Slope Stability 2013 – P.M. Dight (ed)

doi:10.36487/ACG_rep/1308_0.3_Beale

Water and slope stability – the application of a new science

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Abstract

The science of pit slope hydrogeology has rapidly gained momentum over the past 15 years to meet the requirements of larger and deeper mining projects. The advent of new monitoring systems, and particularly the use of grouted-in vibrating wire piezometers, has contributed to a practical understanding of the factors that control the behaviour of water pressure in pit slopes. An expanding global database linking pore pressure with deformation and slope movement is highlighting the role that water pressure plays in slope stability. The talk discusses the importance of water for slope stability, the integration of geotechnical and hydrogeological studies, and the development of a practical approach for project planning, implementation and monitoring.

1 Background

During the 1980s and 1990s, there was an increasing awareness throughout the mining industry of the detrimental effects that water has on pit slope stability. Theory had been advanced to illustrate how groundwater reduces the effective stress of the materials that make up the pit slope and reduces the strength of both the materials themselves, and the geological structures and other discontinuities that are present within the slope. However, the monitoring of groundwater within pit slopes was either lacking or was carried out using open standpipes, Casagrande-type piezometers or pneumatic instruments, making it difficult and expensive to obtain a large amount of pore pressure information at discrete depths, or to provide specific field evidence of how pore pressures respond to changes in hydraulic and geomechanical stresses.

2 Factors that have lead to an improved understanding of pit slope hydrogeology

The past 15 years has seen a significant improvement in the understanding of mining hydrogeology in general and, in particular, pore pressures in pit slopes. The single-most important reason for this is considered to be the advent of the grouted-in vibrating wire piezometer, which has allowed multi-level instruments to be rapidly installed in any geotechnical or mineral exploration drill hole with relatively low incremental cost. Figure 1 shows three vibrating wire sensors installed in a 150 mm diameter hole but, with good installation procedures, four or more sensors can successfully be installed in smaller diameter diamond holes. Therefore, the ability to collect a large amount of focussed high quality data is ever increasing.

Coupled with (and because of) this has come the appreciation that vertical hydraulic gradients around many open pits are as high as, and often higher than, lateral gradients, so there is invariably a departure from the 'hydrostatic line' where the increase in pore pressure is linearly proportional to the depth below the water table. Geotechnical engineers and mining hydrogeologists alike have realised that over−simplification of pore pressures in slope design models provides an inadequate representation of actual conditions, which may ultimately lead to mine production losses, either from conservatively over−designed slopes (i.e. slopes that are flatter than necessary) or under-designed slopes that fail. For the majority of cases, it is no longer acceptable for the design engineer to use generic criteria such as 'the water table needs to be 50 m behind the slope'. Rarely do such simplistic conditions occur in reality.

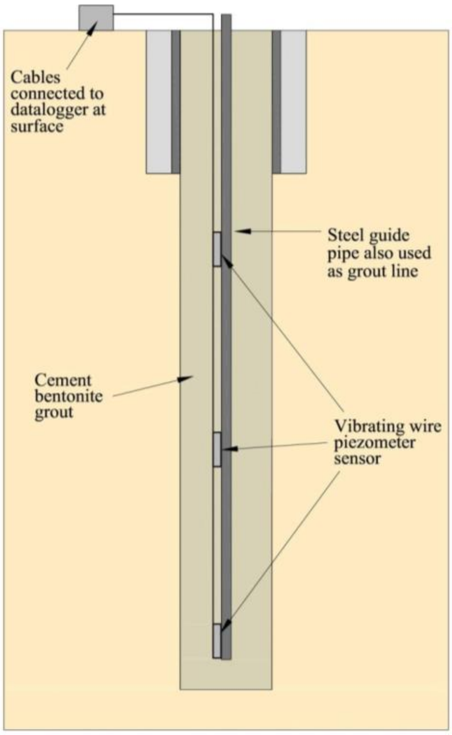


Figure 1 Grouted-in multi-level vibrating wire piezometer installation (source: LOP project)

The third factor that has contributed to an increase in the understanding of pore pressure is the improved knowledge of the slopes themselves. If the geology is properly characterised, the 'weak points' in a slope that may create future instability can often be identified early in the overall investigation program, so that the hydrogeology can be focussed on these areas (Figure 2) rather than using a 'shotgun approach'. Instrumentation can now be installed to measure pore pressure and geotechnical parameters at the same interval in the same drill hole.

