical distance below the phreatic surface. Such a model has limited applicability in practice. For confined flow, a piezometric line may be used to represent pressure in a similar manner, again with limited applicability in practice.

Groundwater flows in response to a gradient in hydraulic energy. True flow velocities are typically so small that hydraulic energy can be represented by Total Head (TH), the sum of elevation head (defined as vertical location relative to some datum) and pressure head (PH, literally the vertical height above the location to which water would rise due to its pressure). Darcy's Law describes how groundwater flows in response to spatial gradients in TH (eg Cedergren, 1967).

Darcy's Law involves a scaling parameter, which is usually (and here) called permeability but more strictly should be called hydraulic conductivity. Most materials are directionally anisotropic with respect to permeability, making it a tensor quantity.

In addition to Darcy's Law, time-dependent groundwater flow requires consideration of the ef-fects of material porosity, which defines the volume of fluid within a volume of porous material. Changes in fluid pressure may be coupled with effective stress changes and both can cause changes to flows (Sullivan, 2007). Specific Storage (Domenico, 1972) is a measure of coupled volume and stress effects, and is typically included in hydrogeological models but not included in routine geotechnical practice.

Modern slope stability analysis requires software that can incorporate any of the above groundwater pressure models, including much more sophisticated application to unsaturated flow. In practice most modelling is two-dimensional. Beale et al, 2013 and Lorig et al, 2013 provide comprehensive discussions on current modelling procedures.

2 GROUNDWATER PRESSURE MEASUREMENT

Groundwater pressure measurement involves many often conflicting considerations regarding ac-cess, timing, and interpretation. For standpipes, equilibration time may be significant. All forms of measurement involve ground disturbance which may influence what is measured.

Pressure is a scalar quantity. A single pressure measurement cannot provide the vector information that is required for interpretation of flow direction and anisotropic permeability, where multiple observations of pressure in relatively close proximity are required. Stacked pressure sensors within a borehole can provide general information on flow direction, but multiple boreholes along a section, preferably each with stacked sensors, provide maximum interpretative value.

3 CASE HISTORIES

Two case histories are described where stacked vibrating-wire pressure (VWP) sensors were deployed as borehole piezometers as part of slope stability monitoring strategies. Both cases involved open cut coal mines, but the principles involved and implications arising are no different for any other aspect of geotechnical slope stability practice.

For both sites, relatively steep slope designs were required. In both cases the slopes were composed of a range of bedded sedimentary rock materials with varying permeabilities. In both slopes, weak bedding-parallel tuffaceous clay layers were known to be present and to have played a direct role in causing previous slope instabilities.

In both cases the 2D analyses were carried out using the SLIDE code (RocScience, 2018). The same procedures could have been followed with equal effectiveness and equivalent outcomes using alternative codes having similar capabilities.

3.1 *Site A*

Cutback of a slope was planned in an area of previously much-shallower mining, involving a rock slope profile about 75 m high overlain with about 55 m of old backfill spoil. The coal measures rocks are typically slake-prone and of low to medium strength, with spoil ranging from high plasticity clay to clayey silty gravel. Several coal seams would be exposed, some with nearby old underground workings, and hard tuffaceous clay bands of high-plasticity. An earlier cutback had experienced slope instability within the spoil and significant lipping movements along the clay bands.

Stability analysis was undertaken using the known or suspected groundwater boundary conditions to check the design. Marginally acceptable stability was identified due mainly to uncertainty about the clay strength and pressures computed from the assumed anisotropic permeability model.

Two stacked VWP piezometers were installed at similar near-crest positions along the length of the slope, with regular automated data downloads. The cutback spoil component of the slope failed, destroying one of the piezometers. An automated prism movement monitoring system was then deployed when the spoil cut was stabilised.

