Planning of
Integrated pit slope depressurization programs

Geoff Beale, March 21st 2013
1. Operational aspects:
   - The presence of water causes:
     - Loss of access to all or part of pit
     - Greater use of explosives
     - Inefficient loading: equipment wear
     - Inefficient hauling: trafficability, tyre wear, weight of ore, inefficient hauling
     - Compromises safety

2. Pit slope stability:
   - Water pressure (pore pressure) reduces effective stress and has a detrimental effect on pit slope stability
The cost of „wet mining“
The role of pore pressure

1. Changes the effective stress of the rock mass
2. May cause a volume change in the material
3. May cause a change in hydrostatic loading

Pore pressure is the only parameter in a rock slope that can be readily changed
1. Framework

- Goals
- Integration with geotechnical and environmental

2. Characterisation

- Existing and Published data
- Piggy-backed data from geology and geotechnical program
- Data analysis and reporting
- Specific hydrogeology
- Drilling and testing
- Benchmarking of sites with similar settings

3. Conceptual model

- Recharge
- Geological and structural model
- Water balance and discharge
- Hydrogeological domains

4. Numerical Model

- Planning
- Model construction
- Integration with Geotechnical slope design model
- Validation
- Design changes

5. Implementation

- General mine water management
- Managing recharge
- Groundwater control
- Surface water control
- Monitoring
- Sequencing
- Display of data

6. Monitoring and reconciliation

- Coupled geotechnical monitoring
- Staffing
- Verification
- Risk assessment
The requirement for pore pressure control
Dewatering vs slope depressurization

General mine dewatering:
- High permeability
- Objective is to lower the “water table”
- Minimize water in workings
- Often high volume
- Normally pit-wide

Slope depressurization:
- Often low permeability
- Objective is to increase the effective stress of the slope materials
- Normally low volume
- Often local to a specific slope sector
- But not effective without general mine dewatering
Types of instability – focussing the program

A: Depressurization required for overall slope stability

B: Depressurization to reduce driving pressure across structures (wedge or planar)

C: Depressurization of unconsolidated material in upper slope

D: Depressurization of isolated zones of weak material

E: Depressurization required to minimise toppling where jointing is sub-parallel to slope

F: Transient pore pressure in over-break zone (wedge, planar or rock mass)
Goals of program – an example

1. Depressurize the overall slopes
   - Goal is to minimize the potential for slope-scale instability
   - Still reasonably good overall depressurization
   - Dewatering effort needs to be maintained as Phase 6 wall comes down
   - Horizontal drains required in most sectors for Phase 6
   - Focus for 2013 on NE, E, SE, S, SW walls

2. Depressurize behind adverse structures (inter-ramp scale)
   - Stair-stepping of pore pressures across primary structures, particularly in NW and SE walls
   - Potentially creates inter-ramp scale instability (NE wall, F55, F25)
   - More robust structural model required to identify secondary structures
   - Feed into kinematic analysis to provide future focus areas for drain holes

3. Reduce occurrence of shallow failures
   - Majority of failures to date have been “skin” type failures (30-40 m deep)
   - Trigger is often surface water and/or shallow interflow
   - Caused by relatively modest transient pore pressures increases and/or erosion and back-cutting
   - Improved surface water management required for remainder of mine life
Cost-benefit analysis

In many cases, lower pore pressure means:

1. Improved slope angle and less mining of waste
2. Improved FoS and slope performance

The cost is always on the “radar screen”
We do a poor job quantifying the benefit
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- Monitoring display of data

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The problem

- Hydrogeologists and geotechnical engineers try to use point measurements to predict bulk-scale behaviour.

- For the hydrogeologist, cross-hole testing provides an opportunity to move away from traditional single hole procedures.

- The geotechnical engineer can increasingly use downhole technology that provides 2D or 3D penetration of the formation:
  - Elastic and rock strength properties from dipole array sonic and bulk density.
  - Fracture Network Characterization from borehole imaging.
  - State of stress/strain from dipole array sonic, borehole imaging, wireline-conveyed packer hydraulic fracturing, fiber optic strain.
  - Mechanical Side-Wall Coring for full lab geomechanical analysis.
Technology used in field programs

- HQ and RC drilling
- “Piggy-backed” data collection
- Integrated geotechnical/hydrogeological data collection
- Directional drilling
- Downhole characterization
- Cross-hole testing
- Westbay instrumentation for multi-port testing
Westbay instrumentation

- Multi-level piezometers monitored: 1) during slug testing, 2) during HW pumping test, and 3) during FW pumping test