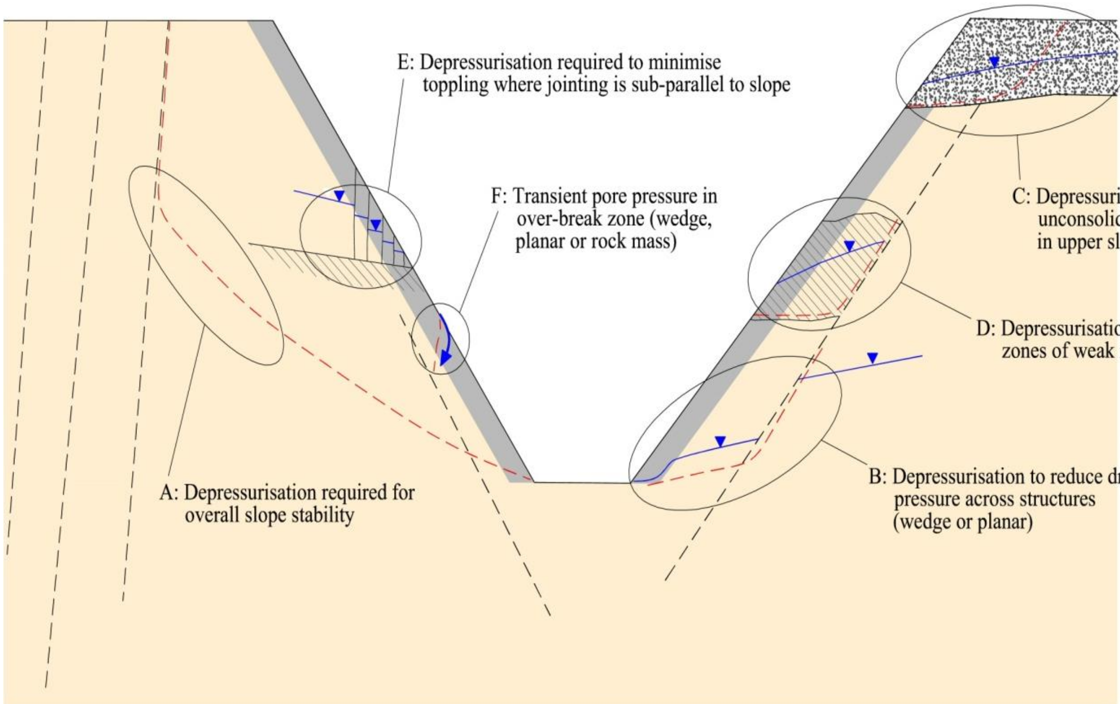


Figure 2 Focussing the hydrogeology program on potential failure modes (source: LOP project)

The amount of coupled data from pit slopes is still quite limited, but a good example is shown in Figure 3. The quality of such data will undoubtedly increase over the coming years and will allow previously non–validated theories of hydromechanical coupling and pore pressure response to be understood in greater detail.

