Mining Geotechnics

A glimpse into the Dark Art

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What is the need for Geotechnics in Mining?

Is this cost really necessary?

- Most commonly used in:
    - Pit slope stability analysis and design (at all scales)
    - Box cut and portal design
    - Underground mining method selection and sequence optimisation (rock mass quality, cavability, stress/strain)
    - Stope design
    - Ground support identification

➢ Mining engineers are “downstream clients”

Mining Geotechnics

- Uncertainty
  - ➢Sparse information
  - ➢Practicality important
  - ➢Need for compromise
  - ➢Adaptable scope (methodology)
  - ➢Geology

You have to play the cards
that have been dealt

Compare with Civil Geotech

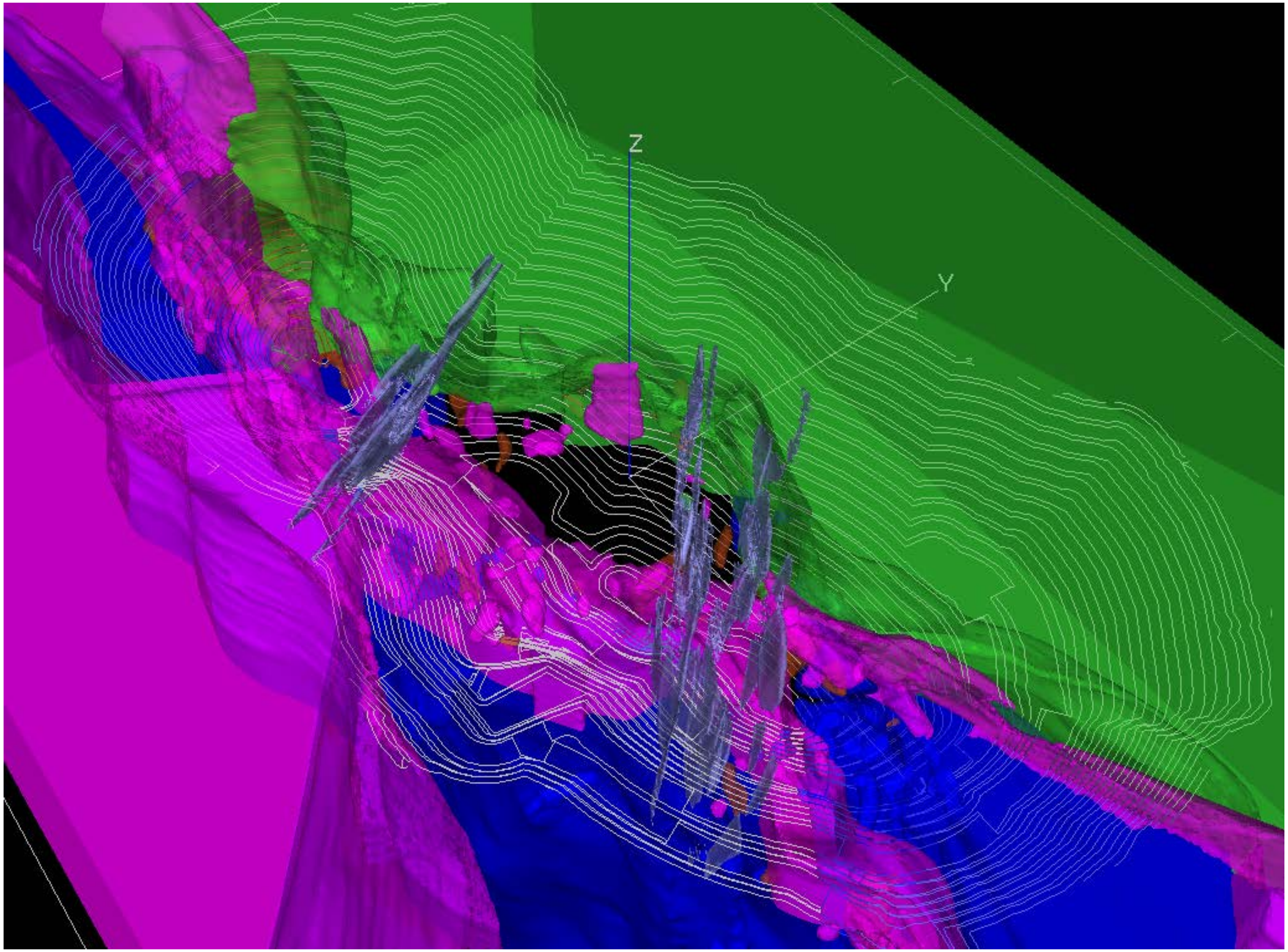
- Excavation scale and depth
- Amendment / control of environment
- Time and budget
- Approach to risk
    - Exposure time (active working environment)
    - Exposure numbers
    - Those exposed

Why the uncertainty?

