HOW OUR UNDERSTANDING OF WATER AND SLOPE STABILITY HAS IMPROVED SINCE 2009

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1. ABSTRACT

An objective of the Large Open Pit (LOP) Project was to improve the understanding of the occurrence and the role of pore pressures in pit slope engineering. New ideas have been developed and investigated by analysing geotechnical and hydrogeological monitoring data from many mine sites worldwide. Standard methods have been developed for inputting pore pressures into slope stability analyses, to investigate the sensitivity of slopes to water pressure, and the cost-benefit of implementing slope drainage systems. The importance of hydromechanical coupling in low permeability rock masses in which pore pressures are influenced by changes in in-situ stress and dilation of the rock mass as it is mined is now better understood. There is better appreciation of the need to optimise the mine site layout and minimize the extent to which seepage from mine facilities impacts the pit slopes. There is also better awareness of the need for good surface water management to minimize the development of transient pore pressures.

2. PORE PRESSURE CONDITIONS

Pore pressure is the only parameter in a pit slope that can be readily changed. To enable optimization of the slope design and improve the performance of the excavated slopes, an increasing number of mines are incorporating controls on pore pressure (slope depressurization) into their basic mining cycle. The cost of reducing pore pressure is invariably small compared with the cost of buttressing, unloading or other forms of remediation or mitigation to improve slope instability.

At any given point below the water table, the water pressure acting on the pore spaces or fractures may be defined as vertical height of the column of water acting through the interconnected pore spaces or fractures on that point, multiplied by its unit weight (9.81 kN/m3). Pore pressure is positive below the water table, zero at the water table, and zero or slightly negative above the water table.

However, most geological sequences typically exhibit poor or incomplete vertical hydraulic connection, so the pore pressure increase with depth below the water table is usually not linear, and conditions are not “hydrostatic”. This is particularly evident around active mine sites where there are large hydraulic stresses acting on the groundwater system. Vertical components of the pressure gradient develop because of flow towards the pit or to the dewatering system (Figure 1), and are a fundamental component of the hydrogeology model. The use of hydrogeological cross sections is often a preferred method for presentation and analysis of vertical gradients.

Around active mining operations, it is not uncommon for vertical (downward) hydraulic gradients to be higher than lateral hydraulic gradients. Downward pore pressure gradients are termed “sub-hydrostatic”, and often occur in the upper to middle parts of the pit slope. Upward pore pressure gradients most often occur in the toe of the slope, particularly during periods of rapid sinking of the pit floor. These may create destabilizing forces in the lower pit walls.

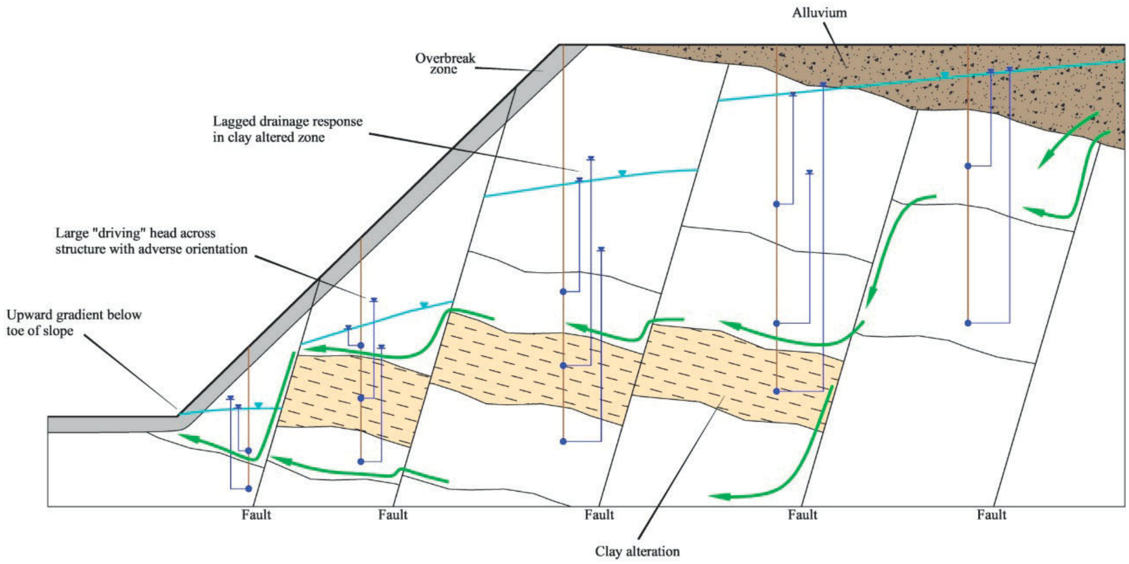

Figure 1: Diagrammatic cross section illustrating how geological conditions and groundwater flow create complex vertical hydraulic gradients behind most pit slopes (reproduced from Beale and Read, 2013)

3. ROLE OF WATER IN SLOPE ENGINEERING

In any pit slope, a change in pore pressure will cause a change to the resistive forces, and a change to the driving forces.

Changes to the resistive forces are captured in the effective stress term. A decrease in pore pressure results in an increase in effective stress and shear strength, and hence, an increase in the resistive forces. Although mine dewatering often causes a slight reduction in total stress (the weight of water is small compared with the total weight of rock, even in porous materials), it can also cause a large decrease in the pore pressure and an increase in effective stress. The effective stress concept is illustrated in Figure 2, before and after dewatering.