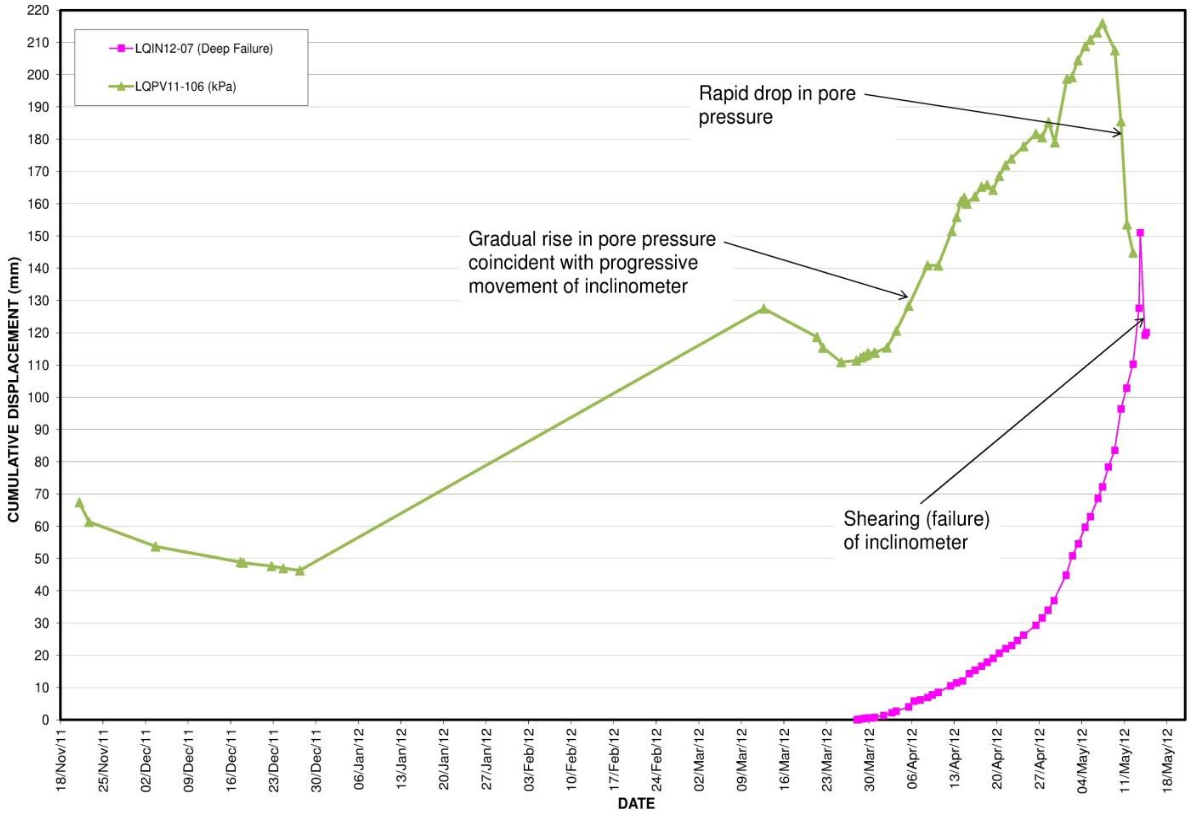


Figure 3 Example of coupled monitoring data (source: Minera Yanacocha SRL)

Along with these three factors is the demand for ever more stringent design criteria as pit slopes get higher, the technical challenges become greater, and safety and production requirements become more demanding. Drilling capacity has also improved so that the length and orientation of both investigation holes and drainage holes can be more flexible, with the ability to focus on key hydrogeological features. However, the ease of in-pit access for drilling has generally reduced because of more stringent safety procedures and it is now often necessary to design access into the mine plan well advance of the time that the actual drilling may be required.

3 Controls on pore pressures in pit slopes

Research carried out for the Large Open Pit (LOP) project has identified that the most important factor for predicting the distribution and behaviour of pore pressures is how the pit slope interacts with the wider-scale site hydrogeology and, in particular, recharge from outside the slope domain. Recharge can take the following forms.

1. Infiltration of incident precipitation or local runoff on the slopes themselves.
2. Recharge from an adjacent surface water body.
3. Recharge from more permeable groundwater units that may occur outside the pit.
4. Artificial recharge from tanks, pipes, diversion ditches, etc.

In some settings, recharge can move en masse into the slope domain from adjacent formations. Attempting to remove this water from point sources (drain holes or pumping wells) can require a large amount of drilling, particularly in lower permeability formations where the areal influence of any one hole is low. Therefore, general worldwide experience has demonstrated that, wherever it is practicable, the interception of recharge before it reaches the slope domain is often the most effective method of pore pressure control. In wet climates, this may mean the implementation of a good in-pit surface water management program.

There is no generic model for pit-slope depressurisation, but there are common factors and processes that must be evaluated as part of the pore pressure characterisation program. In addition to the evaluation of recharge, these are:

1. Evaluation of the water balance of the slope:
   - What is the balance between water entering the slope and water discharging from the slope?
   - How may the water balance change with time as the slope is progressively excavated?
   - Will a pushback of the slope cause new hydrostratigraphical units to be encountered?
2. Understanding compartmentalisation:
   - Is the structural regime causing lateral or vertical compartmentalisation of the slope?
   - Do different parts of the slope need to be dealt with differently?
3. Evaluation of the discharge pathways:
   - Are there natural permeable drainage pathways that provide the potential for water to discharge from the slope at a greater rate than it may enter the slope (resulting in lower heads)?
   - Are these sufficient to create the desired level of depressurisation, or do additional discharge pathways need to be created by installing wells or drains?
4. Understanding the behaviour of the local-scale rock mass and fracture network:
   - How do 'point permeability' data from packer tests and other in situ measurements relate to the 'global permeability' at a scale greater than the immediate area of the drill hole?
   - Is there sufficient permeability in the rock matrix or fracture network for the water to drain into the permeable discharge conduits?
   - If the permeability or connectivity is too low to achieve the desired drainage, will deformation of the fractures as a result of lithostatic unloading lead to depressurisation at a sufficient rate?
5. Evaluation of any localised zones of low permeability:
   - Are there zones of clay alteration, or zones of very low fracture permeability, where a significant lag in the drainage time can be expected?
   - Does the surrounding higher permeability rock mass need to be drained at an advanced rate to provide sufficient time to allow these less permeable zones to depressurise?
   - How can recharge entering these lower permeability zones be minimised?
6. Understanding the importance of transient pore pressure:
   - Is the climate such that seasonal variations in pore pressure need to be considered, either further behind the slope in the saturated zone or at shallow levels in the unsaturated zone?
   - What is the nature of the slope materials, and are there sectors of the slope that may potentially be susceptible to rapid increases in pore pressure at shallow levels where the proportional effect on effective stress may be greater?

- ○ Is it necessary to implement a program of surface water or shallow groundwater control to reduce the potential for seasonal infiltration and therefore reduce the transient build-up of water pressure in the shallow zone behind the pit face?