25 March 2013

Courtesy Texas A&M University
"We currently discard about 75% of all geotechnical information because of the subjective nature of our logging and testing procedures"
Downhole characterization program

1. Slimhole wireline tools in (HQ or RC) mineral exploration holes – use 20-30 holes
   - Bulk density
   - Lithology
   - Bulk porosity, water content, estimated perm.
   - Discrete fracture evaluation (orientation, intensity)
   - Elastic properties (calibrated to some core analyses)
   - Estimated strength (UCS, tensile – calibrated to some core)
   - Overburden stress
   - Indicator of horizontal stress orientation

2. Additional wireline tools in 6-8 custom drilled holes (6 ½ inch or larger RC)
   - Improved lithology/mineralogy
   - Cu ore grade (+ other elements of interest)
   - Matrix water storage (bound and moveable water), permeability
   - Improved fracture evaluation (including fracture aperture/estimated transmissivity)
   - Improved strength estimates (including 3d anisotropy)
   - Principal horizontal stress orientations and magnitude
   - Discrete depth pore pressure, permeability, and groundwater samples
   - Wireline sidewall core for lab geomechanics testing
   - Geologic structure from cross hole geophysics

3. 3D integrated high resolution and block model produced from data
Schlumberger Key Logging Technologies – Geomechanics

Electrical Imaging/ Ultrasonic Imaging
FMI (Fullbore Formation Micro-Imager), UBI (Ultrasonic Borehole Imager)
- Rock structures, fracture aperture, texture, heterogeneity and facies analysis, secondary porosity analysis, borehole geometry

Array Sonic
DSI (Dipole Shear Sonic Imager), Sonic Scanner, slim array sonic
- Elastic properties, rock strength, stress orientation & anisotropy

Litho-Density
TLD (Triple Detector Litho-Density), slimhole litho-density
- Bulk density, total porosity, lithology, thin bed delineation

Modular Dynamics Testing
MDT (Modular Dynamics Tester)
- Mini-hydraulic fracturing for minimum stress, rock strength
- Pore pressure profile, packer testing and fluid sampling

Sidewall Core Sampling
XL-Rock (Large-Volume Rotary Sidewall Coring Service)
- 1.5-in-OD by 2.5-in-long sidewall core samples equivalent to conventional core plugs
- Core for full lab geomechanical and petrophysical analysis

Core Scratch Testing (at lab)
TerraTek Mechanical Properties Profile Service
- Continuous, high-resolution UCS over entire core interval
Current logging capabilities

- **RC and HQ (20-30 holes)**
  
  Litho-density, array sonic, porosity/water content, resistivity, elemental spectroscopy, borehole fluid temperature, gamma ray, SP, caliper, acoustic imaging

- **6 1/2-inch RC (6-8 holes)**
  
  All tools, including litho-density, porosity/water content, resistivity, gamma ray, SP, electrical and acoustic imaging, dipole array sonic, wireline packer testing and sidewall coring, elemental spectroscopy, borehole geometry (oriented 3D profile)
Image Log Analysis for 3D Fracture Network

**Observed Data**
- FMI Image Fracture Analysis
- Stereonet Analysis of Fracture Sets

**Discrete Fracture Modeling Based on Data Analysis**
- Modeled vs. Observed Fracture Sets
- Discrete Fracture Network Model

- Stereonet Filtered Data
  - Fracture Intensity
  - Frac. Intensity
  - Set 0 Set 1 Set 2 Set 3 Set 4 Set 5

- Block/Fragment Size From Modeled Fracture Geometry
Upscale property logs to 3D grid

QC/validate existing data

Rock Strength & Property Logs + Calibration

Fracture Image QC, picking, and interpretation

Import Structure + Property Logs + Fractures Into Integrated Model

Build DFN from fracture sets

Upscale property logs to 3D grid

Distribution of Poisson's ratio controlled by field structures. Also shown are wellbore trajectories (solid straight lines).
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- Data analysis and reporting

3. Conceptual model

- Piggy-backed data from geology and geotechnical program
- Recharge
- Water balance and discharge
- Hydrogeological domains

4. Numerical Model

- Geological and structural model
- Mine planning
- Integration with geotechnical slope design model
- Validation

5. Implementation

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- Model construction
- Integration with geotechnical slope design model
- Design changes
- Design
- Groundwater control
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6. Monitoring

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- Design
- Sequencing
- Display of data
- Verification
- Risk assessment
- Coupled geotechnical monitoring
- Staffing
Integration of data into conceptual model

**Geotechnical Elements**
- Geotechnical Model
  - Geomorphology and Topography
  - Mine Plan and Schedule
  - Geology Model
  - Structural Model
  - Field Programme
    - Drilling and In situ Testing
    - Lab. testing
    - Instrumentation
- Stability Modelling
  - Factors of Safety
  - Pore Pressure Targets