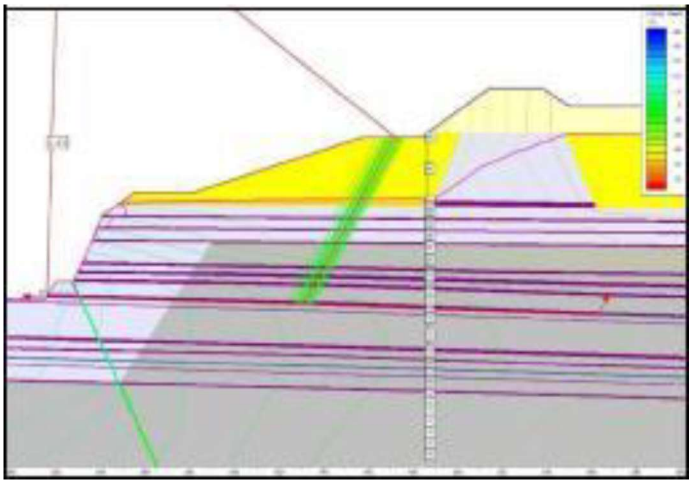

Figure 1. Site A cross-section with Total Head contours, piezometer location, and critical potential instability mechanism (post-backanalysis)

Groundwater pressures were interpreted by backanalysis of piezometer data corresponding to a given stage of excavation (Figure 1). This assumed that the rate of mining was slow enough for flows and pressures to equilibrate to an essentially static condition. Previous transient modelling showed that this assumption was reasonable for site conditions.

Groundwater pressure backanalysis involved adjusting the relative values of anisotropic permeabilities for the different materials. Starting-values were based on previous backanalyses for similar materials where multiple stacked-sensor piezometers had been installed along a slope cross-section.

3.2 *Site B*

Final pit slope design involved a deep cut through basalt, underlying tuffaceous-banded upper coal measures, and deeper seams with weak tuffaceous clay bands. The overall slope height was about 250m. Design checks identified potential up-dip sliding on tuffaceous clays as critical for stability. Previous sections of the pit had experienced such sliding in response to presumably elevated groundwater pressures caused by an extreme rainfall event.

Mining of the basalt and upper tuffaceous-banded coal measures resulted in significant seepage outflows with lipping of tuffaceous layers and artesian groundwater conditions in mid-level blastholes. Stability analysis based on a phreatic surface consistent with observed seepages indicated marginal stability for the final slope profile.

Stacked VWP piezometers were installed at three locations along the current and future pit slope crest to provide data for more detailed stability assessment, and trigger levels for management of potential stability risks as excavation progressed to full depth and laterally. Groundwater pressure backanalysis for the first piezometer section at Site B (Figure 2) involved similar assumptions and procedures as for Site A.

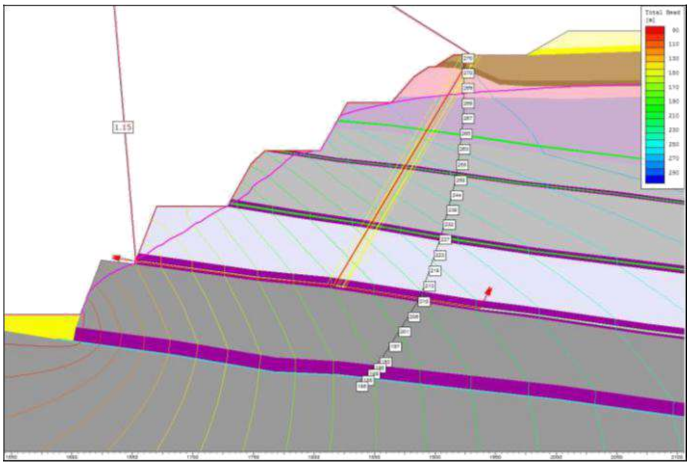

Figure 2. Site B cross-section with Total Head contours, piezometer location, and critical potential instability mechanism (post-backanalysis)

4 BACKANALYSIS METHODOLOGY

4.1 *Permeability Parameters*

Guidance regarding ranges of permeability parameters may be found in many texts and published papers. Some of this information includes effects of anisotropy. Permeability is a tensor quantity because it can be direction-specific. In a 2D section, the permeability tensor is defined by three parameters: the major principal permeability, the ratio of minor to major permeabilities, and the direction of the major principal permeability.