CSIRO (2011)

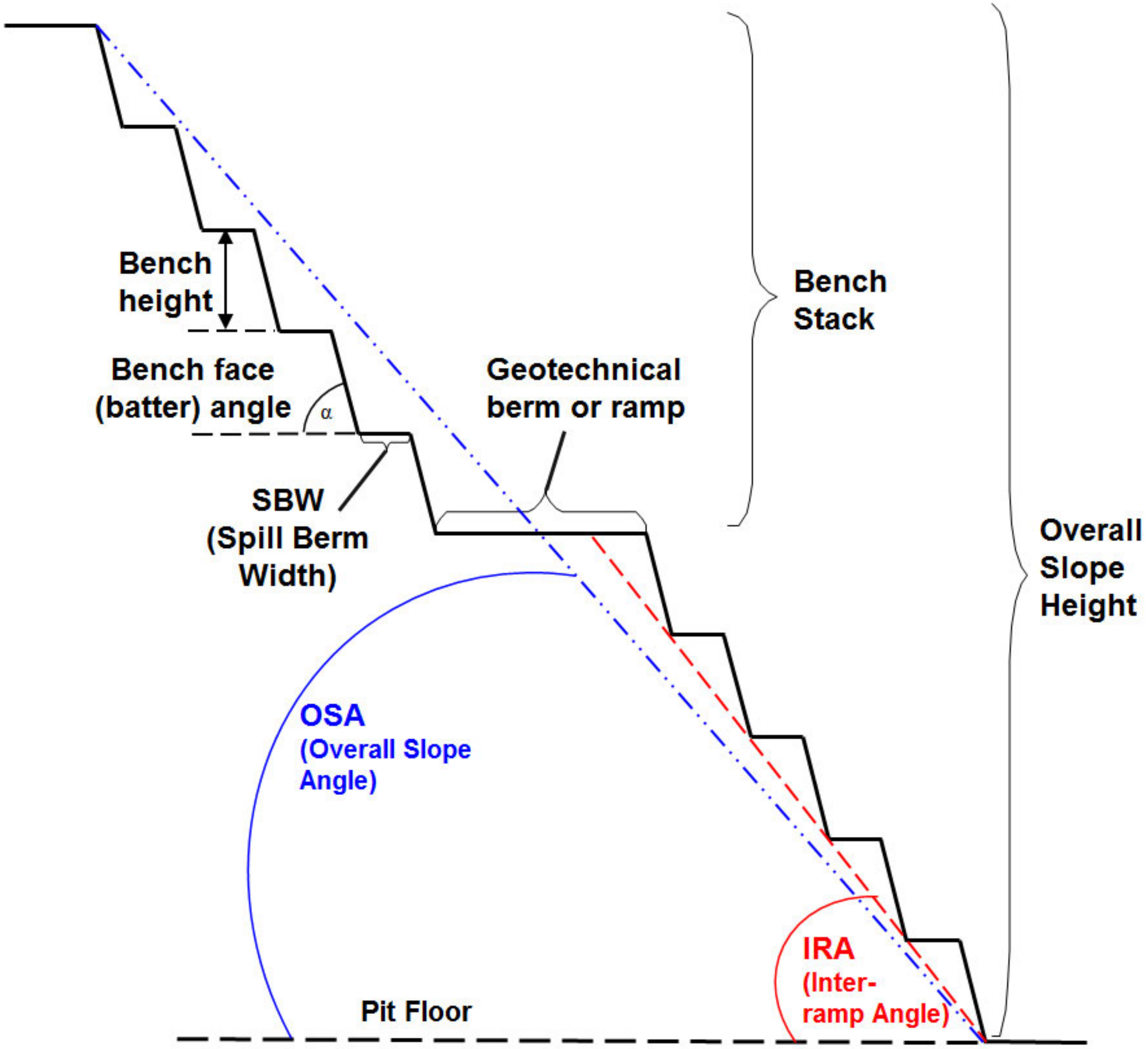
- ✓ Stochastic variability
  - – Uncertainty due to random variation
  - – May be dealt with using probabilistic models
- ✓ Absence of knowledge
  - – Experience / Judgement is required (the essence of the *dark art……*)
  - – Difficult to account for hidden features that may trigger failure

Variability



Pit Slope Design

Sectional illustration of pit slope geometrical elements



Approach

“Cookbook” approaches are perilous

- Every project is unique
- Experience essential
- Need large and varied “toolbox”
- Select correct tools for the job (investigative & analytical)
- Understand sensitivities
- Understand risk *in context*

The Geotechnical Model

“All models are ‘wrong’ but some models are useful”

- George Box

- The aim of geotechnical data collection and interpretation is to provide information that allows for a *useful* understanding, interpretation or “model” to be obtained for the purposes of design or problem-solving.