**Hydrogeological Elements**
- Hydrogeological Conceptual Model
  - Geomorphology and Topography
  - Mine Plan and Schedule
  - Geology Model
  - Structural Model
  - Field Programme
    - Climate data
    - Recharge/Discharge
    - Drilling and Insitu Testing
    - Bulk Stage Testing & Instrumentation
- Hydrogeological Modelling
  - 2D Modelling - Pore Pressures
  - 3D Modelling - Pore Pressures

**Output:**
- Pore Pressure Estimates
- Depressurisation Measures
- Integrated Pit Slope Design
1. Evaluate relevant material from literature search
   • Information from other industries (nuclear, hydrocarbon, construction, academic research)

2. Detailed analysis of data from main case study site
   • Identification and analysis of 37 discrete events from Diavik

3. Detailed analysis of data from 9 supplementary case study sites
   • Chuquicamata, RT, Escondida, Antamina, Cortez Hills, Jwaneng, Cowal, Whaleback, La Quinua
   • Review of structural geology models and DFN models

4. Collection, analysis and interpretation of data from 40 other relevant sites:

5. Development of approach for preparing conceptual model

6. Development of approach for preparing numerical model

7. Development of procedures for input of pore pressures into the slope design
   • Different rock types, alteration zones, structural settings, mine site environments
Diavik NW wall – Piezometer installations
Depressurization in a fractured rock mass

The “A-B-C-D” model

Flow response  Unloading response

But:
- How to characterize the pressure distribution?
- Which pore pressures are important?
- What to input pore pressure into geotechnical models?
Effects of blasting

1. Opening of upgradient fractures and increase in pressure
2. Opening of downgradient fractures and drainage
3. Hydraulic jacking

- 26 m of “instantaneous” pressure rise. Similar response to “slug” test
Andacollo Hypogene Pit - Chile

- High strength material
- Intense jointing, but dense and tight
- Material strength not sensitive to pore pressure
- Slope angle controlled by BFAs and berm width
**Overall results of case studies**

Of the 50 sites studied:

- **Recharge** from outside the slope domain was considered to be a key factor for **all of them**, and the “dominant control” for 37 of them.

- The presence of “**discharge conduits**” was considered to be the “dominant control” at 8 of the sites.

- There were 3 sites (Chuqui, RT, CLC) where “**deformation**” was considered to account for over 50% of the pore pressure reduction.

- There were 7 additional sites with evidence that “**deformation**” played a significant role in **part of the slope domain**, but depressurization would not occur without the prior interception of **recharge** (Jwaneng, Yanacocha Sur, Ekati, Bingham Canyon, Lethakane, Mansa Mina, Round Mountain).
Overall results of case studies

- At least 45 out of the 50 sites exhibit Equivalent Porous Medium (EPM) flow characteristics rather than fracture flow characteristics
  - At the scale of field measurement and modelling
  - Sites appear to exhibit EPM characteristics for a block size of 20-40 m and above
  - Preferential fracture flow causes the “A-B-C-D distribution” only close to new stress points, and only until pore pressures re-equilibrate

- Most of the slopes demonstrate vertical head gradients that are >25% of the lateral head gradients
Characterization of pore pressures

• LOP research has validated that:
  • Rock is pervasively fractured at the scale of field measurement
  • Rock is pervasively fractured at the scale of any modeling
  • Piezometer results and modeling indicate pore pressure occurs as a continuum within individual structures and within the pervasive intervening joint and fracture sets
The role of hydromechanical coupling

1. Changes due to mechanical excavation (over-break zone)
   - Shock wave from blast
   - Pressure wave from blast

2. Deformation as a result of removing the weight of the overlying rock
   - Solid-to-fluid direct coupling

3. Deformation caused by drainage and reduction in pore pressure
   - Fluid-to-solid direct coupling
   - Good data from Coaraze
   - Are there any data from actual pit slopes?

4. Changes in hydraulic properties as a result of slope failure
   - Poorly documented in the field

- Few industry examples of hydromechanical coupling
- How important it in reality?
- Potentially only on small time-frame for most examples
- Therefore important for failure analysis
Examples of coupled responses

Middle-Depth Probes - kimberlite & xenolith zones

Ekati: Fox pit Kimberlite

Yanacocha Sur Clay 2 material

No significant recharge in each case

Failed surface water drains

Courtesy of Minera Yanacocha SRL
Stair-stepped depressurization as a result of lithostatic unloading which is directly correlated with the Phase 15 and 16 mine expansions. 