Over a period of decades, the author has collated a generic set of 2D permeability parameters as tensor data based on published information. This data has been refined to a limited extent by backanalysis of slopes with piezometers. Most naturally deposited soils have some degree of flow anisotropy related to particle shape, preferred orientation, and particle size distribution. Residual soils and cemented soils are also likely to have flow anisotropy related to inherited fabric and the nature of any cementation processes. Permeability of weathered and fresh rocks is more complicated to characterise because flowpaths may include material pores and also fracture networks, both of which may be coupled to fluid pressure and effective stress conditions (Sullivan, 2007).

The backanalysis objective is to determine a set of permeability parameters consistent with measured pressures and/or observed flow conditions, and also consistent with the expected geotechnical behaviour of the materials involved. The likelihood of identifying actual permeability values is very low unless combined with accurate flowrate measurements. The likelihood of identifying a permeability set that can reproduce the groundwater pressure field in all areas critical to stability of a slope is high if based on reliable piezometer data in multiple locations.

4.2 *Model Geometry and Time Effects*

For the 2D backanalyses discussed here, the geometry of the slope and material distribution in vertical sections was based on survey and/or planning data and geological models of reasonable accuracy.

For routine modelling, the permeability tensor for a particular material is assumed to be constant. However, principal permeability directional changes may be caused by geological processes such as folding or geotechnical events such as slumping. Depending on the modelling process, any change to the direction of the major principal permeability may require either a function describing the effects of such change on the tensor, or zonation where different directions are explicitly assigned as necessary to different zones of the same material.

Groundwater flow is a transient process, and the most common use of piezometers is to detect pressure changes in response to drivers such as seasonal or extreme rainfall or construction process such as excavation or loading. Transient flow modelling capabilities are readily available with modern software. For the backanalyses discussed here, transient effects were avoided because the slope excavation rates were judged to be slow enough to achieve pressure equilibration to a steady-state. Backanalysis including transient effects would also have been far more complicated and require flowrate judgements for which there was no evidence.

4.3 *Model Boundary Conditions*

The boundary conditions for any flow model are never straightforward except at the ground surface where the fluid pressure is atmospheric and can typically be set to zero, or where surface water is ponded. Leaving aside 3D effects, very little is usually known about groundwater conditions within any typical 2D section except at the ground surface or at an internal measurement point: a piezometer.

Flow modelling software typically includes a tool kit with many options for specifying boundary conditions. These range from defined pressure or defined TH along boundaries to defined flow across boundaries. Applying such tools raises immediate questions of what condition to apply, and where, in the virtual absence of useful information. Concepts discussed below in the 2D context of this paper may be applied also to 3D but would involve greater data input complexity.

The author's approach to boundary condition specification has evolved over many years of modelling experience and is most easily justified for steady-state flow. For a slope, lateral boundaries at a sufficient distance from the area of detail are unlikely to have much effect on local flows and pressures, provided that the TH conditions are reasonable.