The Geotechnical Model

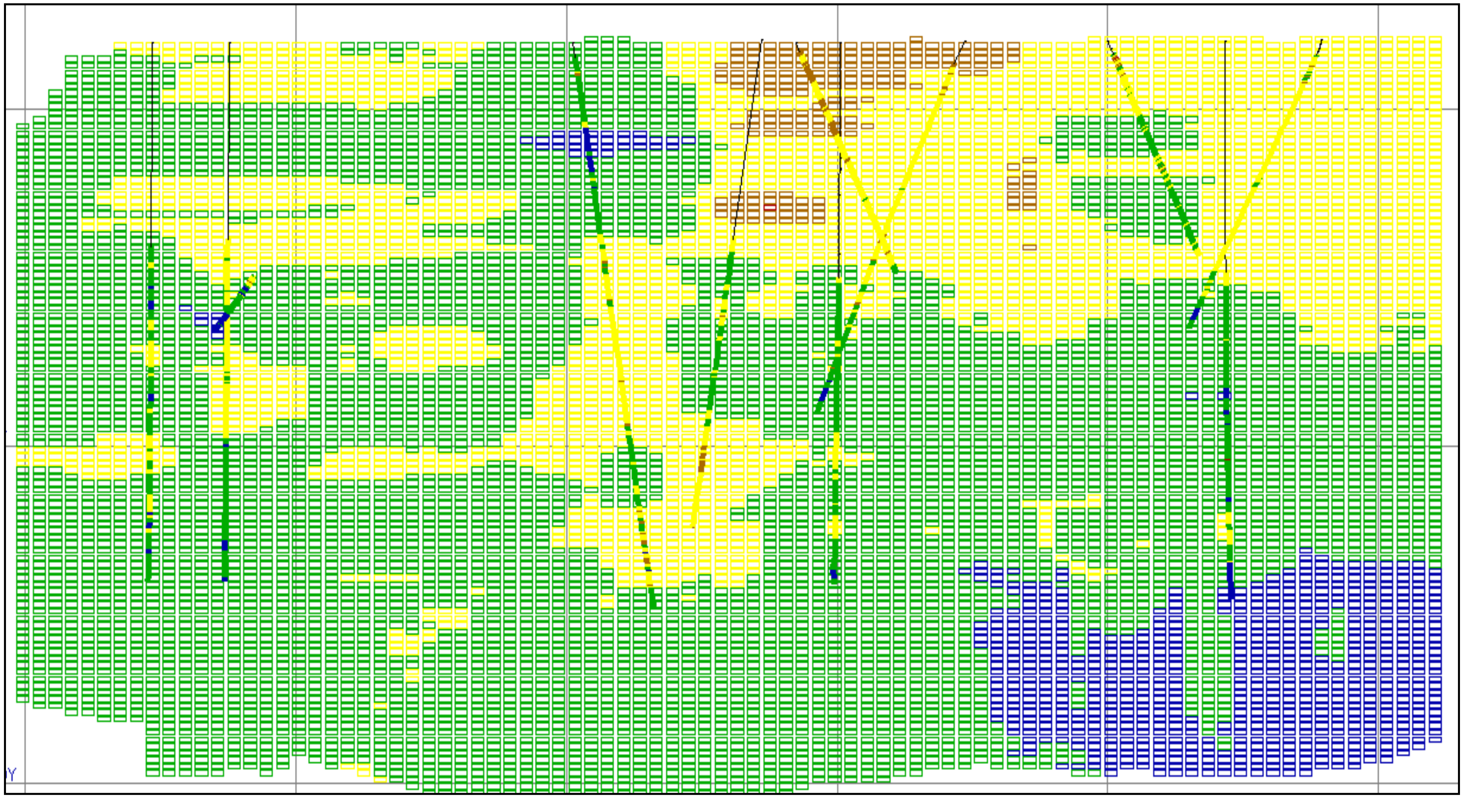
Can the model be used for a *practically*-engineered design?

1) Delineation of: zones of ground in which *geotechnically similar or consistent conditions* occur – Domains.

These may need further rationalisation into zones in which *consistent design inputs* should be applied