Southeast wall; RadomiroTomic pit, Chile
Six key factors controlling water in pit slopes

1. **Recharge**
   - The most important factor for slope depressurization
   - Even small recharge provides more water than created by drainage
   - How much, where, is it possible to intercept it?

2. **Water balance**
   - Balance between water entering and leaving slope domain

3. **Degree of compartmentalization**
   - Are there discrete zones of groundwater flow that need to be managed differently?

4. **Discrete discharge pathways**
   - Permeable beds or structures
   - Provide drainage conduits for surrounding rock mass
   - Create new ones using wells and drains

5. **Local-scale fracture network**
   - Local scale fracture and permeability distribution
   - Distribution, orientation, permeability, interconnection
   - Balance between water entering and leaving slope domain

6. **Other zones of low permeability**
   - Rock mass alteration
   - Fracture alteration
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EPM vs fracture flow analysis

• EPM approach satisfactory for inter-ramp and overall slope stability analyses

• EPM approach typically valid except in rate cases with:
  • Large blocks
  • Large ratio between fracture and matrix diffusivities
  • Fast excavation rate
  • Small model time steps

• For many of these cases, it is possible to achieve a realistic simulation using an EPM model with discrete features

• Few “everyday” situations where Fracture Flow modeling would add value
Example where discrete flow analysis is required
Steady state vs transient analysis

• Steady state simulation is acceptable in very few cases

• Exceptions are:
  • When excavation rates are slow
  • When permeability is high
  • When recharge boundaries are close.

• Pressures predicted by steady-state analysis usually underestimate the actual pore pressures.
Validated numerical modeling approach

- The use “off-the-shelf” porous medium codes is appropriate for most modeling situations.

- Detailed models can be created, with the model grid populated using:
  - Anisotropy in permeability and porosity
  - Discrete fractures, fault zones, permeable horizons and other features based on the hydrogeological interpretation
  - Dual porosity flow characteristics
Importance of H-M coupling

Becomes important where:

- Permeability $< 10^{-8}$ m/s / Diffusivity $< 10^{-4}$
- Rapid mining (deformation)
- Limited recharge (rare)
- Rapid slope movement (failure)
Coupled modelling
Study for ODX carried out using Eclipse and Visage
Coupling process

- The two codes are coupled as follows:
  - ECLIPSE calculates pore pressures
  - These pressures are passed to VISAGE
  - VISAGE recalculate porosity and permeability based on:
    - the pore pressures and
    - changes in stress (pit excavation)
  - ECLIPSE runs again with these new values
  - These iterations continue on short time steps until the changes in porosity and permeability are minimal

- The code is mass conservative (therefore changes in storage do not introduce erroneous water volume to the model)
Input parameters

**ECLIPSE**
- Intrinsic permeability
- Porosity
- Rock compressibility
- Water compressibility
- Dynamic viscosity

**VI SAGE**
- Young’s modulus
- Poisson’s ratio
- Initial stress condition
- Fracture sets (optional)

\[ K = \frac{k \rho g}{\mu} \]
Simulated strain

Most of the strain is seen in the low strength unit.

Compression occurs at the toe of the slope.

500 x vertical exaggeration to displacement

Contours warped to displacement

Grid unchanged
Lower heads in coupled run. Reduction in total stress results in reduced effective stress acting on rock. This results in dilation of fracture aperture and an increase in storage and permeability.

Different geomechanical properties in these two zones result in different responses to unloading (the change in total stress in this region is constant).
Incremental pore pressure reduction due to unloading
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Methods for slope depressurization

1. Seepage to face and pumping from sumps
2. Horizontal drain holes
3. Angled (oriented) drain holes
4. Pumping boreholes
5. Drainage tunnels

- Surface water control
- Permeability enhancement due to blasting
- Directional drilling
- Barrier technology
Horizontal drain drilling

- Long drains at wide spacing targeting fractures to dewater limestone (high flow)
- Shorter drains at tight spacing to depressurise low permeability altered intrusive in the pit slope (low flow)
Examples of drainage tunnels
Directional drilling for slope depressurization

- Numerous possibilities
- Directional pumping wells
- Potentially small diameter mother and daughter holes for slope depressurization
- Small diameter directional drain holes oriented to target vertical pumping well
Barrier technology

“Passive” barrier technology not routinely applied in hard rock open pit mines:

- Selective grouting
- Grout curtains
- Freeze walls
- Slurry walls

- In each case, the goal is typically to “localize” the treatment

- Major problem is “keying-in” and “underflow”
Flowing gel technology

- Goal is to make the polymer flow as a non-viscous solution, and apply the polymer into the water stream over a wide area of aquifer.