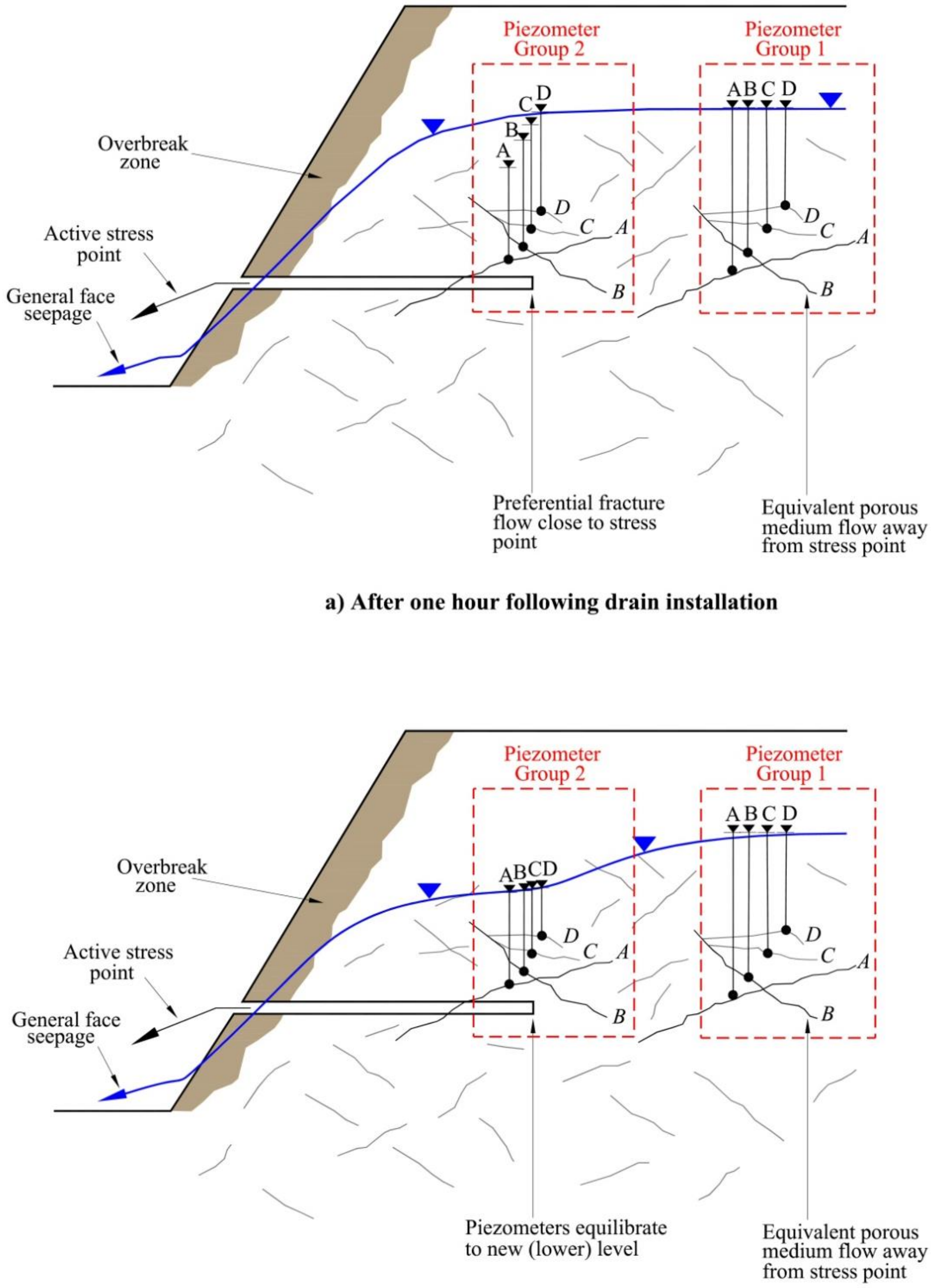
4 Application of a continuum approach

The evidence from most monitoring installations throughout the worldwide mining industry is that, for the majority of settings, pore pressure occurs as a continuum within the main individual structures that cut through the rock mass and the mélange of lesser joints and microfabric of the rock mass between the main structures. At the scale of any practical field measurement or modelling, most rocks can be considered as pervasively fractured, with some form of discontinuity occurring in the rock fabric at least every metre, and most commonly with many discontinuities per metre.

Slope depressurisation measures typically target the major structures or permeable features, and the rate that depressurisation occurs is governed by how many permeable features occur, how these ‘arteries’ extend through the rock mass, and also on the permeability and interconnection of the subordinate joint sets that drain into these features. When new hydraulic stresses are applied, clearly there will be a lag time between the rapid response in the major features and the slower dual-porosity type response in the lower order (smaller) fracture sets. The continuum condition may be disrupted for this period, as illustrated in Figure 4. However, for each new applied stress, the condition eventually becomes re-established. Where the drainage response is lagged by greater than about a week, it usually indicates that the piezometer in question is either (i) too far from the stress point, (ii) on the other side of a barrier boundary to the stress point, or (iii) within rock that has been mineralised or altered resulting in the softening of the rock and healing of the fractures.

Unless modelling of the pore pressures is to consider small block sizes (less than about 20 m) and short time steps (less than about a week), the system can be treated as a continuum. For depressurisation, a conservative approach is to use the pore pressure in the rock mass (smaller ‘D’ fractures in the Figure 4) because the pore pressures in the smaller fractures will temporarily higher than the main structures. However, for re-watering, or where there is recharge into the slope along discrete features, the pore pressure in the main structures may be higher than that in the rock mass, so it may be appropriate to simulate these features discretely.

For the majority of ‘everyday’ situations, it is not practical to characterise each individual fracture set, particularly considering that most fractures are variable along their length. The overall groundwater transmitting capacity is controlled by ‘pinch points’ within individual fractures or by their interconnection with other fractures. This tends to validate the approach of using a continuum (or equivalent porous medium) approach to simulate flow within fractured rock systems. Where individual faults or stratigraphical horizons are judged to be important, and where they can be characterised, they can be added as discrete features within the continuum model.



a) After one hour following drain installation

b) After one week following drain installation

Figure 4 Illustration of the transition between non-continuum (upper) and continuum (lower) conditions (source LOP project)

5 Determining the need for slope depressurisation

Groundwater pressure is the only geotechnical parameter in pit slope engineering that can readily be modified. The following are key considerations for deciding whether to implement an active slope depressurisation program.

1. What are the hydrogeological conditions?
   - Will drainage occur passively, or would there be economic benefit of an active program?
   - Is the permeability of the wall rocks such that an active depressurisation program can achieve the desired results in the time available?

