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Ingeniería de Minas
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
UNIVERSIDAD DE CHILE

Pore pressures in geotechnical analysis and design

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Mine Water Management

Mine dewatering, surface water management and control of pore pressures

- Effective mine water management will require 1 or more of these factors to be planned and well executed.
- Mine water management requires good technical knowledge, integrated teams, allowance for uncertainty and operational plans with clear performance measures.
- Groundwater, surface water and pore pressures are commonly linked, and plans and programs typically require holistic management.
- Mine water management must be proactive, inform mine planning and not be considered as an after-thought.

Pore pressure and hydrogeology

Pore pressure is the pressure of groundwater within the pore spaces of a soil or rock

It is defined as the pressure required to support a column of water below the water table

1. Porous flow

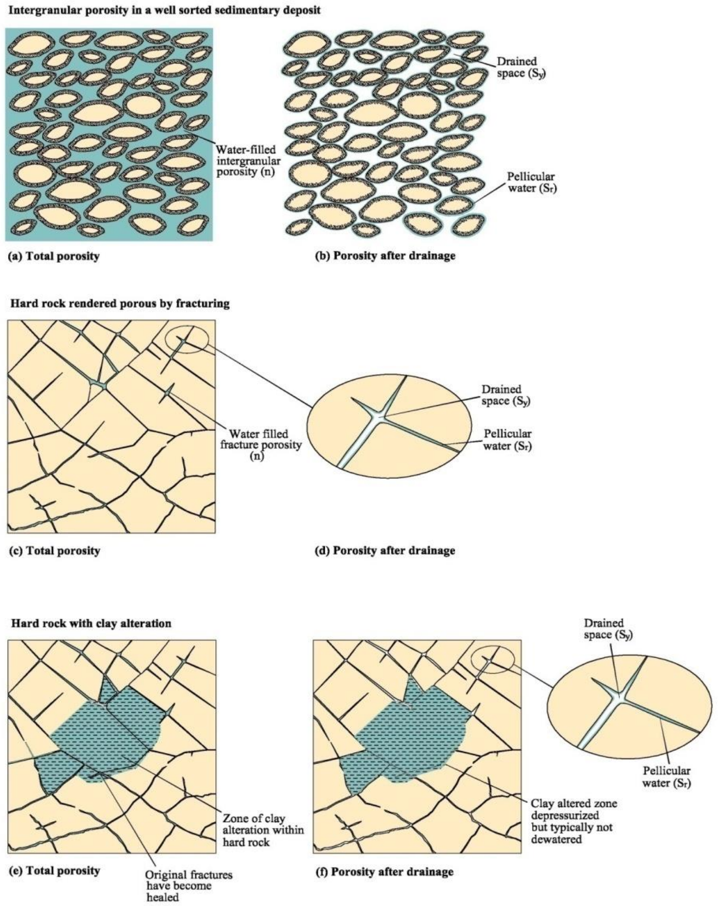
- Drainable porosity relatively high
- Weathered rocks

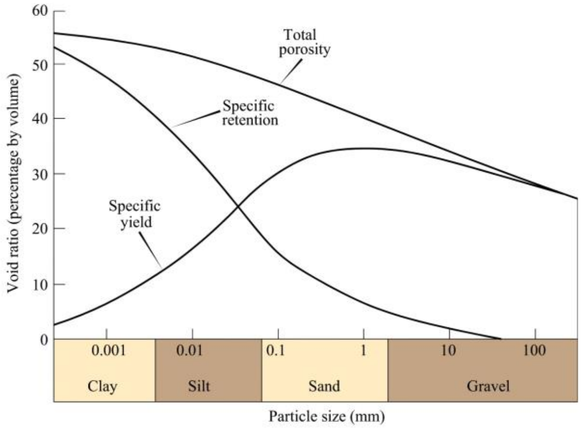
2. Fracture flow

- Low drainable porosity
- Multiple order fractures
- Fractures can be clay filled

3. Dual porosity

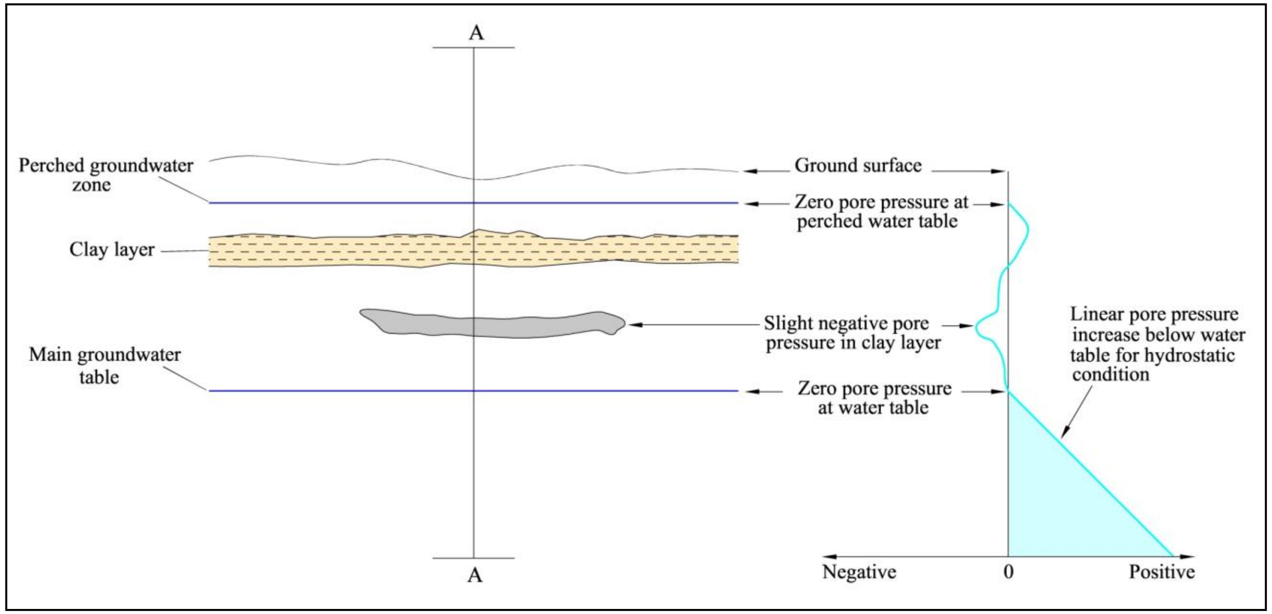
- Weather and fresh rocks
- Where alternation occurs