- Once the polymer is in place, the gelling agent within the solution acts to solidify the polymer.

- Retarders can also be included in the mixture to achieve a flow time of up to 30 days, prior to gelling.

- Thus, the system can be used to “treat” large volumes of aquifer.
Typical polymer applications in oilfield

- Reduce water inflow to production wells:
  - Leaks in casing
  - Flow behind casing
- Seal dynamic oil-water contact
- Reduce preferential flow
  - Fracture zones
  - Permeable layers
- Seal fractures cross connecting oil and water horizons
- Seal water-flooded layers to exclude water
  - “Local-scale”
  - “Reservoir-scale”
Example: Foam-gel
Fractured sandstone, Rangely, Colorado (water/CO₂ injection)
1,000 ft well spacing
Change in vertical injection profiles

CO₂ and H₂O injection profiles

Pre-treatment    Post-treatment

Depth (feet)

Volume % injectant entering zones

Pattern Oil Rate (BOPD)

Foam-Gel Treatment I

-126 BOPD / yr
+36 BOPD / yr
. Application holes placed at 20-40 m intervals across the alignment of the palaeochannel.
. Polymer injected into one hole while pumping from adjacent hole to create hydraulic control.
. Hole “pairs” moved progressively across the width of the palaeochannel.
Iron ore mine, WA

1. Objective is the placement of a hydraulic barrier across the southern end of the “palaeochannel” using flowing gels
2. At least half an order of magnitude is required along the line of the palaeochannel
3. OrganoSEAL-F to be placed perpendicular to the line of the palaeochannel to minimise the amount of product required
4. Requirement for high penetration and high volume treatment
   - Typically into more pervasively fractured systems
5. Essential that fracture interconnection is characterised
   - Laterally (directional)
   - Vertically
Characterization

1. Geophysics
2. Boreholes
3. Tracers
   - Use between injector and producer to identify:
     - Fracture interconnection
     - Lateral diffusion
     - Vertical diffusion
     - Travel times
   - Design of polymer application based on test results
POLYMER GELS: PACKAGED SOLUTION

1. Full hydrogeological characterisation
2. The right diagnostic interpretation
3. The right location for the “barrier”
4. Choice of polymer
5. Design of injection and hydraulic control system
6. Compliance with regulatory constraints
7. Controlled pilot testing
8. Expansion of pilot test
Budget cost

Site investigation programme: $450-650,000
(includes drilling, geophysics, tracers, data analysis, modelling and interpretation)

Small-scale pilot: $450-650,000
(between 3 injection points – 50 m interval; assumes 5,000 bbls)

Placement of full barrier: $4-8 million
(across full CID channel; includes drilling additional injection and control points; assumes 75,000 bbls)

Potential savings

Pumping and operating costs: $75 million over 5 years
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Monitoring

• Advent of vibrating-wire piezometer systems has greatly improved our understanding of pit slopes
• Coupled monitoring becoming increasingly common
• However:
  o Still few examples of coupled pore pressure & slope movement monitoring
  o Few examples of H-M coupling
  o Few documented examples of pore pressure behaviour during material failure
VWP Installation – upward holes

- 2 VWP 0-1.7 Mpa and 0-0.7 Mpa
- 230 m signal cable
- 2 Multilevel Housing and Data logger
- PVC pipes and Slit Coupling
- Cement-Bentonite grout
Coupled Instrumentation

- VWP Cable
- Cement-Bentonite Grout
- PQ Diamond Drillhole
- PVC or Steel Tremmie Pipe
- VWP Tips
- Inclinometer Casing
- PQ Diamond Drillhole (123mm Ø)
- Cement-Bentonite Grout
- PVC or Steel Tremmie Pipe (27mm OD, 21mm ID)
- Groves in casing for probe
- VWP Tip (21mm Ø)
- Inclinometer Casing (70mm OD, 59mm ID)

Graph:
- Rapid drop in pore pressure during
- Gradual rise in pore pressure coincident with progressive movement of inclinometer
- Shearing (failure) of inclinometer

Graph dates:
- 18/11/11 to 11/12/12
Monitoring example from La Quinuia, Peru
So..............

1. We have developed theory of how pore pressure effects the performance of pit slopes
   - We are now developing the supporting field data

2. We have developed a good understanding of the mechanisms that control pore pressures in pit slopes
   - Recharge is the most important control

3. New technology may be used to support the slope design studies:
   1. Westbay piezometers
   2. Downhole characterization
   3. Coupled modelling
   4. Directional drilling
   5. Barrier and flowing gel technology
Thanks for your attention