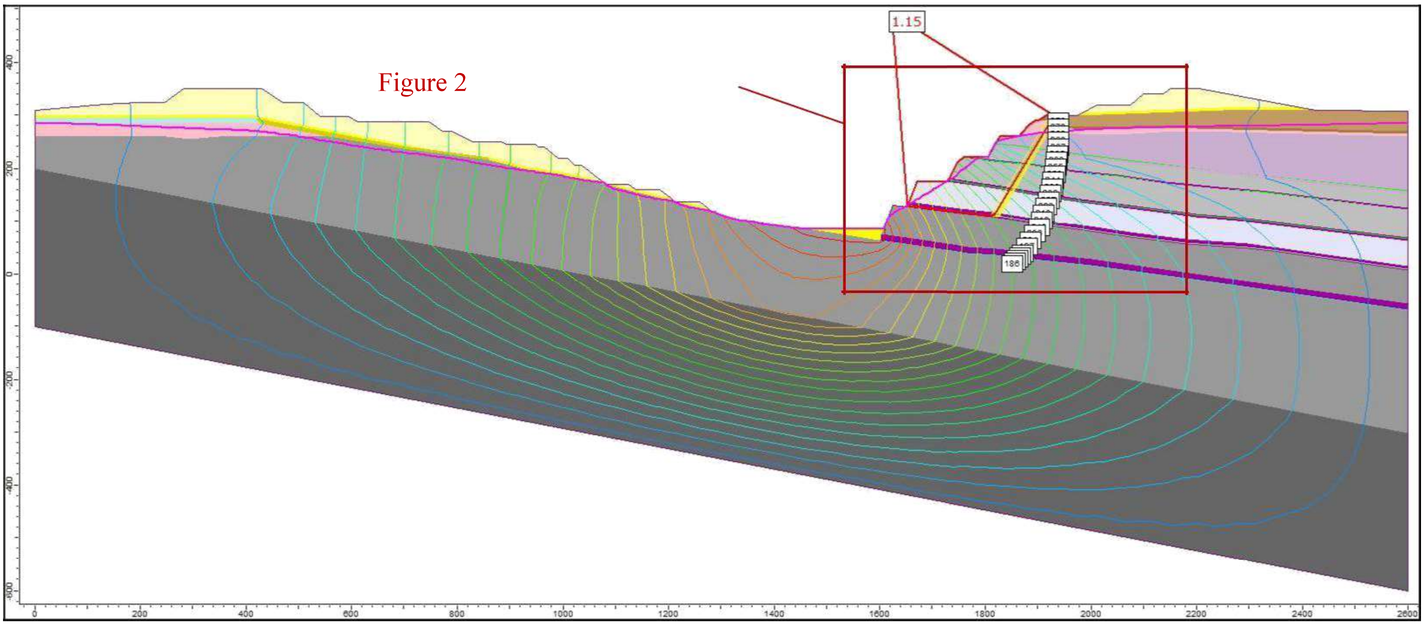

Figure 3. Site B full model cross-section with Total Head contours (equipotentials) showing distances to lateral and basal boundaries relative to slope size, with base oriented to strata dip; showing piezometer location and critical potential instability mechanism

The simplest TH condition at lateral boundaries is a constant value based on the inferred or measured depth of the phreatic surface. The constant TH condition is equivalent to hydrostatic, implies no vertical flow, but places no restriction on horizontal flow. Above the phreatic surface and extending laterally across the modelled ground surface between the lateral boundaries, the flow condition is unknown but the pressure condition is atmospheric unless specific constraints such as ponded water are applied locally. Along the base of the model, which requires careful selection as discussed below, the simplest solution is to apply a linear variation in TH between the two lateral boundaries.

The base boundary orientation should be chosen to be deep enough to have little effects on flows in the region of interest, but also parallel to the direction of average principal permeability near the base of the model. The intent is that this will minimise the impact of the base boundary on the area of interest. Combining all of the above boundary specifications is equivalent, in the author's opinion, to producing a model that respects as far as practicable the effects of Specific Storage variations on the flows in the region of interest.

The effects of the above boundary condition methodology can be checked by testing model outcomes within the area of interest (eg groundwater pressures along a query line, where piezometer measurements may be available). Variations in the location of the lateral boundaries and the location and orientation of the base boundary should cause insignificant changes to the model outputs for given values of TH applied to the lateral boundaries.

Figure 3 shows the full model for Site B, including the region of greatest interest reproduced in Figure 2. The non-vertical piezometer location was an outcome of borehole deviation influenced by the rock mass jointing associated with the strata dip. While the pressures and TH contours close to the lateral boundaries are not necessarily realistic, their influence on groundwater pressures within the region of critical stability outcomes is negligible.