2. What are the geotechnical properties of the wall rocks?
   - Would an active slope depressurisation program increase the strength of the materials sufficiently to permit an increase in the slope angle?
   - Will the control of water reduce seepage-induced erosion or mitigate piping or deformation of the softer materials within the slope?
3. What is the nature of the geological structures?
   - Would depressurisation of the identified structural zones lead to reduced risk of failures associated with shearing or toppling?
   - Will the structural zones provide conduits to enhance the recharge to the wall rocks?
4. Is it necessary to reduce the amount of recharge to the slope materials to allow them to depressurise more efficiently?
   - Is the rate of recharge sufficiently high that the slopes will not depressurise unless the recharge source is cut off?
   - Is it necessary to protect the weaker, more deformable materials exposed in the slope from continuing infiltration of surface water?

General mine dewatering and pit slope depressurisation are closely linked. A mine dewatering program will typically benefit the stability of the pit slopes. However, it is normal that, even if the pit is successfully dewatered, residual water pressures may remain in certain sectors of the slopes, so that a specific pit slope depressurisation program may be required. For a large number of pits, it is not possible to achieve the required pit slope pore pressure goals without the operation of an efficient general mine dewatering system.

As mining proceeds, it is common that steep hydraulic gradients may develop across primary and secondary structures and 'stair-stepping' of pore pressures has the potential to create destabilising conditions, particularly for those structures that have an adverse dip into the wall. The mine structural geology model should therefore be used to identify primary and secondary structures and feed the information into a kinematic analysis to provide 'focus areas' for slope depressurisation.

Benchmarking and judgment based on past experience are important in making a practical decision. The first step is to carry out a basic characterisation of field conditions.

6 Mining-induced changes

Mining may result in changes to the hydraulic properties of the slope materials in four ways:

1. Changes induced by mining and mechanical excavation. These predominantly result from the shock wave during blasting, and create the 'over-break' zone, which may typically be 5 to 40 m in thickness. In addition to this, the pressure wave resulting from the blast may move through the inter-connected fracture network and create fluid-to-solid hydromechanical changes, and these may propagate deeper into the slope than the mechanical effects of the shock wave.
2. Deformation caused by removing the weight of the overlying materials (lithostatic unloading). This may create solid-to-fluid changes ('direct coupling'), which most typically create an expansion of the fracture aperture and pore space, and consequently cause a reduction in pore pressure. Because of the low porosity of most fractured rock masses and the high bulk modulus of water, there is potential for significant drops in pore pressure to occur as a result of unloading. However, in reality, large pressure reductions are seldom observed in fractured rock because transient flow of water occurs towards the depressurised area to equalise the pressure drop. The solid-to-fluid changes may also cause an increase in permeability if the deformation also affects the fracture interconnectivity, particularly if there are associated changes in the stress patterns, which lead to

slippage on the fracture surfaces. As a result, the equalisation of pressure changes can occur quickly, depending on the availability of water in the system.

3. Deformation caused by drainage and reduction of pore pressure. This ‘indirect’ fluid-to-solid coupling may increase effective stress which, in turn, may lead to a reduction in fracture aperture and permeability. It may be permanent or temporary, depending on the nature of the materials. In unconsolidated materials, where the pore space often forms a large proportion of the rock volume, it may create a volume reduction and lead to consolidation.

4. Changes in the hydraulic properties of materials as a result of slope failure. Failure of the slope materials causes changes to the mechanical properties of the intact rock. Although poorly documented in the field, failure is also expected to have a large influence on the hydrogeological properties of the materials.

The research by the LOP project indicates that effects of deformation on pore pressure in fractured rocks start to become important in zones where the permeability is less than 10^{-8} m/s (Read and Stacey, 2009; Galera et al., 2009) and where the diffusivity is less than about 10^{-4} m^2/s.

7 The importance of surface water and shallow (transient) pore pressures

Transient pore pressures occur as a result of short-term changes to the hydrogeological system. They may be:

- Seasonal as a result of climatic fluctuations (wet-season, dry season; frozen, unfrozen).
- Short-term as a result of discrete rainfall events (or blasting events).
- Short-term or progressive as a result of movement of the materials within the slope.

In wetter climates, surface water may cause erosion and back-cutting, and surface water infiltration often leads to the development of transient pore pressures in the shallow zone behind the slope. Groundwater in the ‘over-break’ zone behind the slope may create destabilising conditions when the downslope flow is interrupted by clay layers or where there is adverse (slope-parallel) jointing that has become dilated close to the slope. An increase in pore pressure at shallow levels may be particularly important because of the low confining stresses and the back scarp of many worldwide slope failures occurs at a relatively shallow depth behind the slope. Transient pressures may occur in slope sectors which have no pore pressure for the majority of the year.