The Geotechnical Model

Example of a block model created using geotechnical drillhole logging data

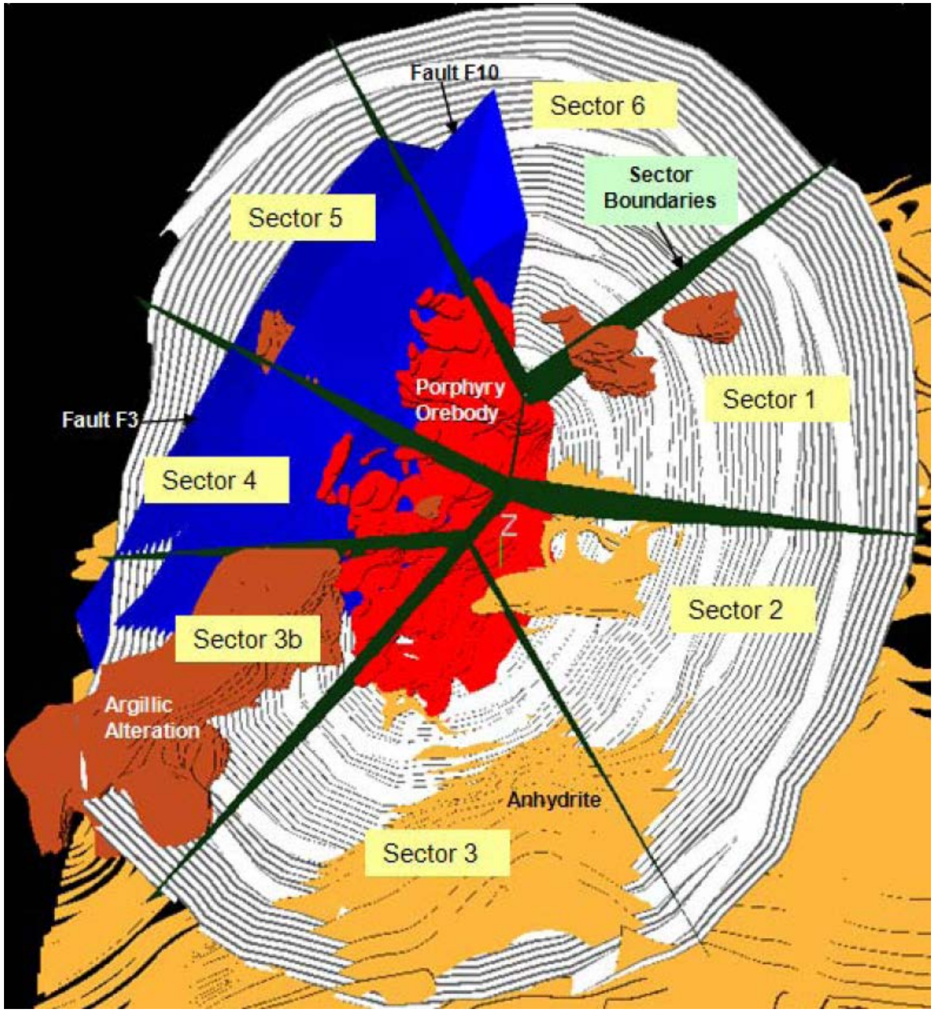


RMR Legend

- 🟥 0 – 20
- 🟫 20 – 40
- 🟨 40 – 60
- 🟩 60 – 80
- 🟦 80 – 100

The Geotechnical Model

An example of rationalisation of the geotechnical / geological model into pit design sectors



The Geotechnical Model

All the input you need for stability analyses and design evaluations

2) Characterisation of Domains

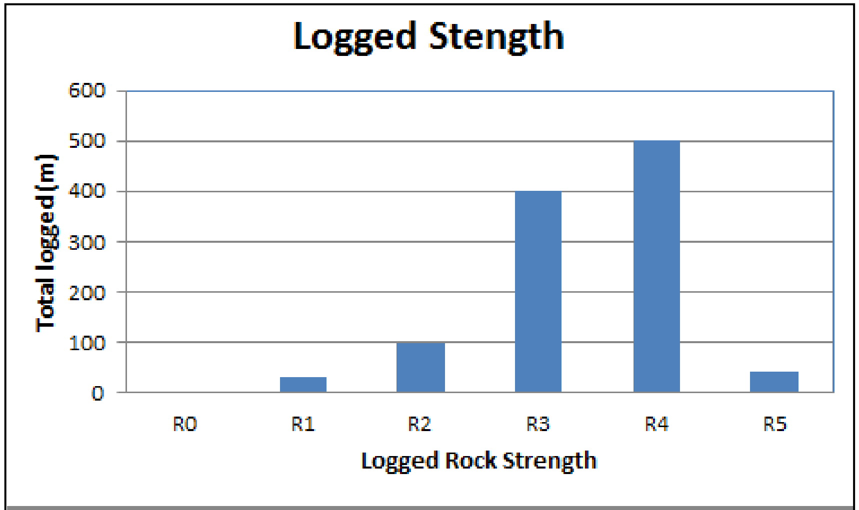
- Rock *Mass* Characteristics
- Intact Rock Characteristics
- Rock *Fabric* Characteristics
- Hydrogeological characteristics

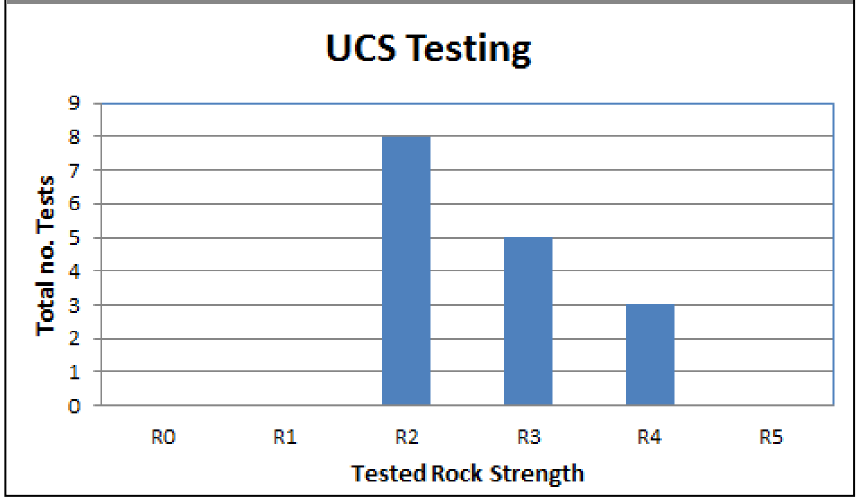
➢ Geology and Major Structural Models are very important inputs for domaining and for stability analyses

Understand your data!