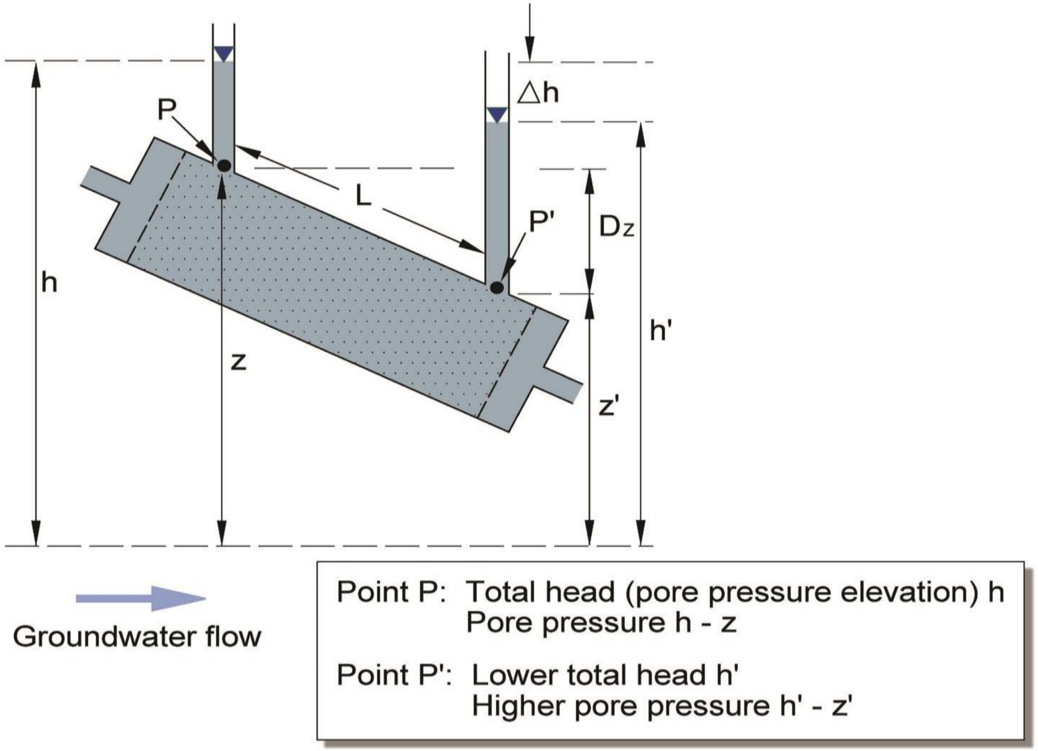


Source: Beale and Stacey, 2013

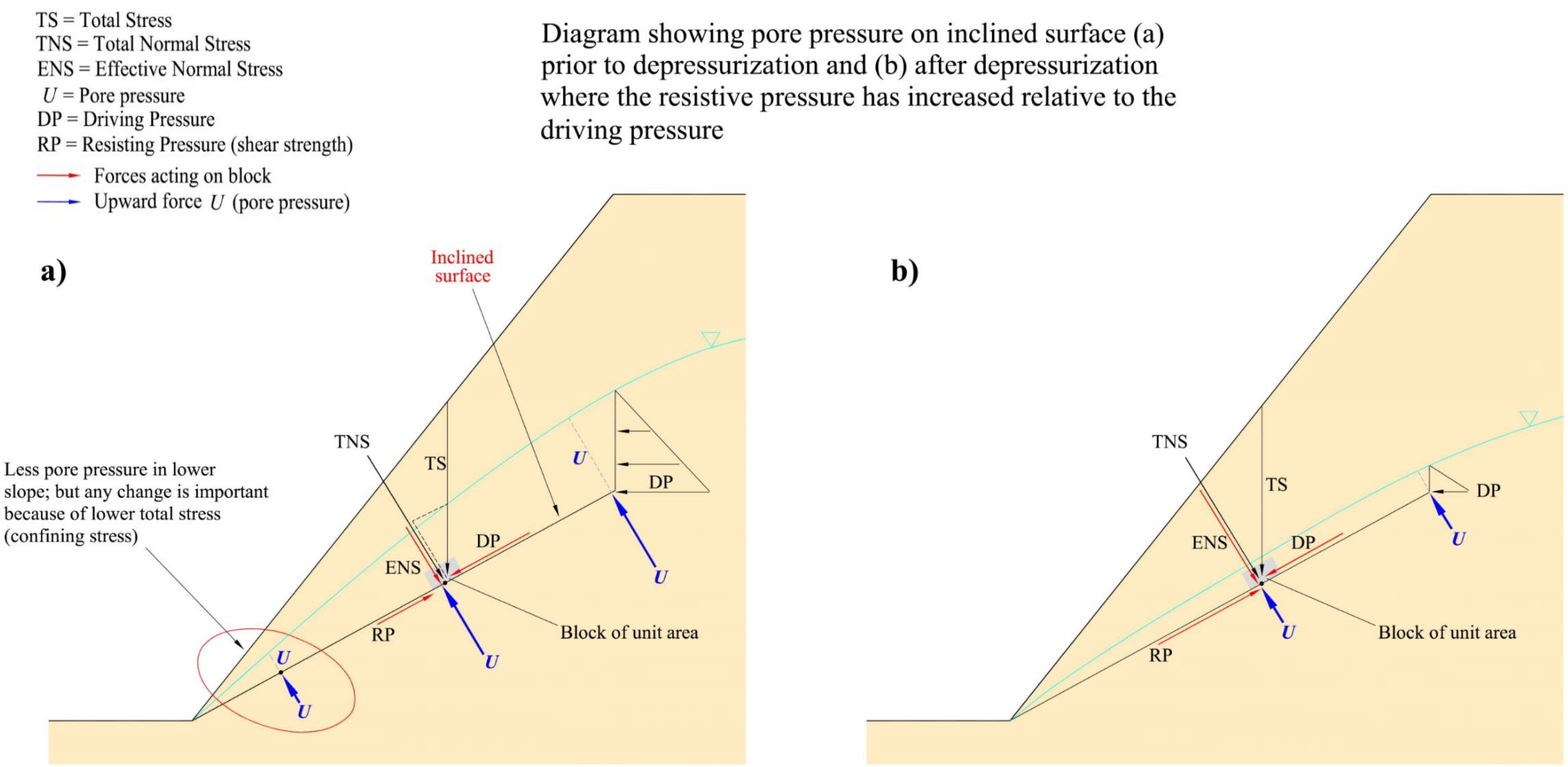
Pore pressure and hydrogeology



Beale and Stacey, 2013. Pore pressure is zero at the water table, positive below the water table, and negative above the water table.



Effects of depressurisation in slope stability



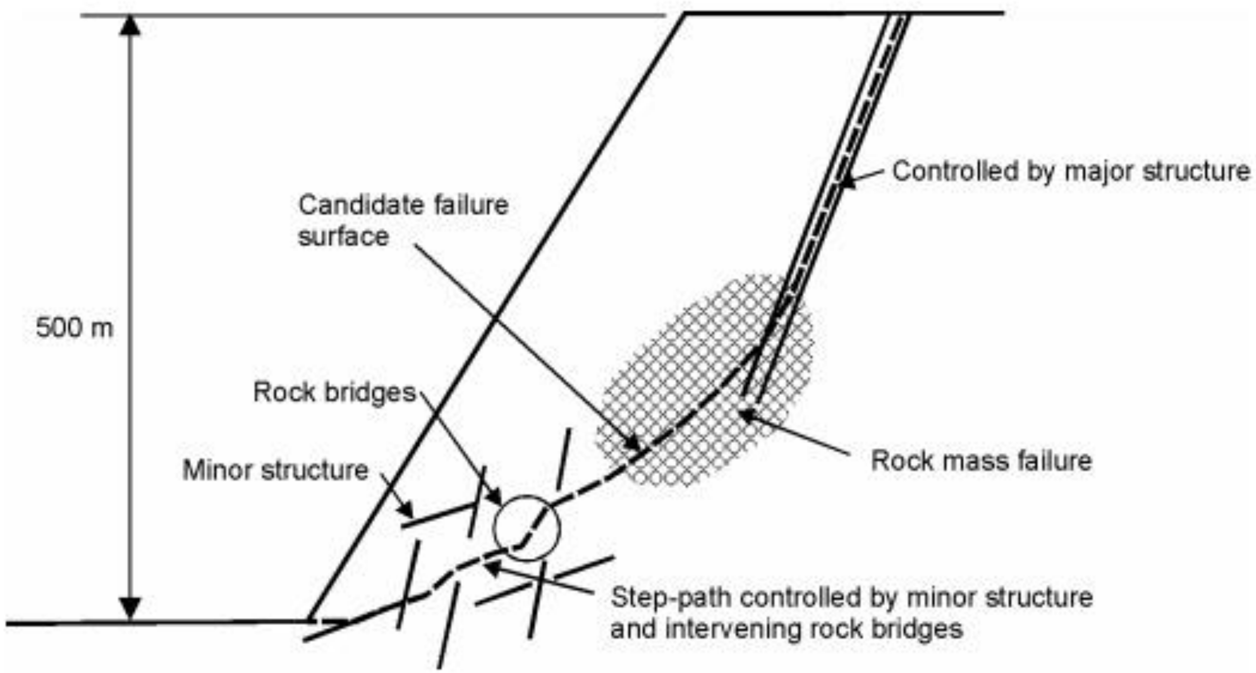
Beale and Stacey, 2013.

Understanding pore pressures in a failure mechanisms

Controlling pore pressures in geotechnical risk areas

To interface between hydrogeology and geotechnical must:

- Understand the plausible mechanisms of failure, how water contributes to these mechanisms and the factor of safety.
- Learn the geotechnical drivers, sensitivities and language, and how geotechnical parameters can be used in hydrogeology.