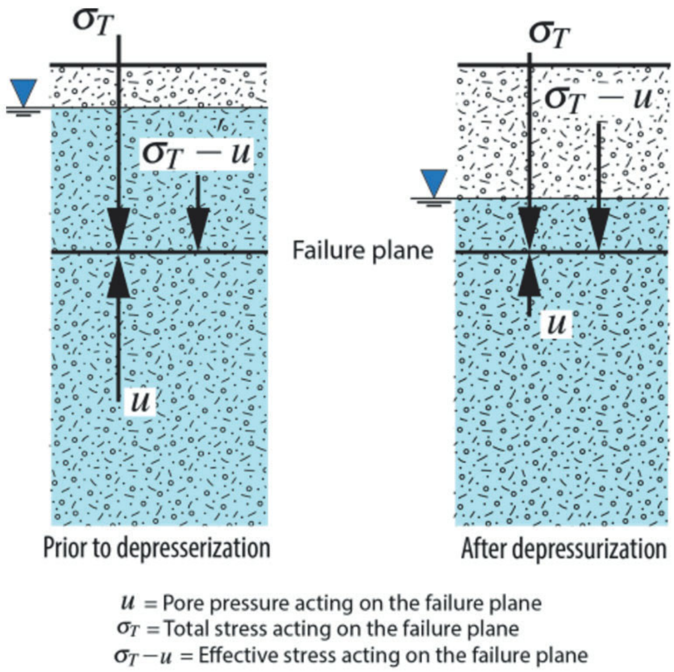

Figure 2: Diagram illustrating changes to the effective stress before and after depressurization. Note that dewatering also reduces total stress by a relatively small amount (reproduced from Martin and Stacey, 2018)

Figure 3 shows an inclined surface before depressurization (left) and after depressurization (center and right). Depressurization increases the effective stress acting normal to the failure plane. On most failure surfaces that derive at least a portion of their shearing resistance from friction, the resisting force is a function of the effective normal stress, so increasing the effective normal stress results in an increase in shearing resistance. In addition, water pressure also acts as a driving force, and decreasing the pore pressure decreases the driving forces.

As shown in Figure 4, natural drawdown induced by the mine excavation results in a pore pressure gradient towards the slope face (gradient=A/X). As mining of a new pushback occurs, there may be an overall reduction in pore pressure due to seepage/drainage towards the face, but the pushback increases the pore pressure gradient towards the slope (new gradient=B/Y>A/X) and may therefore increase the driving forces.

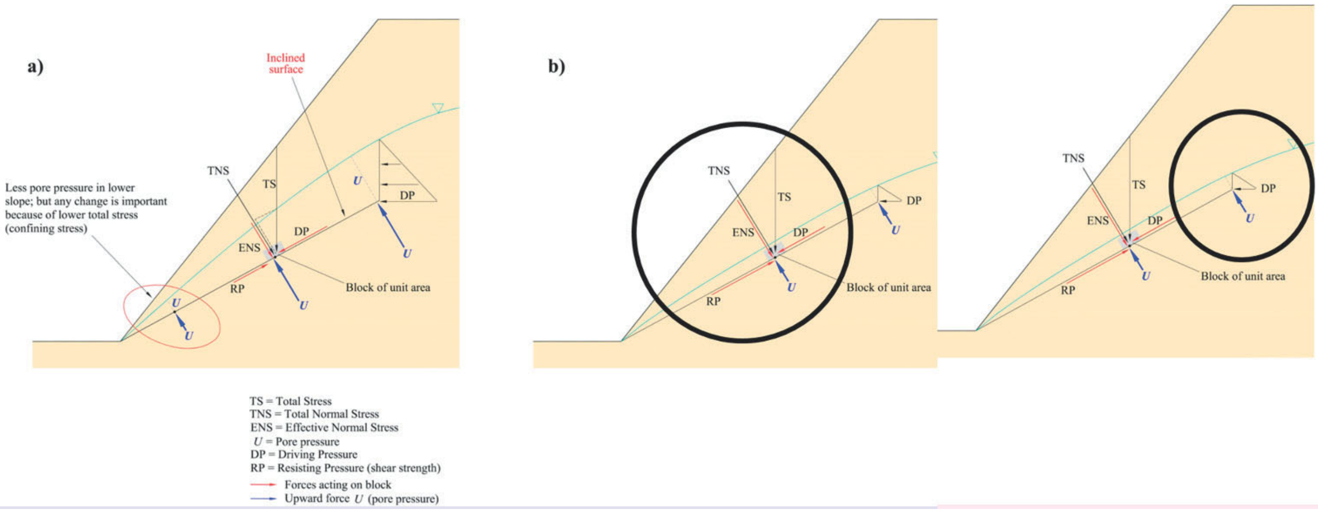

Figure 3: Illustration of how depressurization increases the resistive forces (RP, center diagram) and reduces driving forces (DP, right-hand diagram) (reproduced from Beale and Read, 2013)