A simple example

A purely statistical approach might not be appropriate



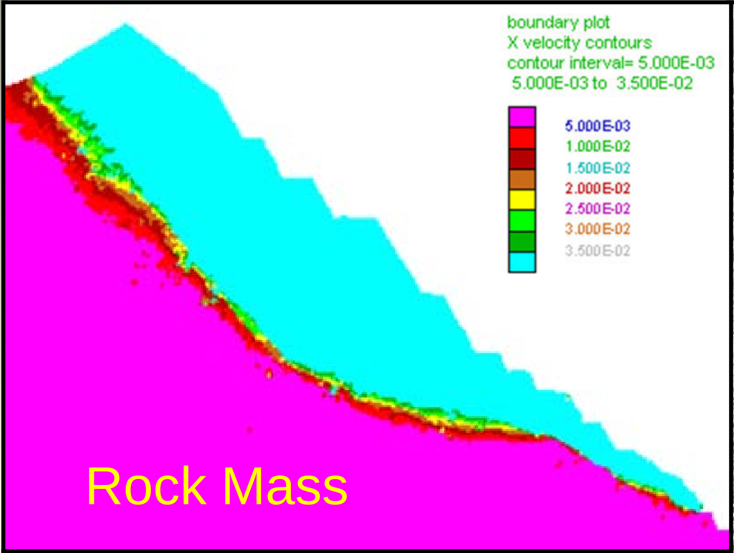


Scale-dependent (to a degree)

Mechanisms of Failure

- Failure development through existing structures, weakness planes (incipient structures) and intact rock
    - o Discrete structurally-controlled failures (sliding, toppling, wedge / block: simple and complex)
    - o Rock mass failures (may require failure of rock bridges)
    - o Hybrid

Mechanisms of Failure



The Investigation

How long is a piece of string?

What constitutes an appropriate density of data?

It depends on:

- Level and purpose of study (Conceptual, Pre-feasibility, Feasibility, Detailed or Working Design)
- Complexity of the rock mass / environment
- Budget and timeline constraints (where compromise comes in…)

The Investigation

Previous investigations for other purposes may also be helpful.

A phased approach to investigations is often beneficial

- The first phase of investigations "sets the scene", allowing for initial interpretations to be made and problem areas to be identified.
- These problem areas may include regions of complex conditions, areas where suitable data is lacking (or has not been able to be collected) or areas where the sensitivity of earlier assumptions needs to be tested/confirmed.

Example: An Iron Ore Project in Western Australia

Overview

- Two proposed Large Open Pits:

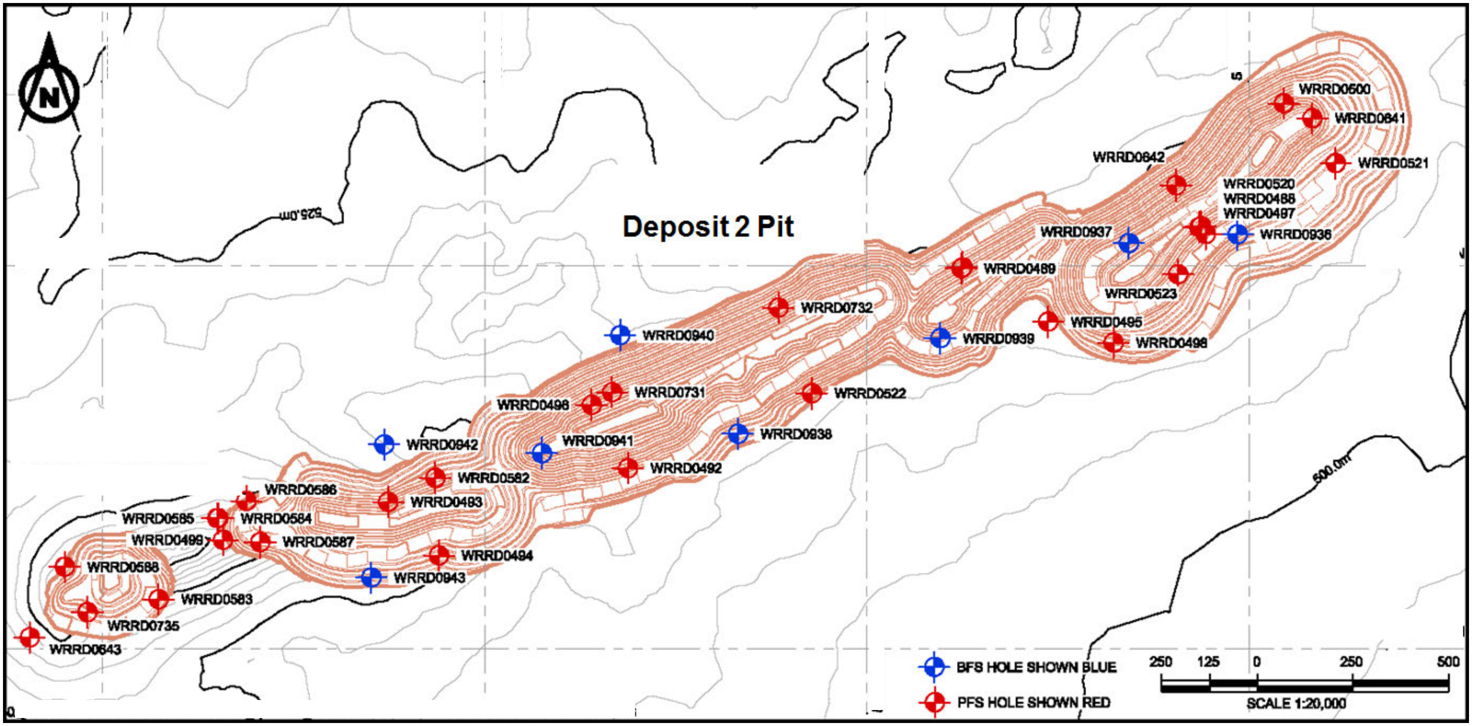
  Each 4 km along strike; 250 - 300m depth