Source: Hoek, Read, Karzulovic and Chen

Why Mine Dewatering and Depressurisation

Lowering of the groundwater surface to a predetermined level

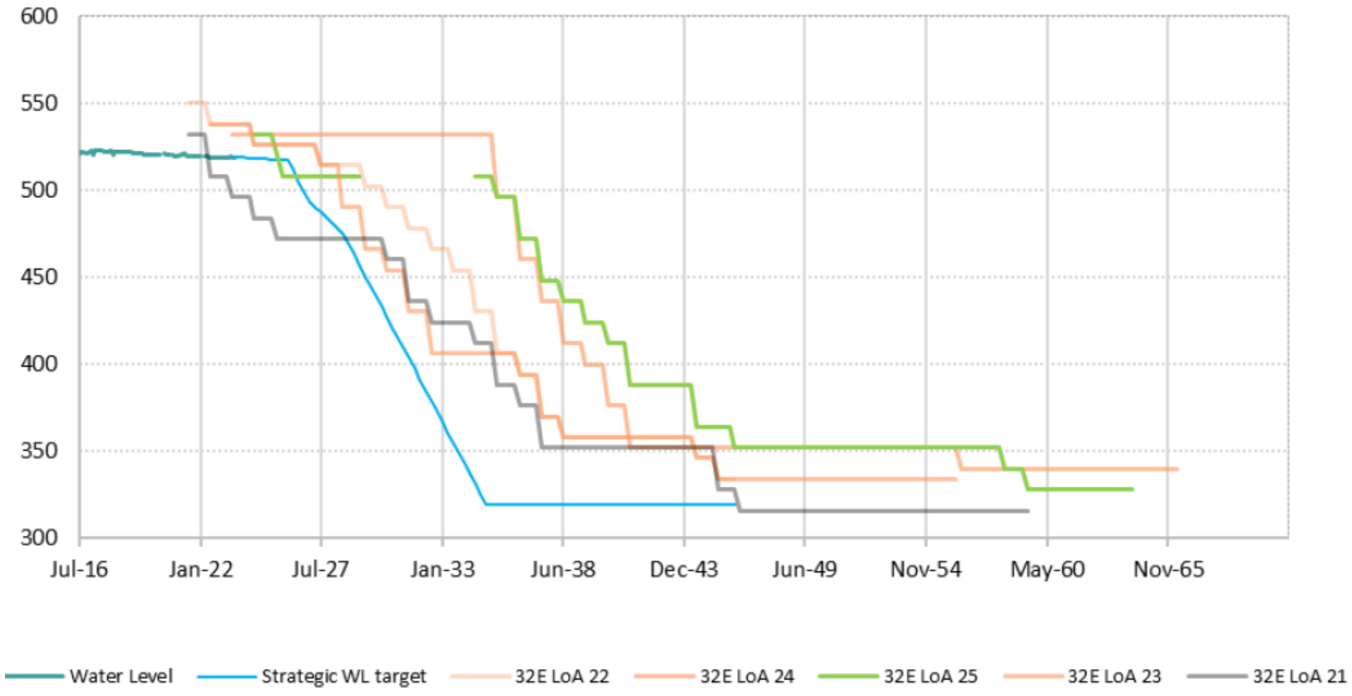
Dewatering and depressurisation is a part of the mine production.

The value of dewatering delivers and the risk of not achieving production should drive the prioritisation, investment and effort.

Proactive mine dewatering and depressurisation can achieve higher mine production rates.

Depressurisation and dewatering for:

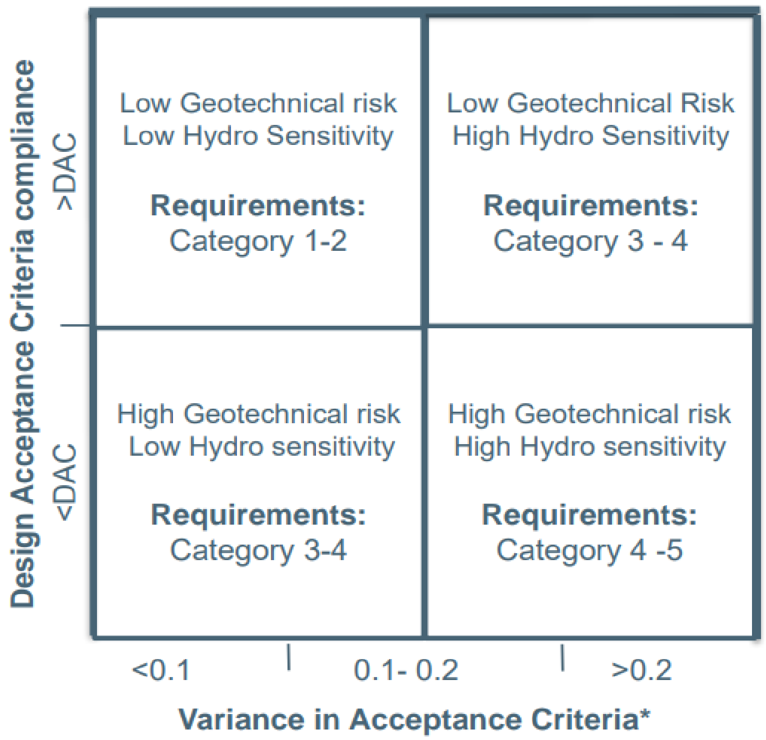
- Drained and optimised slopes
- Dry blast conditions
- Dry and safe operating conditions
- Deliver a water supply



Proactive dewatering can enable a more aggressive mine plan. Example above shows multiple mine planning options are available, all requiring a different dewatering effort, timeframe and volume. The selected dewatering design allows for flexibility in most mine planning outcomes

Evaluating Depressurisation Requirements

Sensitivity of pit slope stability to pore pressure



Technical Characterisation Requirements				
Category 1	**Category 2**	**Category 3**	**Category 4**	**Category 5**
Geotechnical designs have a low sensitivity to pore pressure	**Geotechnical designs are partly sensitivities to pore pressures.**	**Geotechnical designs are moderately sensitive to pore pressures.**	**Geotechnical designs and assessments are highly sensitive to pore pressures.**	**Geotechnical designs and assessments are critically sensitive to pore pressure**
A low level of confidence in hydrogeological and hydrological information is adequate.	The conceptual model should consider transient pore pressure collected and interpreted in areas of geotechnical significance.	Hydrogeological controls become an important driver for slope design.	Hydrogeology focus on features of geotechnical risk and detailed groundwater flow mechanisms.	Detailed conceptual model to support pore pressure predictions and slope design assumptions.
Hydrogeology and pore pressures are informed by conceptual models which are validated by data within the mine and surrounding region.	Some multi-level piezometer data required to support stability analysis.	Pore pressure are verified through multilevel monitoring required for key slope sectors; supported by field testing	Empirical field testing to quantify pressure responses through targeted hydraulic testing, drainage or recharge monitoring.	Extensive field trials add monitoring required, with 5-10 multi-level piezometer installations in key slope sectors
Pore pressures and groundwater levels are typically inferred and can be input to the geotechnical analysis.	Analytical or numerical models (nominally 2D) required as input to geotechnical analysis. Transient water levels and piezometric data is used to deliver pore pressure predictions	2D or 3D models need to incorporate vertical pressure gradients and transient pore pressures; and need to define requirements for active depressurization	Analytical or numerical models must be calibrated to hydraulic stresses	Numerical modelling to be fully calibrated to field trials
			Sensitivity analysis should be used to develop active depressurization programs	Slope mitigation must consider consequences if target pore pressures are not achieved
				Continuous improvement and validation required.

Figure: Example of how to evaluating the importance of pore pressures in design, to support the level of assessment required.