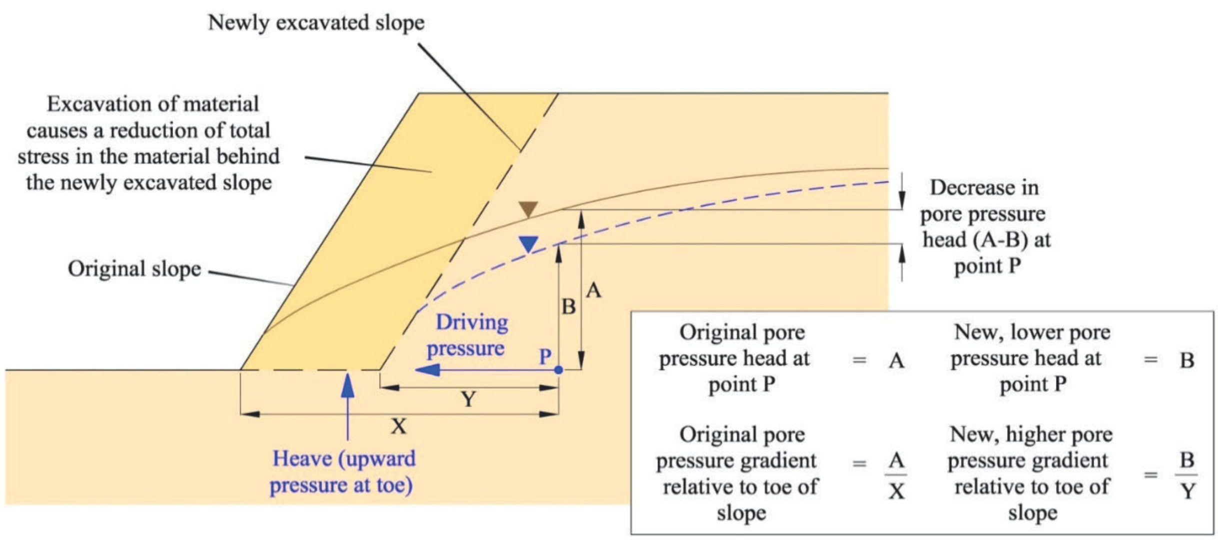

Figure 4: Mining of a pushback may create a reduction in pore pressure due to seepage but may also increase the gradient, and hence driving pressure towards the slope (reproduced from Beale and Read, 2013)

The increasing hydraulic gradient is often greatest across a structure or other discrete discontinuity plane. Water pressures often become "stair-stepped" across structures. Creation of driving pressure gradients across adversely oriented structures is one of the key risks of instability for slopes excavated in strong rock. The pushback removes confinement, and drainage to the slope (or to drain holes) in front of the structure creates the driving pressure gradient.

4. HOW DOES DEPRESSURIZATION OCCUR?

A goal of the LOP project was to provide improved insight on how depressurization of a rock mass occurs. The 'A-B-C-D' concept of fracture flow was proposed (Figure 5), which is linked to the principle of a size-order relationship within the fracture network. A typical fracture network might comprise a few highly-transmissive and pervasive 'first order' fractures (A), many more less transmissive second order fractures (B), and so on for third (C) and fourth (D) order fractures. In more porous rocks, or rock types containing a pervasive network of micro-fractures, 'D' may also be considered as the rock matrix. The permeability of the fracture network is dependent on the scale of this distribution.

At the scale of most analysis and modelling, and for the majority of hydrogeological settings, most rock types are pervasively fractured. Pore pressure is distributed throughout the entire rock mass, not just around the main faults and fractures. Even the smallest aperture low order fractures contain pore pressure.