- Strongly developed weathering profile overlying basic igneous rocks and subvertical BIFs resulting in significant thickness of weak saprolite and underlying weathered rock.

- Comparison of outcomes from Pre-feasibility Study (PFS) and subsequent Bankable Feasibility Study (BFS)

Investigation

Illustration of drillholes providing geotechnical information



PFS: 34 geotechnically logged geology investigation holes (in red)

BFS: 19 carefully–targeted additional drillholes (in blue) including 11 holes at Deposit 1 and 8 holes at Deposit 2. Reduced spacing of geotechnical information centres to 300m or less (which is pretty good for geotechnical investigations!).

Geotechnical Model

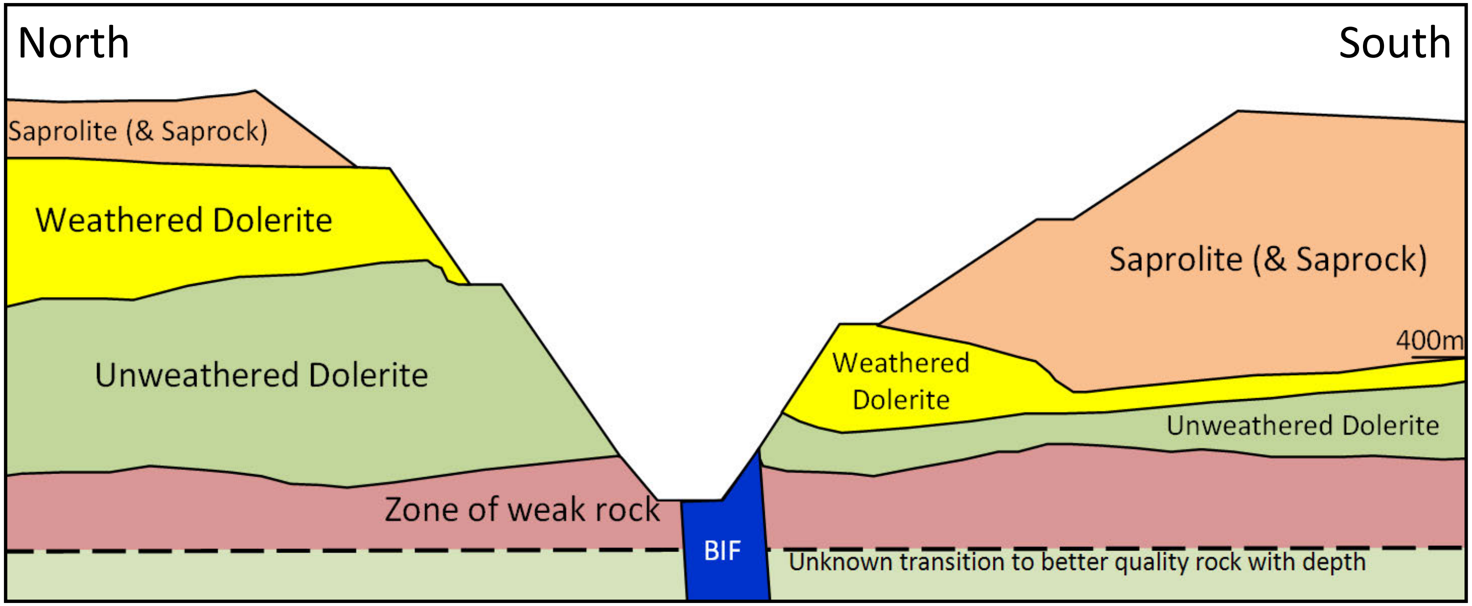
Geotechnical Domaining

- The *positions* of and data provided by the PFS drillholes supported the interpretation of a pseudo-horizontal layering of saprolitic material, weathered rock and unweathered rock (deeper to south of pits)
- Apparent layers of weaker, intensely weathered material at depth