Predicting pore pressures models

Why develop a model

Needs a good conceptual model modelling objective

Design optimization

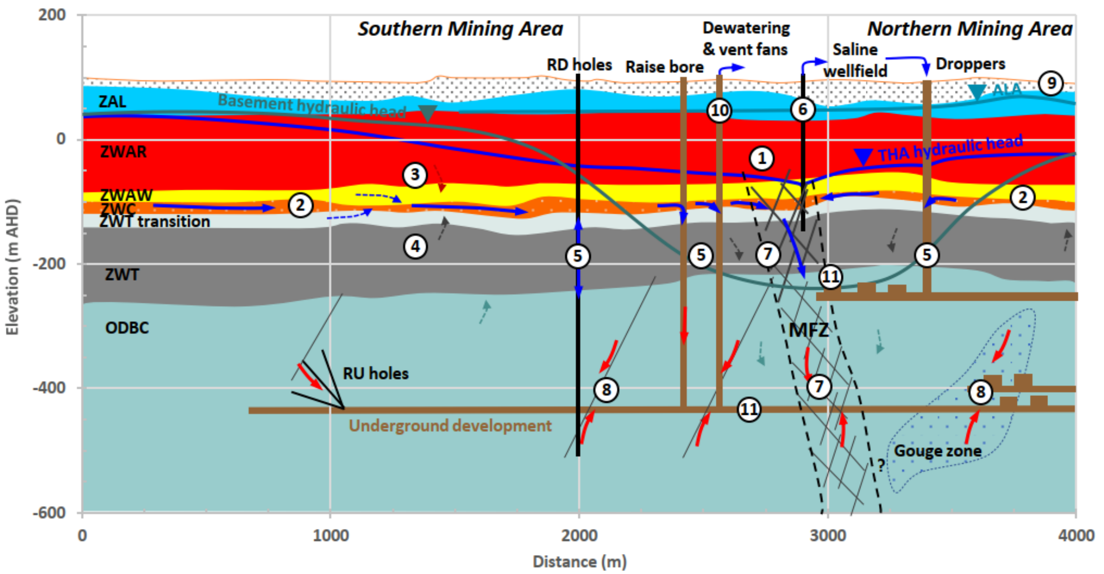
- Drain spacing and location
- Well location
- Tunnel and infiltration and recharge effects

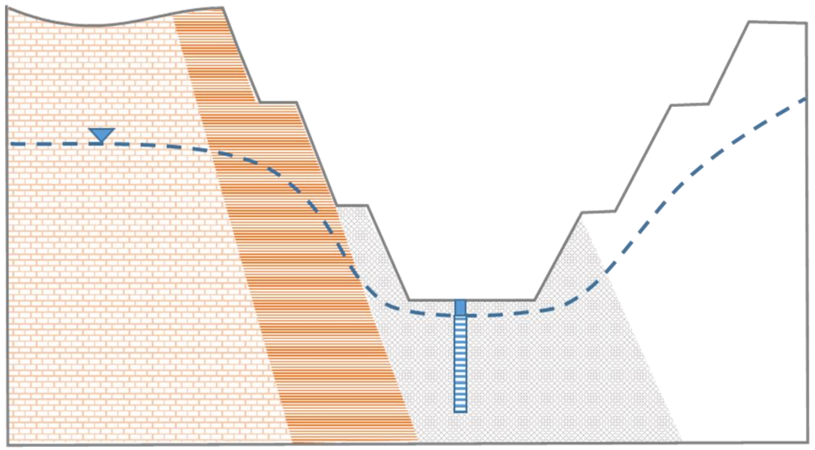
Testing sensitivity

- Role of pore pressures in geotechnical analysis
- Testing conceptual models

Predictions

- Volume and rate of dewatering depressurisation
- Rate of pore pressure decline





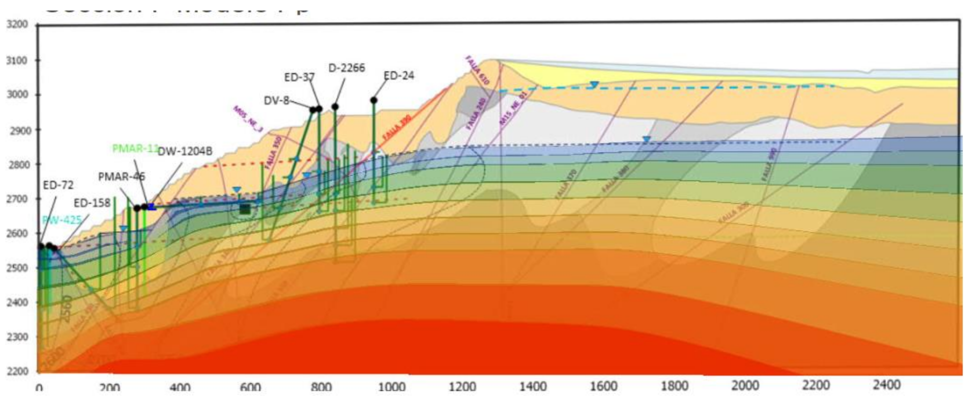
Conceptual models can be simple to more complex

Predicting pore pressures

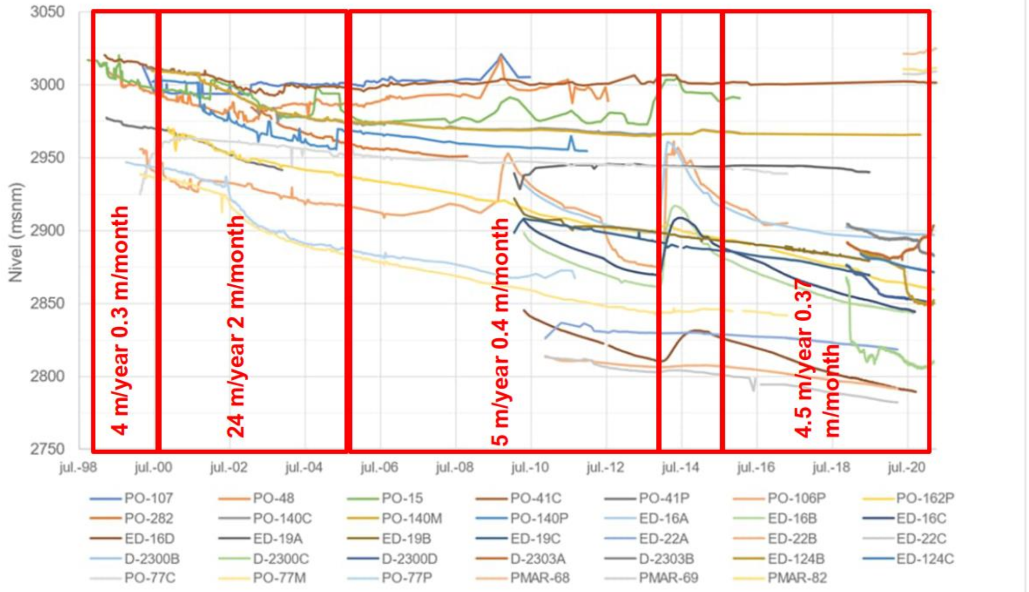
Different Approaches

- Phreatic surface
- Ru
- Hu
- Empirical trend analysis
- 2D section model and pore pressure grid
- 3D pore pressure grid
- Uncertainty analysis

Less to more complex



2D numerical analysis



Empirical analysis, predicting future conditions using past trends

Predicting pore pressures

Uncertainty analysis

Adriana to include slides here – use recent conference paper

Uncertainty in model

Uncertainty analysis

Research areas - GMDSI

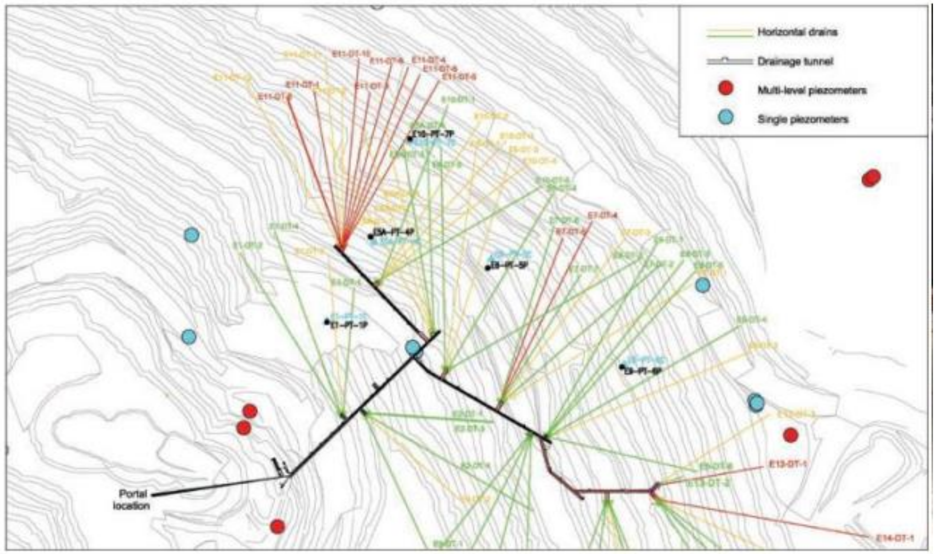
Machine learning

Depressurisation Methods

Options to manage elevated pore pressures

Where pore pressures effect slope stability there are a couple of choices:

1. Lower pit slopes and increase the stripping ratio.
2. Slow mining to allow for natural depressurisation, if possible.
3. Manage slope failures, if located and predictable.
4. Carry out focused depressurisation using:
   - Pumping wells
   - Horizontal drains
   - Wick drains and vertical drains
   - Tunnels and drainage drives
   - Managing surface water infiltration



Horizontal drains

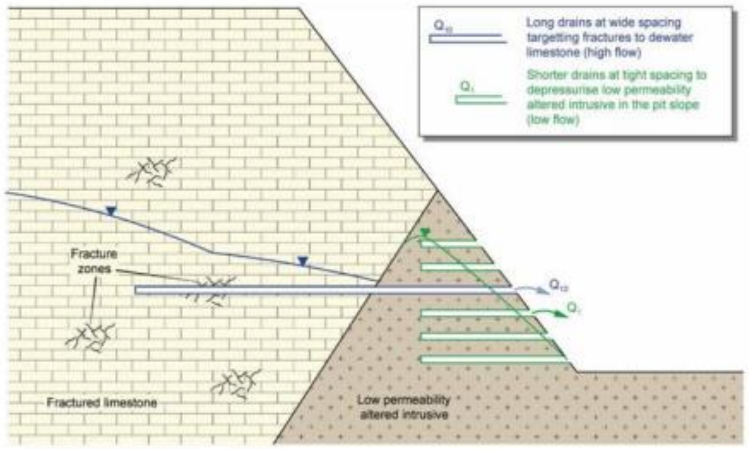
Depressurisation of a pit slope using an array of designed holes to optimise slope design

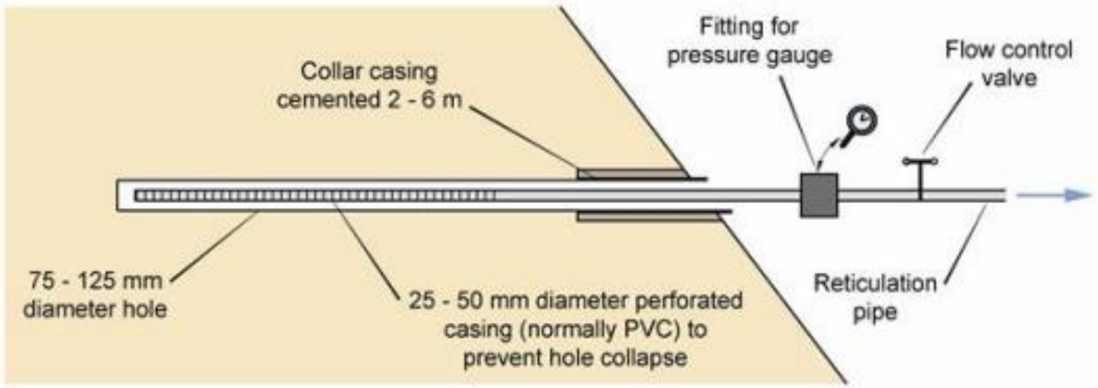
Application in pit slopes:

- Depressurising low permeability rock mass
- Targeting structure or structural domains
- Access to hydrogeological compartments.

Considerations

- Build into the operational mine plan
- Plumb into water management infrastructure
- Will operate long term as pit floor advances
- No or low flow doesn’t mean no depressurisation
- Hydrogeology determines orientation, spacing and length
- Access may require purpose built benches
- Uncontrolled flows can cause recharge to the face