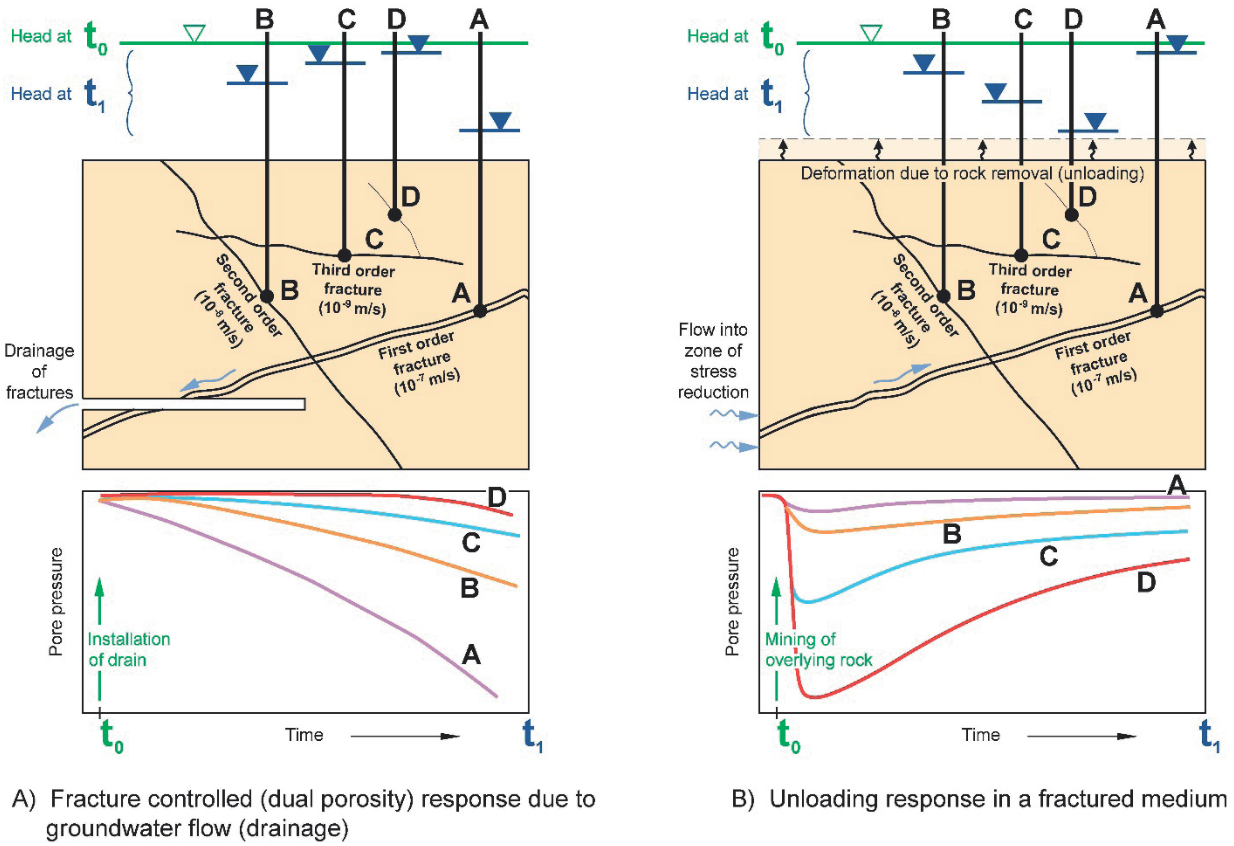

Figure 5: Illustration of fracture-controlled (dual-porosity) drainage response due to (a) groundwater flow and (b) unloading response in a fractured rock mass (reproduced from Read & Stacey, 2009)

Research involving a review of pit slopes from over 80 mining projects has shown that the biggest factor influencing pore pressure is the wider-scale hydrogeology setting, and particularly, the sources of recharge. Estimating the sources of groundwater recharge is a fundamental part of any pit slope analysis. Recharge may be derived from adjacent groundwater units outside the pit, infiltration of precipitation on the slope itself, or surface water run-on to the slope. A key issue for many mines is the recharge derived from mine facilities in the project area, including tailings facilities, leach pads, leaky pipes and tanks, process areas, stormwater drains and ponds, etc. A challenge that faces the industry is the improvement of the site layout to minimize the risk of artificial groundwater recharge influencing the pit slopes.

Because of the pervasive nature of fracturing in most settings, "off-the-shelf" equivalent porous medium (EPM) codes are appropriate for virtually all practical modeling situations. Detailed models can be created using EPM codes by populating the model grid with anisotropy in permeability and porosity, discrete fractures, fault zones, permeable horizons and other features based on the hydrogeological interpretation, and dual porosity flow characteristics. There is rarely (if ever) a need to construct fracture flow models.

5. INPUTTING PORE PRESSURES INTO A GEOTECHNICAL ANALYSIS

There are three main methods to incorporate pore pressure into a geotechnical analysis. These are:

- Ru values
- Water tables or phreatic surfaces (created analytically or using numerical models)
- Pore pressure grids (created analytically or using numerical models)

An essential first step is for the hydrogeological and geotechnical groups to work together to identify the key controls for geotechnical stability. This will help ensure that the specific goals and required outputs of the hydrogeological analysis are clearly defined. It often advisable that the geotechnical model is first used for an initial screening analysis to evaluate the sensitivity of the slope materials to water and to identify the most important and sensitive areas in the slope. The screening analysis can be used to define the priority slope sectors for hydrogeological analysis (and also those sectors that may be of lesser concern).

Ru is defined as the ratio between the total upward force due to water pressure and the total downward force due to the weight or overburden pressure. A value can be calculated for any point where the pore pressure and the properties of the overlying materials can be estimated. If the rise in transient pore pressure can be measured (or estimated), the Ru values can calculated and entered directly into the inter-ramp scale or bench scale geotechnical analysis.

The Ru approach may be appropriate for early-stage analysis, investigating the sensitivity of the geotechnical analysis to water, and estimating the effects of transient pore pressures where surface water infiltrates into shallow joints and fractures that are above the main water table. It is particularly useful for simulating pore pressures that result from perched groundwater zones in interbedded stratigraphy.

The use of a water table (phreatic surface) may be appropriate where the vertical component of the hydraulic gradient is relatively small, where there is a limited amount of data available, or where a relatively rapid analysis is required to evaluate the sensitivity of the slope to water. Phreatic surfaces for 2D geotechnical models may be created easily and are therefore widely used. Unless otherwise constrained, they assume hydrostatic conditions below the phreatic surface. The sensitivity to vertical gradients can be simulated by reducing the pore pressure below the phreatic surface to say 75% or 50% of hydrostatic in certain hydrogeological units, in defined zones, or globally. Where conditions are known and the analysis can be constrained, the zonation of sub-hydrostatic conditions can be an extremely useful and robust method for inputting pore pressure to the geotechnical analysis.

The level of required pore pressure analysis will typically increase as the project develops. The hydrogeology results need to feed into the geotechnical analysis, and there is often insufficient time to carryout detailed numerical analysis in the early stages of an investigation. For early project stages, there is seldom enough data to justify detailed numerical modelling.

Development of pore pressure grids using numerical analysis may be appropriate where multi-level piezometers are installed in the main hydrogeological units and on key identified cross sections, and if there is a sufficient amount of supporting data to justify the model. If numerical analysis is to be considered, there should be some form of hydraulic stress and response data with which to calibrate the model.

It may be possible to use a trend analysis to forward-predict the future decline in pore pressure for each piezometer, based on future drainage assumptions. This approach may provide an alternative to numerical modelling. A number of mine operators have prepared pore pressure grids for snapshots in future time by contouring the results of forward-predicted piezometer hydrographs.