Geotechnical Model

Geotechnical Domaining

Illustrative Cross-Section through Deposit 2 Pit – initial interpretation



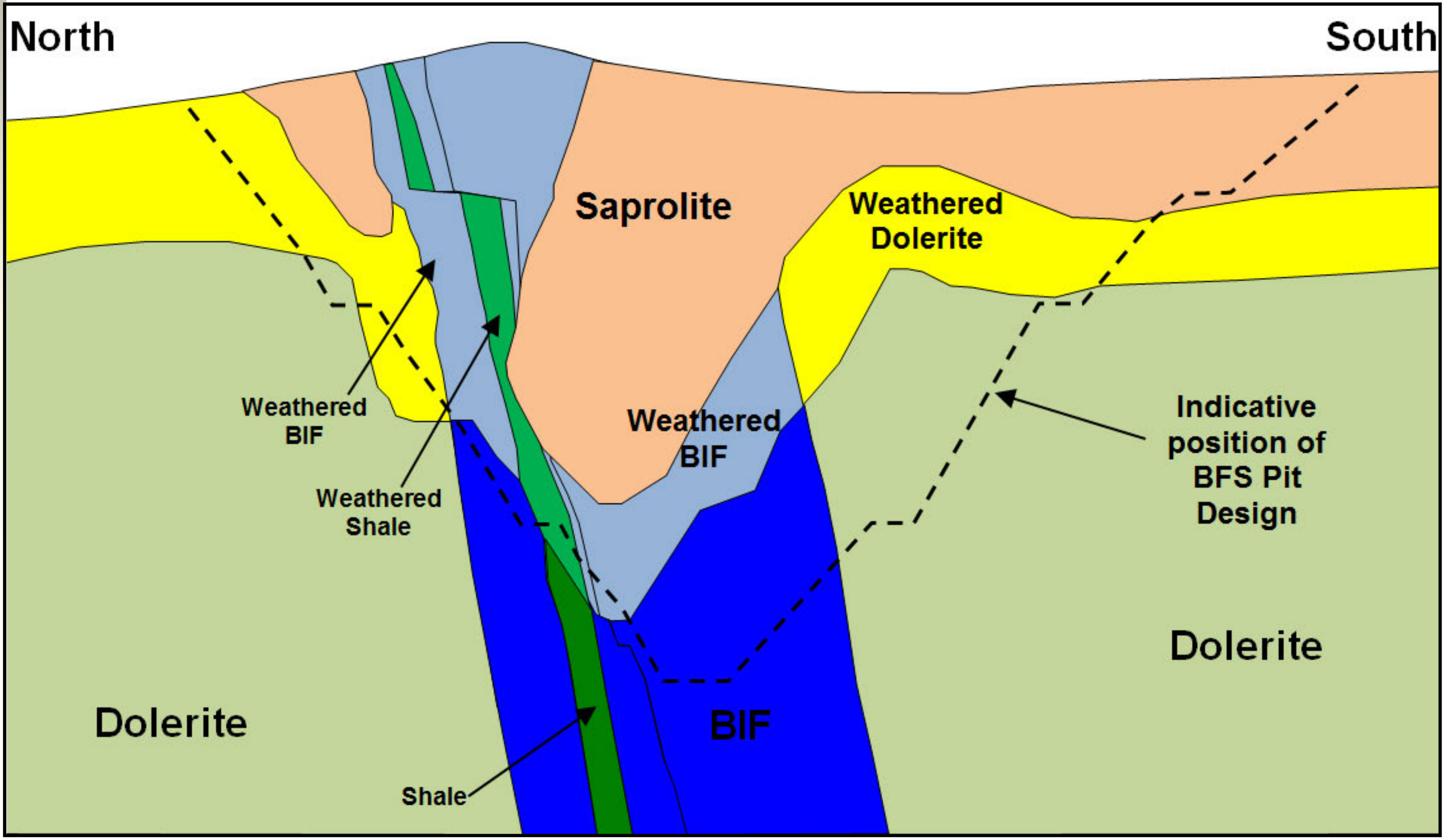
Subsequent Findings

- The PFS study findings were used to plan the BFS investigations
- It was then discovered that:
    - The highly weathered, weak and poor quality material was associated with deep vertical weathering along the margins of the BIF units and at the positions of major fault dislocations.
    - The weak “layers” interpreted at the toe of the PFS pit shell design are therefore not laterally continuous in cross-section