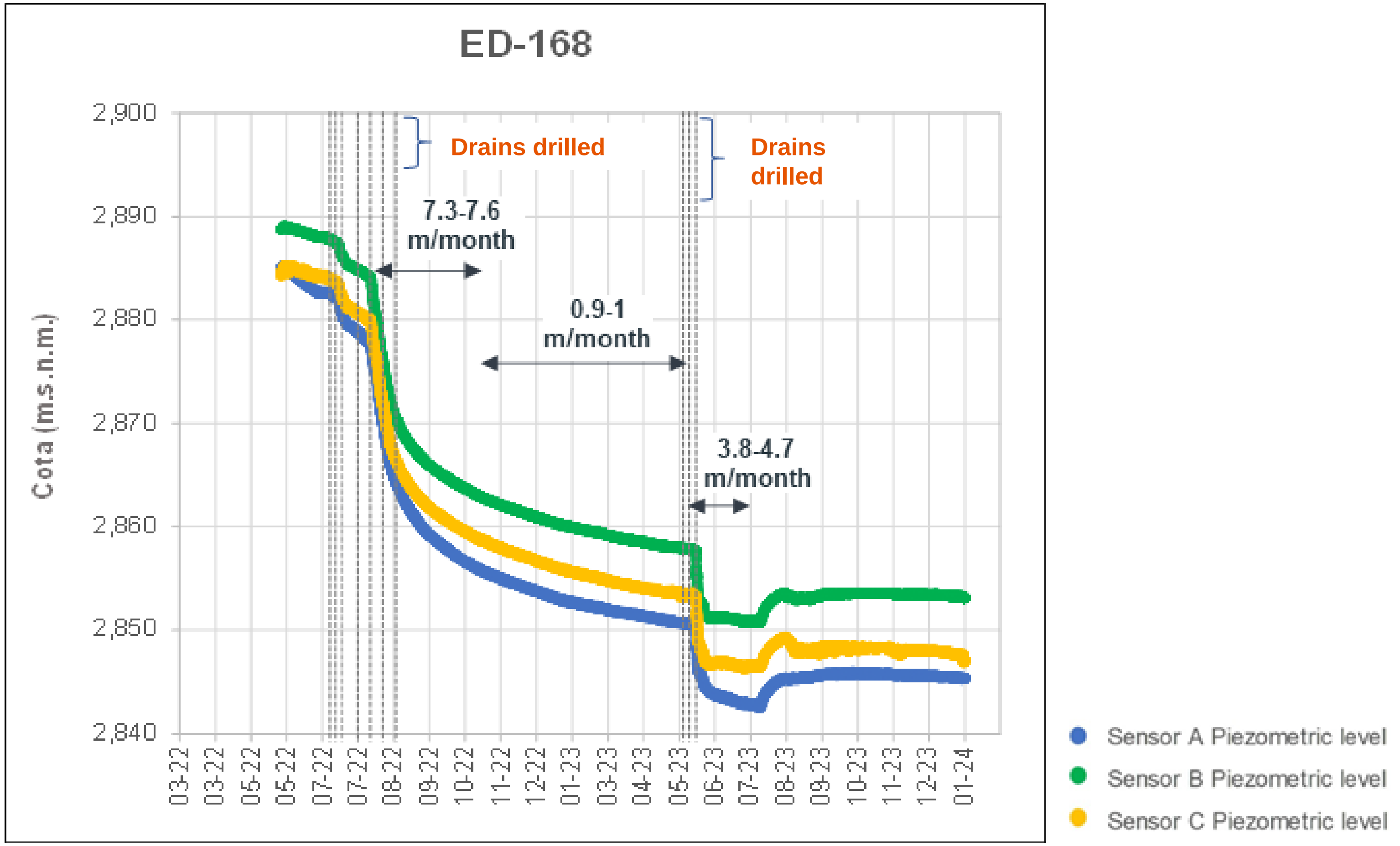




Source: Beale and Stacey, 2013

Horizontal drains

Monitoring the drainage response is critical to optimise designs and locations



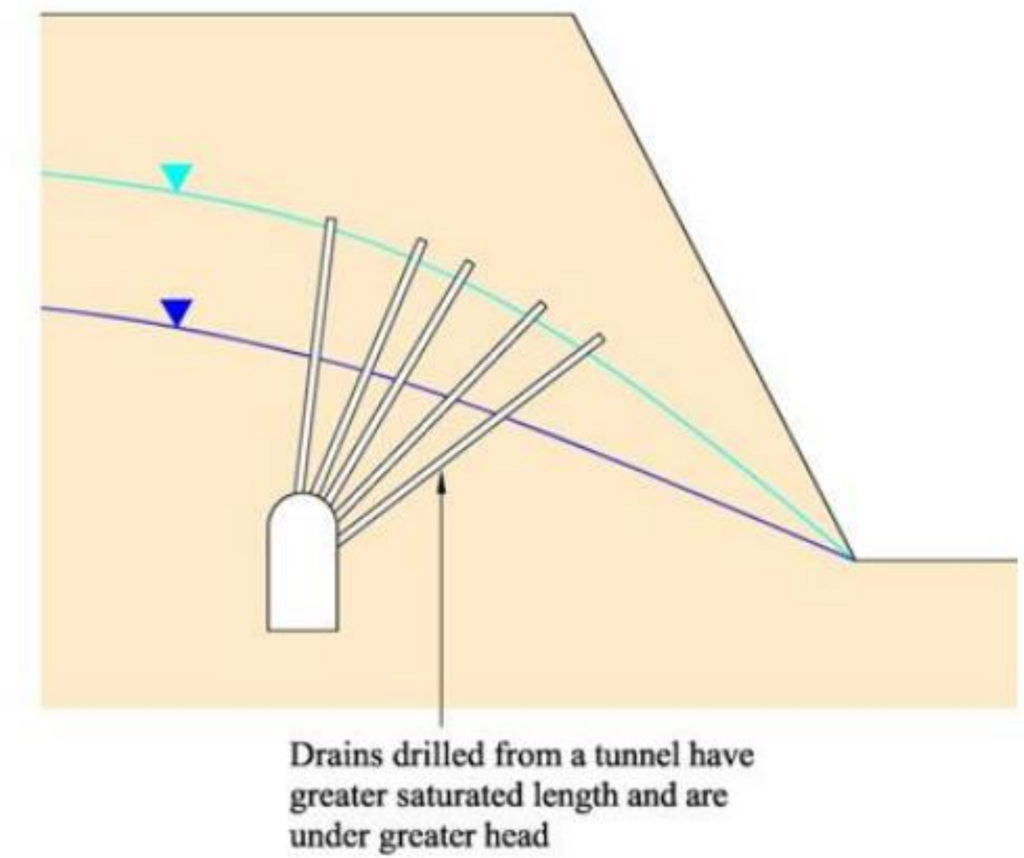
Source: Example of the drainage response from a porphyry copper mine

Drainage tunnels and drives

A tunnel is typically driven behind large slopes to drill drain holes and actively manage pressures

Application:

- Used in large open pits where long term drainage is needed.
- Tunnel must be coupled with drain holes to be effective.
- Allows access during operational congestion.
- Allows for synergies with other services.
- High upfront costs.
- Requires active maintenance, different mining methods, safety requirements.



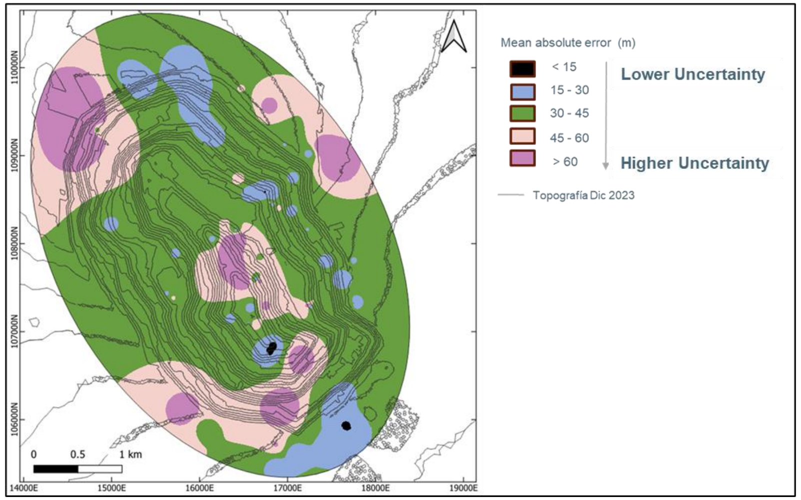
Source: Beale and Stacey, 2013

Monitoring pore pressures and monitoring density

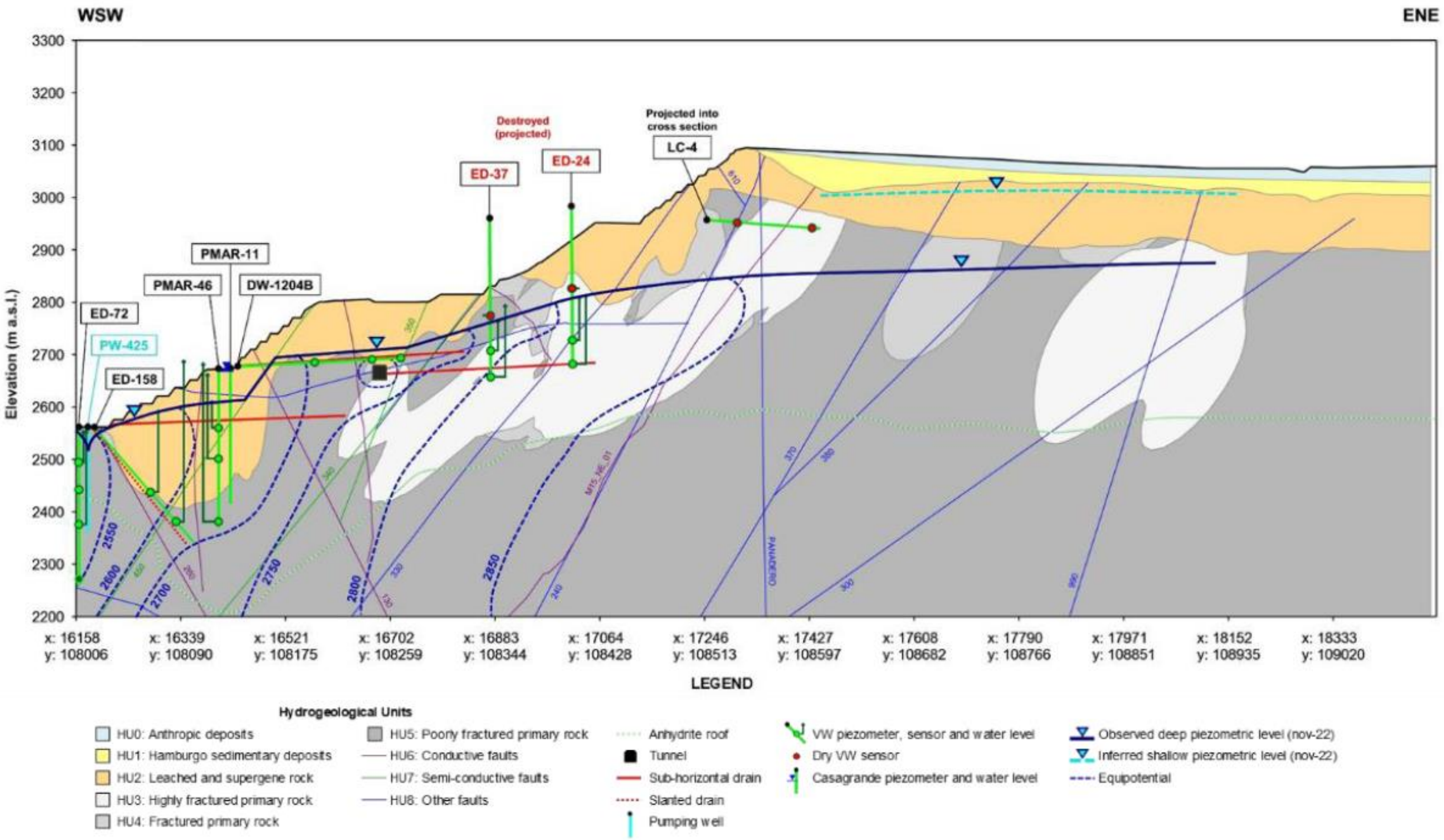
Monitoring density and locations depend upon risk and uncertainty in knowledge

Monitoring density depends upon:

- Compartment dimension (stepped pressures across fault)
- Triangulation of monitoring points : flow direction
- Importance of vertical gradients and stratigraphic horizons
- Main faults and rock mass with stability concern
- Drainage target performance



Example of uncertainty distribution based on model error informing monitoring requirements and gaps.



Example of a hydrogeological cross section showing monitoring detail, geology and pore pressures in a porphyry copper mine slope. The hydrogeological sections should be aligned to geotechnical sections. Villa et al, 2024.