6. HYDROMECHANICAL COUPLING

Geotechnical theory shows that the removal of material by mining reduces the total stress on the materials remaining within the slope, so their volume slightly expands. The pore spaces and/or fracture apertures will therefore increase slightly. Consequently, there will be a tendency for the pressure of the water to reduce (solid to fluid coupling). Where the permeability of the formation is low enough such that groundwater flow is negligible, the response to the stress change is taken up entirely by the formation and is termed an “undrained response”.

However, for most pit slopes, particularly those excavated in strong rocks, the evidence shows that an undrained response is observed only when the permeability of the units within the zone of relaxation is low. Experience has shown that, where the permeability of the formation is greater than about 10-8 m/s, or where there is any significant recharge to the slope materials (i.e. the majority of groundwater settings), the influence of groundwater flow (drained response) becomes increasingly dominant, and the effect of deformation on reducing pore pressure becomes less. The decrease in head within the zone of relaxation will cause water to move in quickly from surrounding material unaffected by the decrease in total stress, damping the undrained response. Therefore, for most settings, depressurization occurs because of groundwater flow.

Where hydromechanical coupling is evident, there is often a stepped response that correlates to mining of individual benches (Figure 6). However, there is still a limited amount of worldwide empirical data with which to validate responses. A key issue for feasibility studies is that it is not possible to obtain actual site-specific data until the mining starts, and there is limited worldwide experience to provide support for the study.

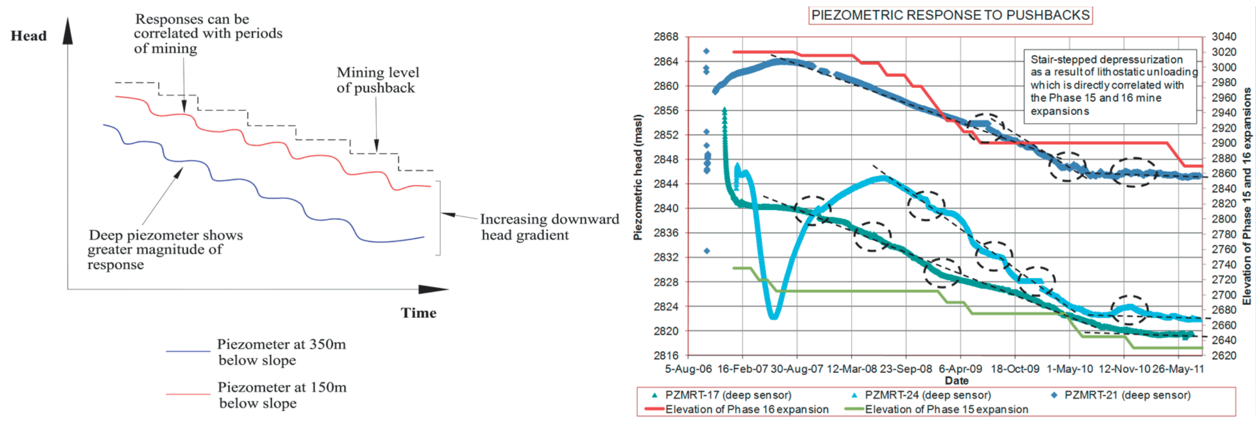

Figure 6: Stepped response to hydromechanical coupling from mining a slope in theory (left) and observed data (right). In hard rock settings, a strengthening downward hydraulic gradient may be observed because of the coupling processes

The presence of preferential groundwater flow paths and increased hydraulic diffusivity in low permeability materials is important for damping undrained responses. These factors are often overlooked in geomechanical studies, particularly where parameter values have been averaged. In many settings, the presence of closely spaced exploration drill holes creates enhanced vertical permeability and is often a significant factor.

Monitoring

Hydrogeological monitoring is an integral component of any pit slope, and may take the form of boreholes that are temporarily left open (with or without liner pipe), standpipe piezometers or observation wells (single or multi-level), vibrating wire piezometers (VWPs) placed in sand packs, grouted-in VWPs, horizontal piezometers, or specialist Westbay piezometers. The piezometer provides a means to measure the pore pressure and the total groundwater head at any given location.

Since the late 1990s, the mining industry has pioneered the application of grouted-in VWPs to provide multi-level pore pressure monitoring to help understand the complex heterogeneities and compartmentalisation common to pit slopes. The grouted-in method allows a large number of piezometer sensors to be instrumented in a single borehole to measure pore pressure and hydraulic response at various discrete depths, and to understand the vertical gradients. The increasing use of grouted-in VWPs has greatly increased the general understanding of mine hydrogeology.

Figure 7 shows an example of multiple grouted-in VWP sensors. Typically, 2-5 sensors are placed in the hole but, in some cases, it is possible to install six or more sensors in HQ or RC holes, and some operators have pioneered the installation of as many as ten. However, where field experience at a given site is limited, it is usually sensible to start off with fewer instruments in the hole (say two to three) and to slowly increase this once the site-specific conditions are better understood, and when site-specific installation procedures are developed by the mine operator. Grouted-in VWP installations are frequently made by piggy-backing on mineral exploration or geotechnical drill holes. Consequently, the cost is low, and it is often not necessary to drill a dedicated hole. Many installations can therefore be made rapidly at any given mine site.