5 BACKANALYSIS OUTCOMES

Figure 1 and Figure 2 show the groundwater fields represented by TH contours for Site A and Site B respectively. Two sources of anisotropy influenced these pressure distributions: permeability anisotropy of materials, and permeability contrasts between materials. Each model also uses a simplified representation of the permeability changes from the saturated to the unsaturated flow condition. Negative pore pressures above the modelled phreatic surfaces are explicitly ignored in the stability analyses.

2D finite element analyses of groundwater flow involved graded meshes of approximately 6000 6-node triangle elements for each site. Interpretation was based on matching TH values at piezometer sensor locations, together with matching hydrostatic TH values to known borehole or pond levels at lateral boundaries.

5.1 *Site A Groundwater Pressure Modelling*

Figure 4 is a plot of Pressure Head versus Eleva-tion (effectively, relative Depth) at the piezometer. Also shown is the hydrostatic line corresponding to a phreatic surface level of 15 mRL. Over a period of more than 2 years, the lower three sensors showed an essentially hydrostatic condition, but the uppermost sensor showed a significant decline as mining progressed deeper. The data are consistent with essentially horizontal (bedding-parallel) flow below the D2 coal sensor, and an upward component of flow above that level.

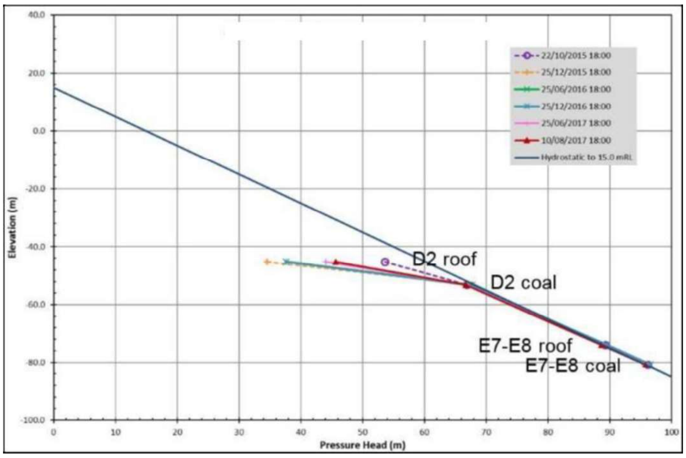

Figure 4. Pressure Head – Depth for Site A piezometer, showing essentially hydrostatic relationship except for D2 roof