Hydrogeology in slope design, Diploma Geomecánica

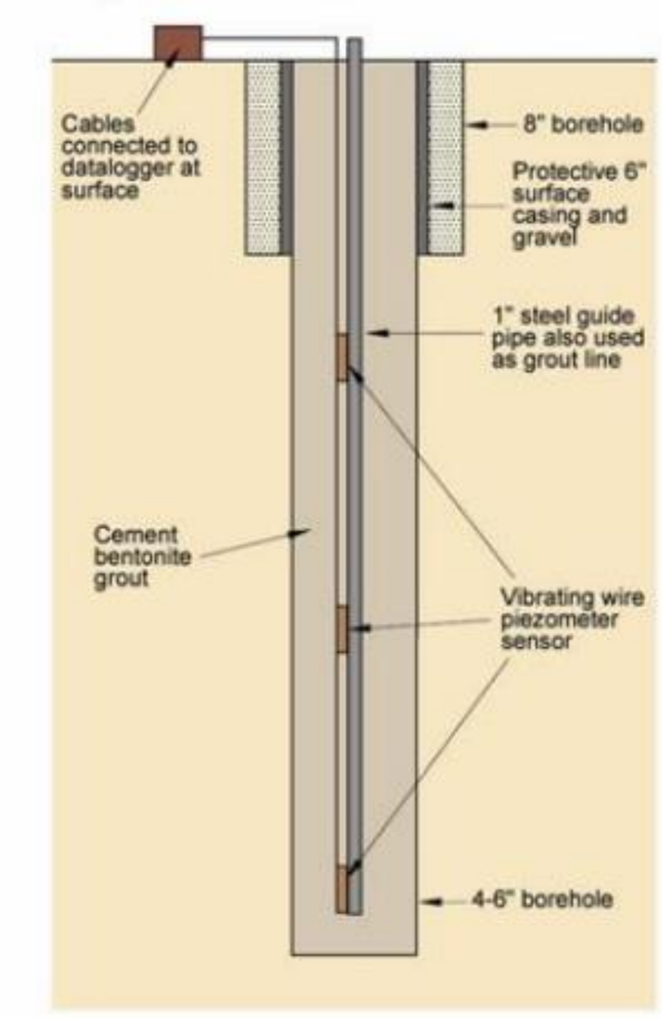
VWP installation and monitoring

Grouted in multi-level piezometers are standard to monitor pore pressures

Vibrating wires used to individually or collectively in low permeability rocks to:

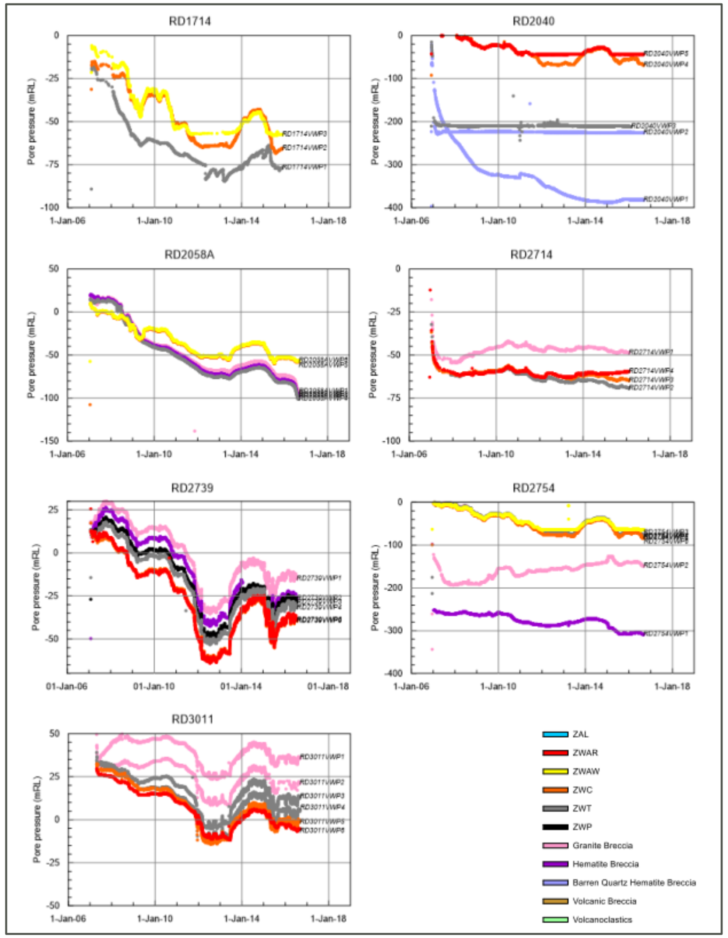
1. Define vertical gradients
2. Establish a pore pressure profile in the slope
3. Monitor depressurisation

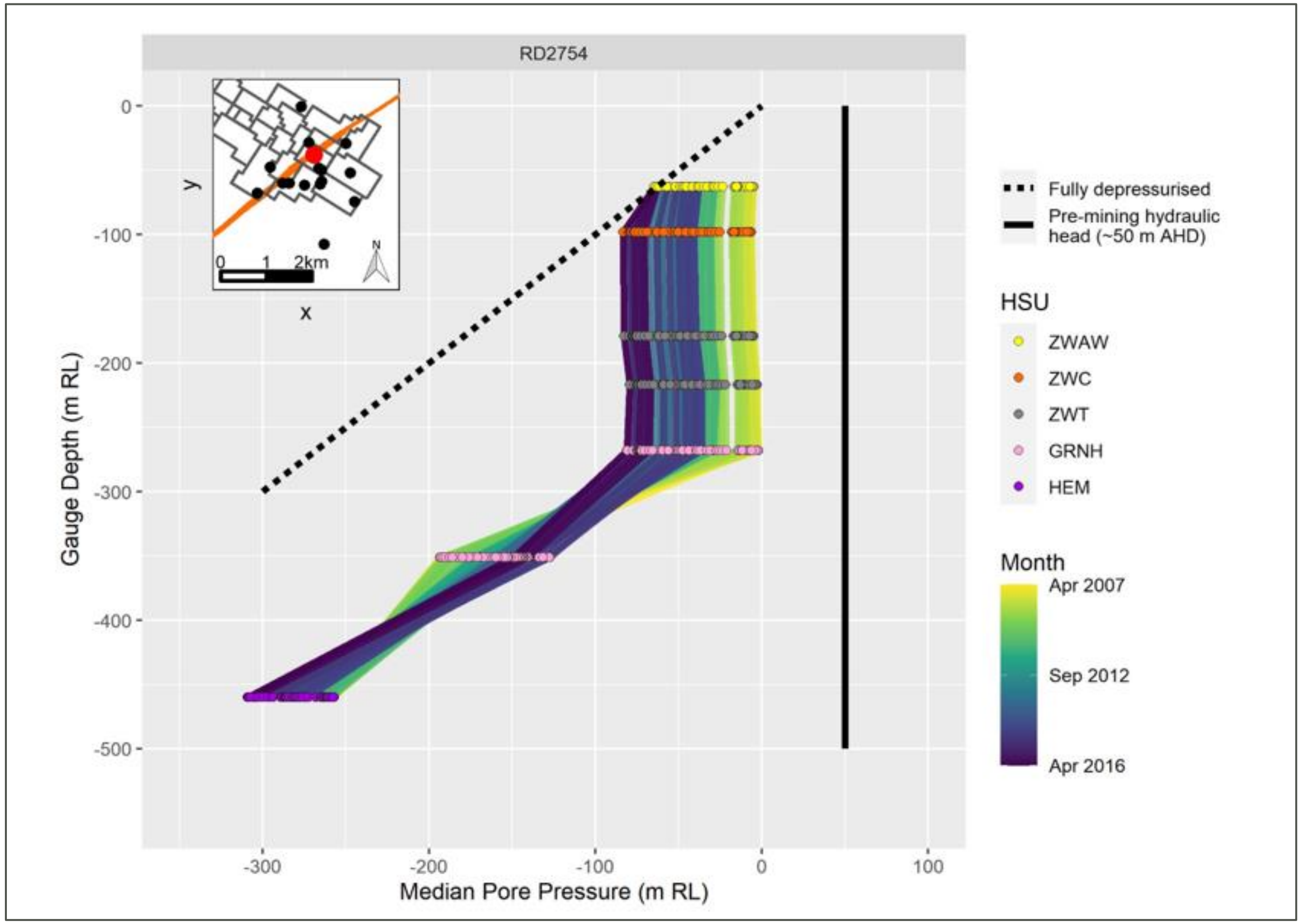
- Generally, highly precise but require calibration.
- Can observed hydrogeological effects and effective stress.
- Can be paired with TDRs.