The rapid rise in the general number of piezometer installations worldwide will undoubtedly lead to a greater understanding of the relationship between movement of materials within the slope and transient pore pressure changes, and this area of pit hydrogeology warrants further future study.

8 The application of a hydrogeology program

Most mines now incorporate a hydrogeology program at all stages of the mining cycle, driven by engineering and mine economics, and also by increasing regulatory constraints. At an early stage of the mine (or mine expansion) evaluation process (most often pre-feasibility), it is important to implement a hydrogeological characterisation program specifically to help quantify the likely pore pressure conditions in the future pit slopes. The hydrogeologist and geotechnical engineer must work hand-in-hand throughout all stages of the program, and a properly integrated approach will allow:

- Joint hydrogeological and geotechnical boreholes, with mutually beneficial testing programs.
- Piezometers installed in the same holes as inclinometers, TDR systems and other geotechnical instruments.

- Focus of the hydrogeology program on key sectors of the slope based on identified potential failure modes.
- Importation of pore pressures directly from the hydrogeological model to the geotechnical model and interaction between the two models to determine the slope depressurisation requirements for optimal slope design and performance.
- Development of hydrogeological monitoring targets based on the geotechnical model.

A typical approach for implementing a slope depressurisation program is shown in Figure 5. There are six main steps, as follows:

1. Defining the framework and planning the program: For the majority of mine sites, and even Greenfield sites, there is ample existing data available to provide an early assessment of the key issues and to allow an integrated program to be planned. Benchmarking with other operations is important at all stages of the program and a good comparison to other similar sites can add considerable value to the early stages of the program.
2. Data collection and characterisation: This is an on-going process through all stages of the operation and much of the hydrological data required for the pit slope evaluation can be gained by ‘piggy-backing’ on the ore-definition and geotechnical investigations. There is a tendency to over-use conventional packer tests in slope depressurisation studies. Such short duration, single−hole tests typically provide information only for the local-scale in situ permeability of the material or fracture systems immediately surrounding the well bore. However, the overall groundwater flow system is controlled by the broader-scale bounding features, and particularly geological structures, which are not possible to characterise in the field by single-hole testing. Therefore, knowledge of the groundwater system can only be determined from a testing program that places hydraulic stress at one (or more) location(s) and allows the response to that stress to be measured at other surrounding observation points.
3. Development of a conceptual model: This is the most important part of the program. If the conceptual model is not correct, the subsequent numerical model, implementation and monitoring programs will lack focus. For the conceptual model, it is essential that the pit slopes are evaluated within the context of the wider site-scale hydrogeology.
4. Development of a numerical pore pressure model: The mining industry has come to realise that poorly focussed numerical models provide misleading results, so it is essential that any numerical modelling is under-pinned by a good conceptual model, is focussed on the decisions that need to be made, and is benchmarked against other mine operations. The output from the numerical model may be a simple water table (phreatic surface). However, for most situations a 2D or 3D pore pressure grid is preferable for simulating both lateral and vertical pore pressure gradients. The pore pressure model output can be imported directly into the geotechnical model, and the two models must be used in parallel to determine achievable pore pressure targets that will form the basis for the slope design.
5. Implementation of the depressurisation program: There are numerous permutations for slope depressurisation, but the basic components of the system can be divided into six categories: (i) passive seepage, (ii) horizontal drain holes, (iii) vertical or inclined drain holes, (iv) pumping wells, (v) drainage tunnels, and (vi) surface water management (typically required for mines where the mean annual rainfall is greater than about 250 mm/year). Selection of the preferred combination relies on a detailed understanding of materials and pressure gradients within the slope, the cost−benefit of achieving the anticipated pressure reduction, and in-pit access considerations (Figure 6).
6. Monitoring and reconciliation: If the pit slope design is predicated on achieving a given future pore-pressure profile, it is important that year-by-year pore-pressure targets are developed to

ensure depressurisation is occurring at the desired rate. The final slope design must include piezometer installations in the most critical areas for slope performance. Target pressures would then be developed for each piezometer, for each year of mine operation.