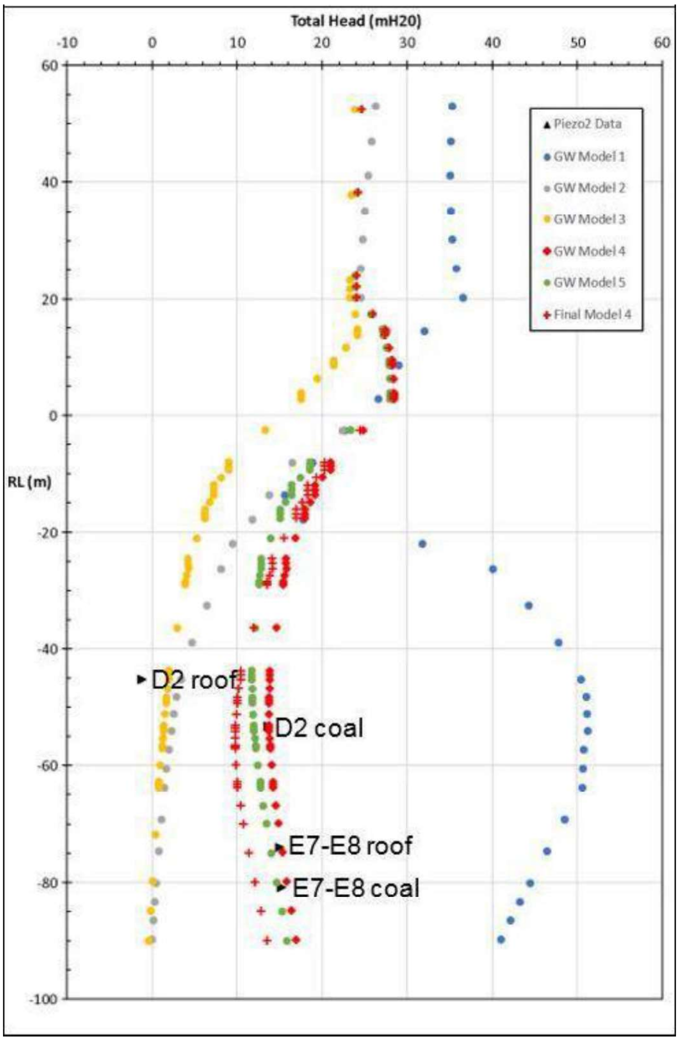

Figure 5. Site A Total Head – Depth comparison of modelled and measured pressures

The Site A slope is located adjacent to mined-out underground and open cut workings, the latter backfilled with dumped spoil. During the backanalysis process it was relatively straightforward to match (Figure 5) the TH data for the three lower sensors based on drawdown from an adjacent pond level, but it was not possible to match the upper sensor without incorporating an arbitrarily selected localised out-flow zone. Since the analyses were undertaken, addi-tional mining has exposed a previously unmapped fault which is believed to be draining rock above the upper sensor towards old underground workings.

The higher permeability of the coal relative to the interburden rocks, and the presence of multiple closely-spaced seams, both contribute to significant overall drawdown of groundwater pressures within the slope. The curvature of the TH contours closer to the slope face, with downward-directed flow, resulted in the minimum computed Factor of Safety (FOS) of 1.43 being significantly higher than what had been determined in the original design check.

5.2 *Site B Groundwater Pressure Model*

At Site B the upper basaltic materials infilled a deep palaeochannel cut into tuffaceous-banded coals. In Figure 2 and Figure 3 the basalt is shown as the upper brown layers under the yellow spoil dump zone. The fractured nature of the basalts provides a high-permeability, high-storage reservoir for recharging the underlying slope.

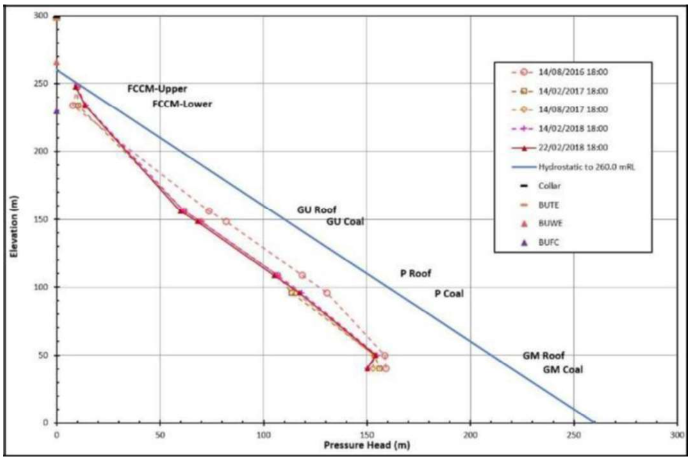

Figure 6. Pressure Head – Depth for Site B piezometer, showing essentially non-hydrostatic downward flow

Figure 6 shows the profile of Pressure Head versus elevation for the eight sensors. There was a consistent negative departure at each sensor from the hydrostatic line corresponding to a level within 5m of the base level of the basaltic infill known from nearby exploration drillholes, and very close to the base of weathering observed in the piezometer drillhole. The departure from the hydrostatic line increased as mining progressed deeper. These observations are consistent with general downward-directed flow caused by the drainage effect of the coal seams relative to the interburden rocks.

In the absence of even a semi-automated seepage backanalysis routine in the available software, the Site B profile involved an unmanageably large number of tensor variables, so simplifying assumptions were introduced. The upper tuffaceous-banded coals were modelled as two materials corresponding to weathered and unweathered. Underlying fresh rock and target coals were modelled with two materials rather than as individually variable strata. One exception was an interburden unit comprising massive sandstone (paler grey in Figure 2 and Figure 3) that was modelled with higher strength and lower permeability.