VWP data presentation

Time series data from multiple vibrating wires in a hole are useful to understand vertical gradients





Examples of data series of multiple piezometers in a borehole, presented as hydrographs and as a pore pressure profile in relation to the phreatic surface.

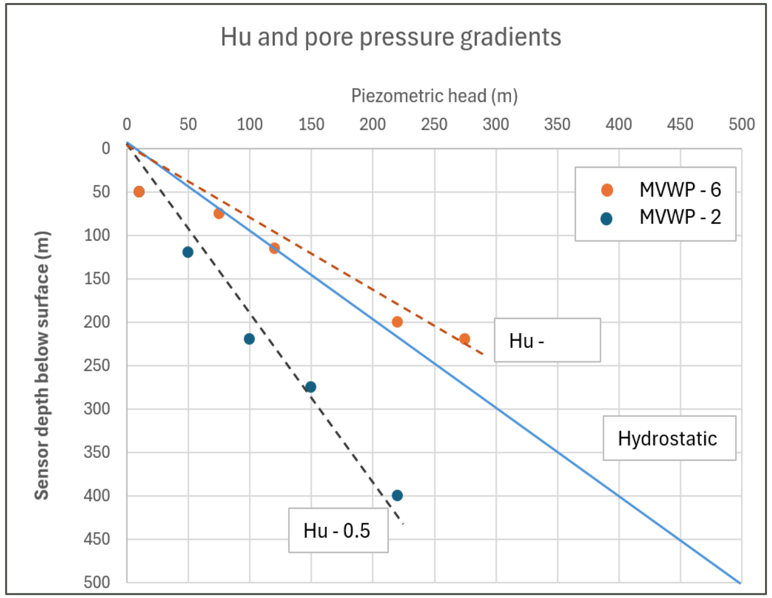
Setting depressurisation targets

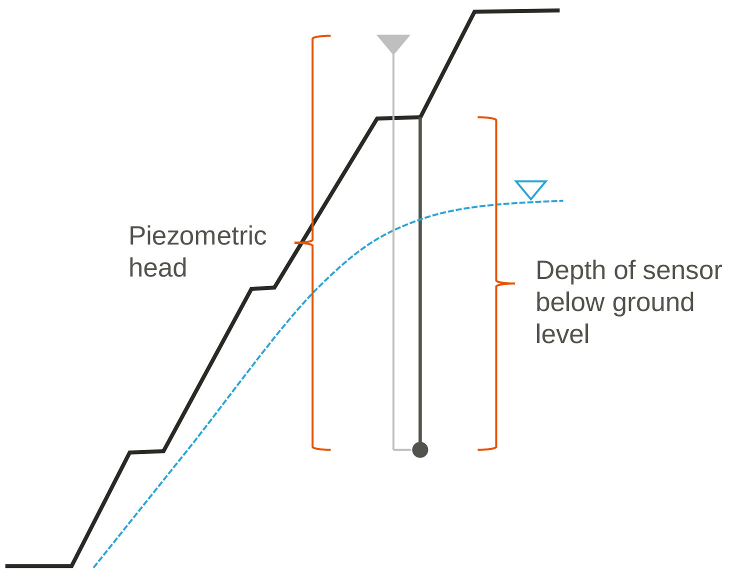
Setting and tracking depressurisation

Geotechncial analysis define the pore pressure targets:

- Simple methods assign the Ru
- Hu value allows for variability with depth
- More complex method predict pore pressure grids using 3D numerical model
- Other methods include projecting historical trends

The application of a phreatic surface is sufficient when there is monitoring evidence to support downward hydraulic gradients.

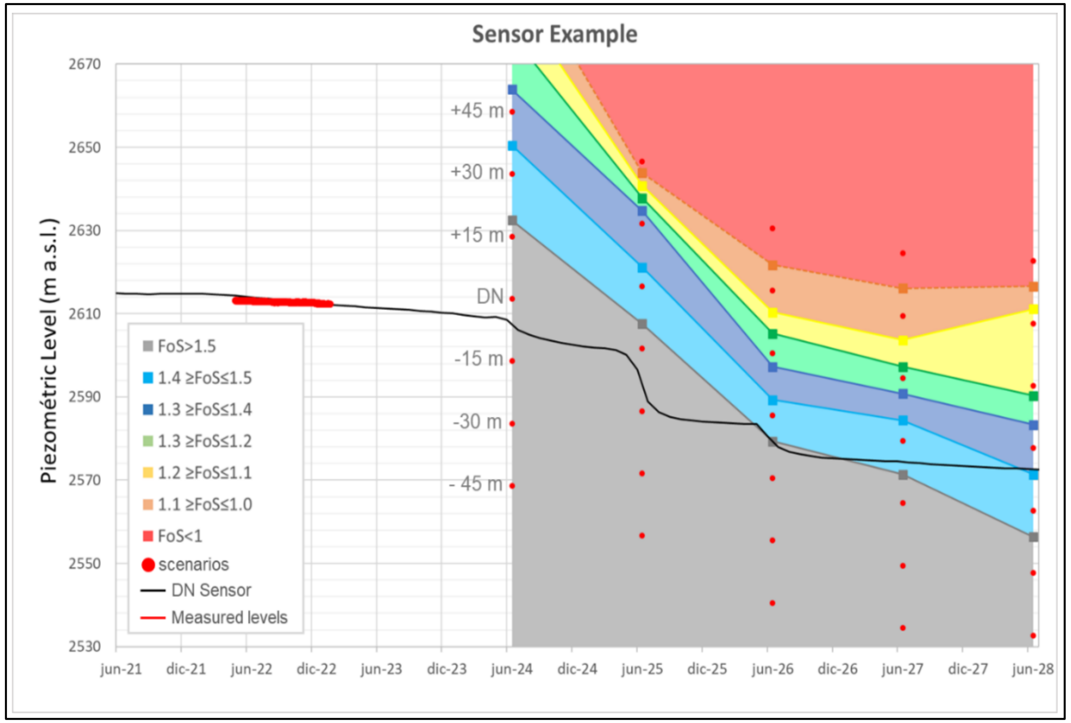




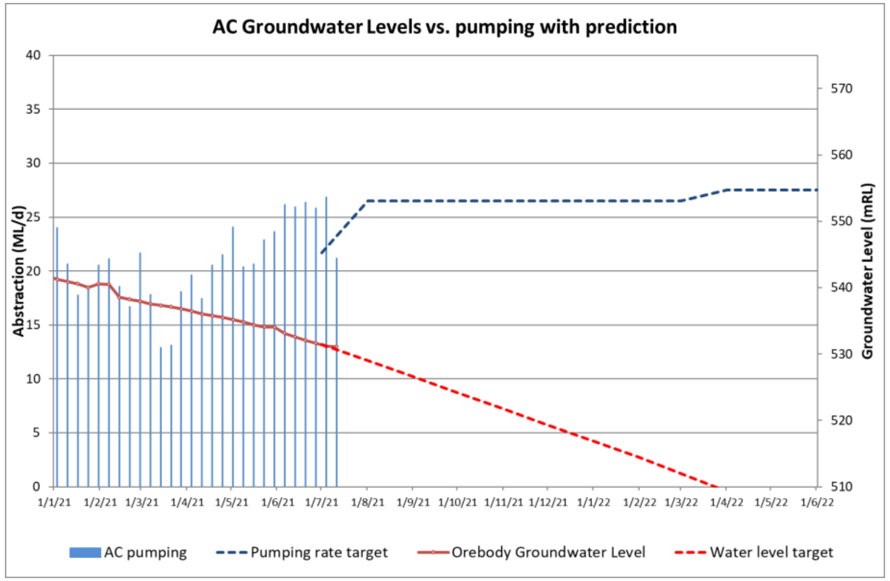
Example of presenting pore pressure relative to a phreatic surface, using a Hu coefficients. Hu values >1 indicate potential geotechnical risk zones or the potential for artesian conditions.

Setting depressurisation targets

Setting and tracking depressurisation



Villa et al, 2024. Factor of safety chart related to piezometric levels for a sensor for different wall progressions and pore pressure sensitivities, comparing observed and predicted pressures



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