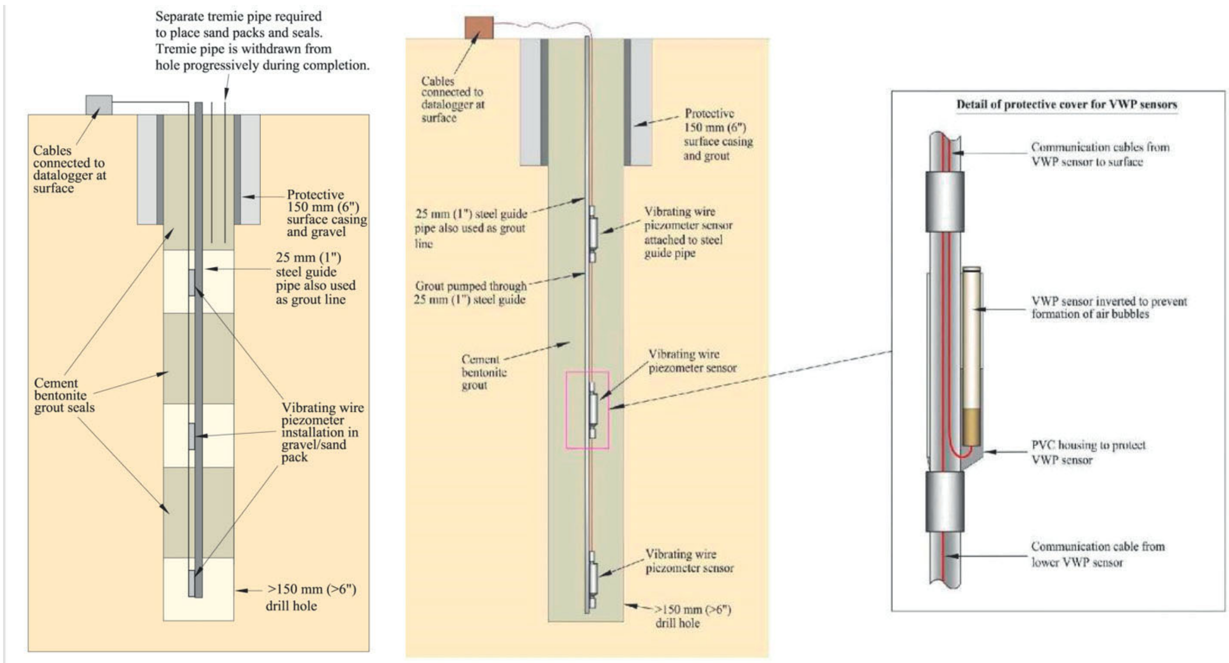

Figure 7: Examples of vibrating-wire piezometer installations. The grouted in approach has been pioneered by the mining industry and is now used worldwide (reproduced from Beale and Read, 2013)

The relatively small diameter of the VWP sensors and cables leaves space within the borehole for additional geotechnical instruments, such as inclinometer casing, TDR cables, accelerometer arrays and borehole extensometers. The frequency of pore pressure readings is often modified to match the monitoring frequency for the geotechnical instruments. There is an increasing tendency to integrate plots of geotechnical parameters from radar, prisms, TDRs, inclinometers or extensometers with pore pressure hydrographs, pumping hydrographs, timing of horizontal drain installations and precipitation data.

7. SURFACE WATER AND TRANSIENT PORE PRESSURE

Slope instability most frequently occurs at shallow levels in the slope (within say 50 m) where disturbed conditions exist and where confining stresses are low. Shallow water pressure is often a contributing factor. The less the confining stress, the greater the potential influence of the pore pressure change. Transient pore pressure changes may occur in materials that are already saturated (and therefore have positive pore pressure) or are unsaturated (and therefore have zero or slightly negative pore pressure).

Transient pore pressure changes may be observed due to a number of factors, including:
Blasting (very rapid response, potentially milliseconds, possibly creating water hammer effects in strongly jointed rock)

- Deformation or failure of the slope materials (often a rapid response during failure, potentially minutes)
- Changes in rainfall patterns (often causing an hourly or daily response)
- Seasonal changes (often causing a daily to monthly response)
- Mining related deformation of the slope materials (potentially on the scale of a week in areas of rapid mining, but generally longer term)

Shallow pore pressure changes are usually related to the infiltration of surface water. The infiltration may be derived from surface water run-off due to precipitation on the slope itself, run-off from above the crest of the wall (channels, overland flow, shallow sub-surface interflow), uncontrolled groundwater seepage from higher up the slope, or water from wells and horizontal drains that have no reticulation. It is also common that shallow pore pressure changes are caused by leakage from pipes, tanks or other mine facilities.

A change in shallow pore pressure influences the effective stress and resistive forces. In porous materials, changes in water content and consequent volumetric changes of the materials may also influence their strength, and may influence the total stress acting on the underlying materials. Instability in weak rocks, or toppling in sandstones and other jointed rocks, can be triggered by transient pore pressure caused by recharge.

In settings with high rainfall or rapid melting of snowpack, it may be advantageous to install shallow piezometers above the water table to monitor transient pore pressures close behind the slope in rocks that are normally dry (Figure 8). Piezometers that go dry as the dewatering program progresses should be retained if there is a potential for seasonal re-saturation and transient pore pressure.

Input of transient pore pressure to the geotechnical analysis can use an R(u) analysis, pore pressures applied specifically along potential failure surfaces, zones of transient pore pressure applied through the entire rock mass, or contoured piezometer data. As for any analysis, the geotechnical modelling has much more value if it can be constrained by real data collected from shallow piezometers, and if the sensitivity of the analysis to water pressure is investigated.