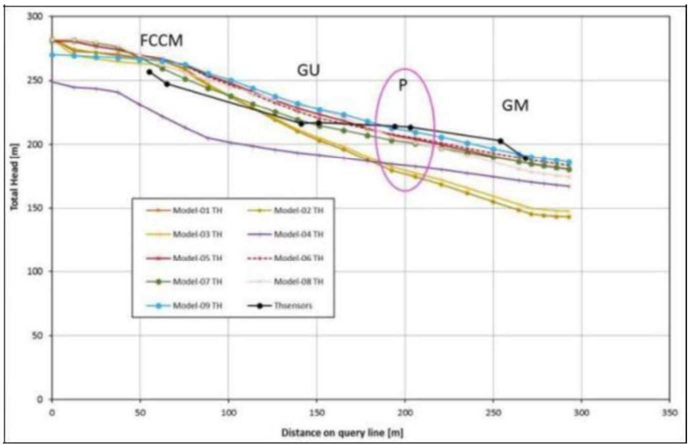

Figure 7. Site B Total Head versus Distance along piezometer line comparing modelled and measured pressure conditions

The piezometer drillhole profile was deflected horizontally by dominant joint intersections which were aligned perpendicular to bedding structure and (fortuitously) in the plane of the section. The departure from vertical was replicated in the querying of TH analysis outcomes, which for simplicity were plotted in Figure 7 versus distance along the piezometer.

With the above permeability simplifications and limited time resources, it was not possible to fully match the Site B TH profile. The most reasonable match was selected as a reasonable overall agreement with the closest estimation of the P seam values that were critical for stability analysis outcomes.

From Figure 7 it might be concluded that many of the pressure model trials were relatively similar in terms of TH values. Table 1 lists the critical FOS outcomes associated with each pressure model trial, together with notes regarding the matches shown in Figure 7. The FOS outcome was unexpectedly sensitive to changes in modelled permeability details.

6 IMPLICATIONS

Site A demonstrated that matching of essentially hydrostatic piezometer conditions, even with lateral flow, could be readily achieved with appropriate selection of lateral boundary conditions. However, departures from the hydrostatic trend proved difficult to replicate without invoking local effects that remained a matter of speculation due to lack of data.

Site B demonstrated that apparently minor changes in groundwater pressure outcomes could have a correspondingly larger effect on FOS outcomes. This may have been partly due to the site, but nevertheless showed that significant variation in stability analysis outcomes should be expected from relatively small changes in groundwater pressure models.

Table 1. Factor of Safety (FOS) outcomes for different groundwater pressure backanalysis trials, Site B

Model	FOS	Comments on Pressure Model Match
1	1.36	poor overall match
2	1.36	incr. anisotropy in rock, still poor
3	1.35	decr. anisotropy in rock, still poor
4	1.47	decr. ratio of rock to coal, too low
5	1.19	change tuff ratio to rock, P too low
6	1.19	reduced tuff anisotropy, similar to 5
7	1.25	decr. rock aniso. & coal/rock, skewed
8	1.19	as for 7, but incr. coal/rock, worse
9	1.15	minor tweaks to 6, closest P seam match

Many uncertainties influence the outcomes of stability analysis, and the effects of groundwater pressure uncertainty should not be underestimated. Groundwater pressure models are usually based on minimal information and are rarely amenable to verification because directionally anisotropic permeability makes backanalysis challenging.

For both Site A and Site B, simplistic pressure models using the computed phreatic surfaces would have resulted in significantly lower FOS outcomes, and have resulted in revisions to design with significant economic implications. There is a strong case for using detailed groundwater pressure models.

In practice, there is a requirement for greater detail in groundwater pressure measurements for design verification of critical slopes. Even with good piezometer data, detailed groundwater pressure modelling is essential for reducing uncertainty in the outcomes of stability analysis, particularly when designing slopes to satisfy critical stability criteria.

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