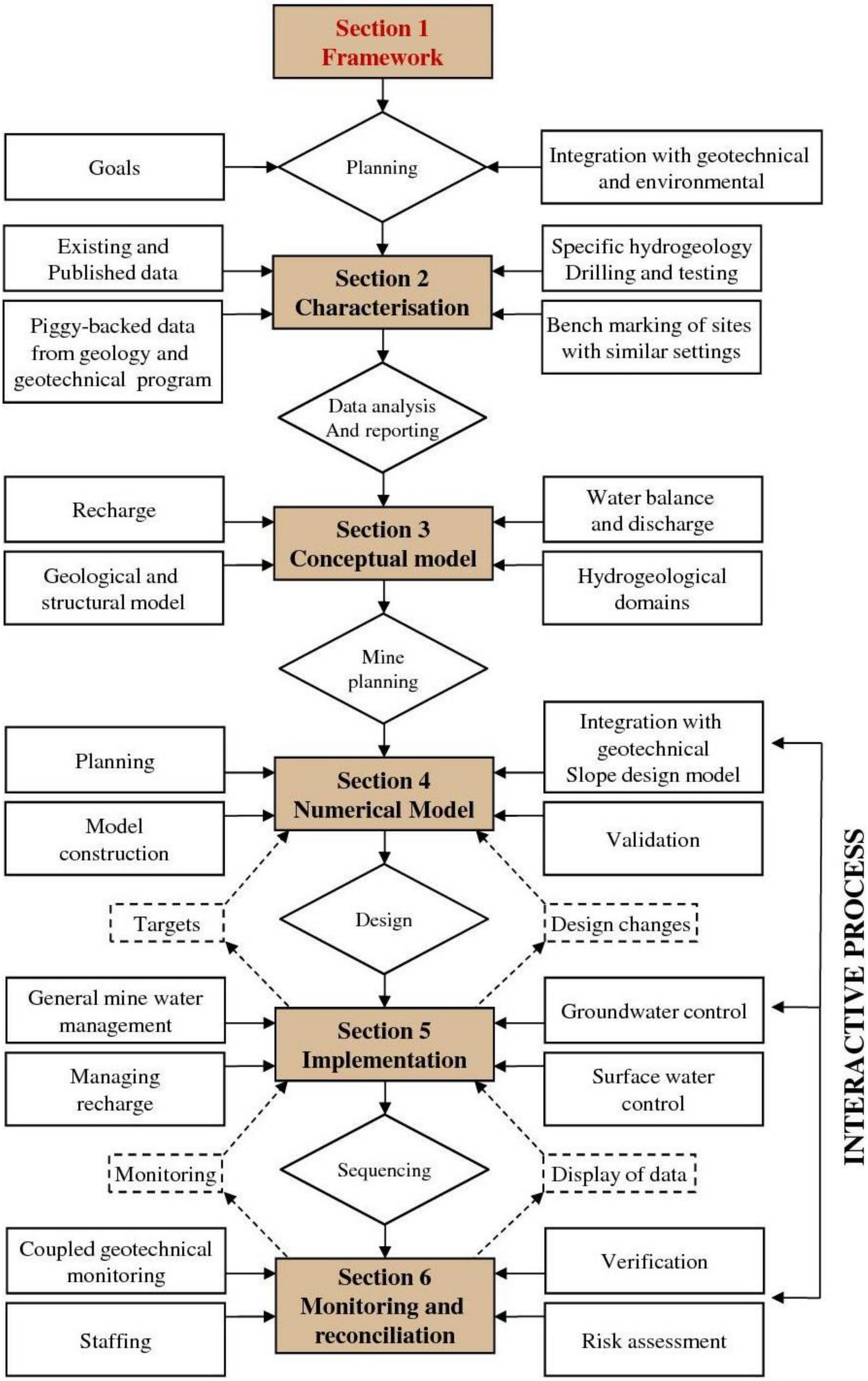


Figure 5 **Approach for pore pressure studies, implementation and monitoring (source LOP project)**

Figure 6 Installation of in-pit pumping well for slope depressurisation

Acknowledgement

This paper draws partly on research carried out for the Large Open Pit Mining (LOP) project. Some of the material within the paper is excerpted from the forthcoming book 'Guidelines for the Evaluation of Water in Pit Slope Stability' being published by CSIRO for the LOP project.

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