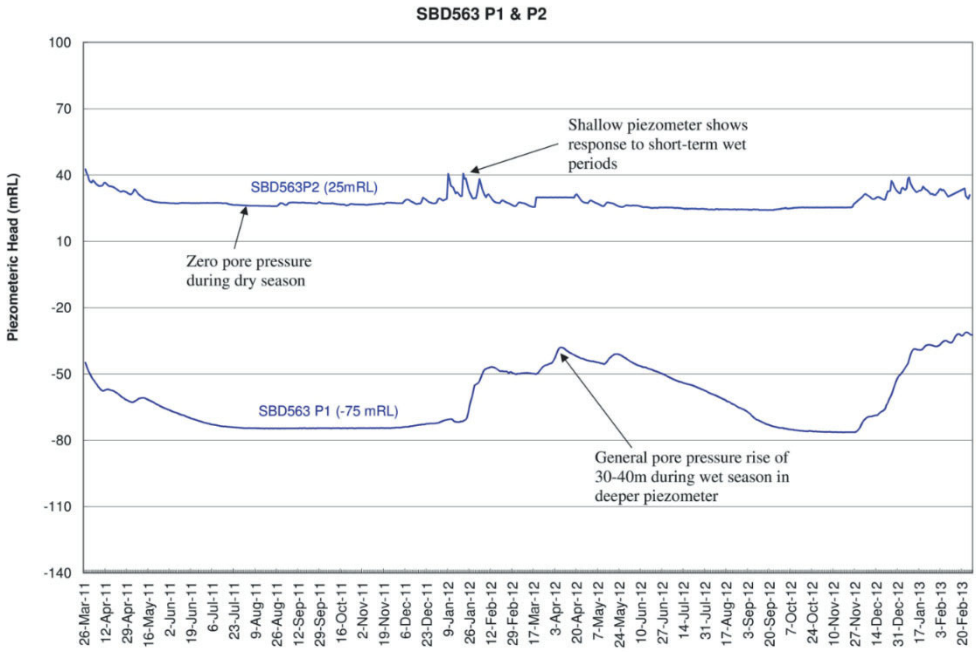

Figure 8: Example of transient pore pressure from two piezometer sensors in the same borehole. The piezometers originally measured permanent saturation, but went dry because of the dewatering program. The upper sensor shows the transient pore pressure effect of individual rainfall events. The lower season show a seasonal transient pore pressure change (reproduced from Beale and Read, 2013)

8. KEY INDUSTRY CHALLENGES

There are a number of common hydrogeological challenges to the mining industry. Discussion amongst the LOP sponsor groups has indicated the following concerns:

1. Improving groundwater characterization
2. Integrating pore pressure with the geotechnical analysis
3. Providing better support for feasibility studies
4. Adopting a “mine, monitor and adjust” philosophy

5. Laying out the mine site to reduce the influence of facility leakage
6. Prioritizing the surface water and groundwater management plan

IMPROVING GROUNDWATER CHARACTERIZATION

Historically, packer testing has been widely used to characterize the permeability of the site materials. However, conventional packer testing only provides characterization of a very small volume of material immediately adjacent to the borehole. For the majority of groundwater settings, these "point-scale" permeability tests have little bearing on the overall groundwater flow system, which is more commonly controlled by wider-scale connectivity of the fracture systems, the locations of faults or lithological contacts (Figure 9), and the wider-field influences. Recharge and "water availability" is usually more important than local-scale permeability.

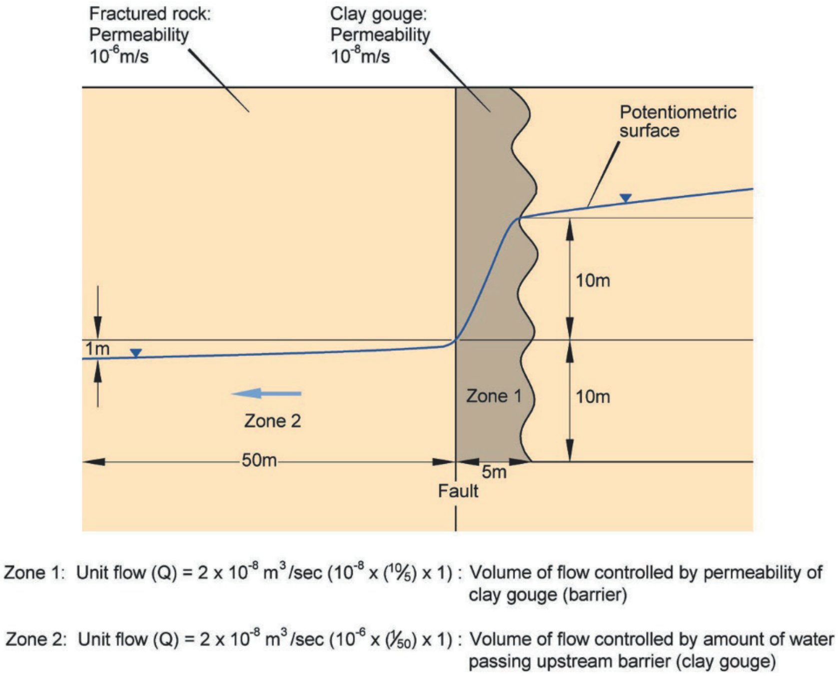

Figure 9: Illustration of how groundwater is controlled by wider-scale features rather than "point-scale" permeability (reproduced from Beale and Read, 2013)

The interpretation of piezometer responses to short or long-term changes in hydraulic stress allows a more realistic assessment of the wider-scale groundwater setting. Therefore, it is important to carry out as many "groundwater stress tests" as possible, where the response to the hydraulic stress is measured at surrounding observation points. "Cross hole testing" allows characterization of the wider flow system rather than the "point-scale" permeability.

INTEGRATION OF PORE PRESSURE WITH THE GEOTECHNICAL ANALYSIS

At all stages, it is normally advisable to use a range of water conditions for input to the geotechnical analysis, rather than "absolute" conditions. This allows the sensitivity of the slope to be understood, and allows the slope depressurization program to be focussed. Where there is insufficient time or supporting data, alternatives to numerical modelling should be considered. If numerical modelling is carried out, critical validation of the results is essential prior to use in the geotechnical analysis.

PROVIDING BETTER SUPPORT FOR FEASIBILITY STUDIES

One of the goals of the LOP project has been to provide guidelines on the data required for each stage of project development. This includes the hydrogeology program. Many feasibility studies in low permeability settings are difficult to support because they do not include empirical response data. Cross-hole testing at a local scale (10-20 m hole separation) is being increasingly used to provide piezometer response data with which to validate the studies. The LOP has also defined the importance of benchmarking with as many sites as possible in similar hydrogeological settings.

WHEN TO ADOPT A "MINE, MONITOR AND ADJUST" PHILOSOPHY

The inherent local scale variability of mine geology often makes precise geotechnical or hydrogeological modelling difficult. Analytical or numerical model results require careful interpretation to determine their applicability at a local scale. Where conditions are uncertain, the observational ("mine, monitor and adjust") approach is often used, in part, because of the increasingly high quality of monitoring data (Figure 10).

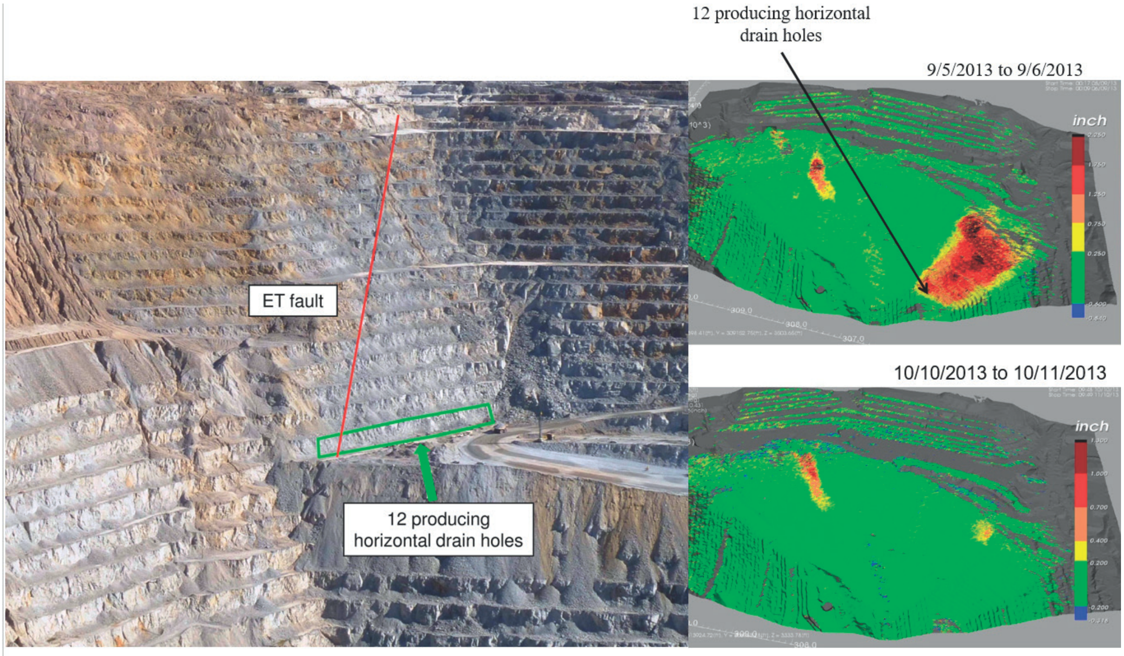

Figure 10: Example of using radar monitoring to constrain the slope depressurization program (courtesy of Steve Borron, Todd Ashinhurst and Jeremy Dowling; reproduced from Martin and Stacey, 2018)

LAYING OUT THE MINE SITE TO REDUCE THE INFLUENCE OF FACILITY LEAKAGE

At many mining operations, elevated pore pressure conditions in some slopes are "self-inflicted" and occur because of uncontrolled leakage losses and infiltration from mine site facilities. A key challenge is to optimize the site layout, and to create good construction control on facilities that surround the pit (or will surround the future pit).

Pit expansions are inevitable, and many of the issues occur due to historic facilities, or because multiple expansions have progressively moved the pit crest closer to the artificial recharge source. Any effort to define and control the recharge sources in advance may help reduce the burden of slope depressurization.

PRIORITIZING THE SURFACE WATER AND/OR GROUNDWATER MANAGEMENT PLAN

An on-going challenge for the mining industry is the smooth link between "engineering" and "operations". In some situations, surface and groundwater designs are only implemented and maintained if the maintenance group has adequate resources. At operations where resources may be limited, it is often difficult to prioritize the construction and maintenance of water management facilities that may have a slow rate of economic return.

Water management has become an integral part of the mining cycle and often requires similar attention and maintenance as all other mining systems and equipment. Regular (systematic) field inspections and on-going maintenance is a key factor. At many operations, the primary purpose of the surface water management system is to protect the pit slopes. As such, the surface water program should often be led by the by the geotechnical group. Mine geotechnical staff should be responsible for the design and regular inspection of the system, and for driving the maintenance program.

7. ACKNOWLEDGEMENT

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