Case Study: Iron Ore Project

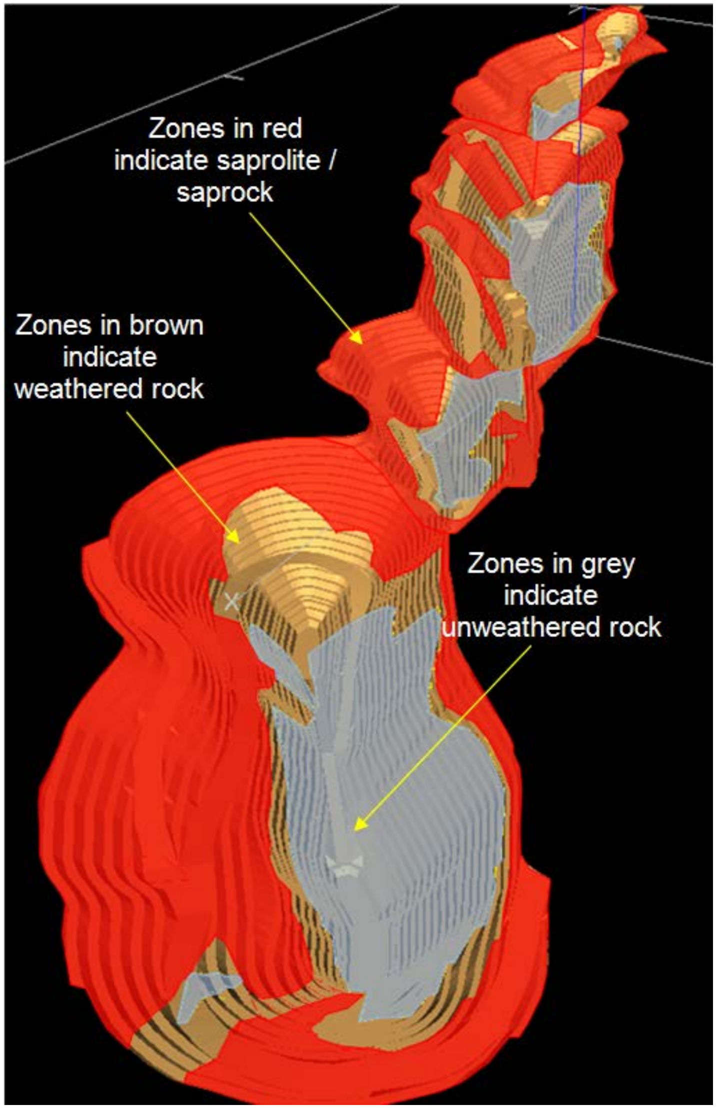
Sections vary significantly along strike

Illustrative Cross-Section through Deposit 2 Pit – revised interpretation



Pit Walls

High lateral variability in conditions



Case Study: Iron Ore Project

A new "ball game" for pit design

- The re-interpreted conditions result in a most complex pattern of interaction between the geotechnical domains and the pit shells.
- The materials likely to be exposed in the pit walls will vary greatly in thickness along strike of the pits, and are highly dependent on the exact position of the pit wall.
- A different design rationale was required to achieve practical pit slope design recommendations to deal with this variability.
- The pit wall designs may need to be significantly altered should the size, width, depth or position of the pits be altered in the future.

The Investigation Toolbox

It is most important to select the right tools for the job

- ❑Rock/soil mass characterisation/classification
  - Geotechnical logging (of diamond core)
  - Geotechnical mapping
  - In situ testing (SPT, permeability testing etc.)
- Intact Rock Properties
  - Geotechnical logging (subjective)
  - Field point load testing (be careful of axial/diametral bias)
  - Laboratory testing

The Investigation Toolbox

Make sure that sufficient time is allowed for data processing and collation / comparison.

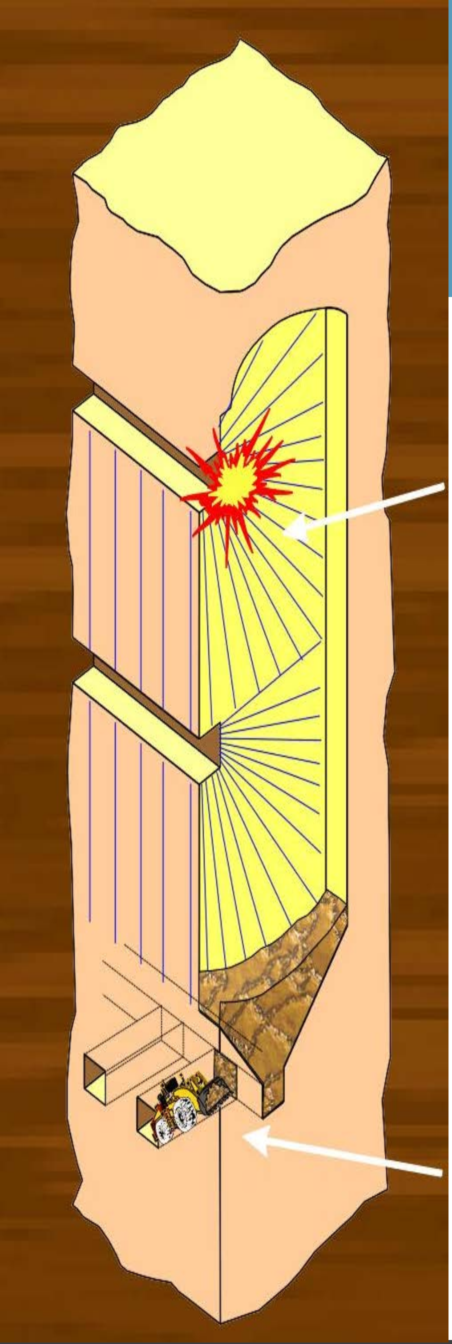
- ❖ Rock fabric identification & characterisation (joint set orientations, spacings and surface conditions)
  - Structural logging of orientated core
    - o Physical orientation (using orientation tool)
  - ATV/ OTV surveys
  - Geotechnical mapping
  - Photogrammetry

Geotechnical Mapping

Even limited mapping can clarify or confirm drilling data or data patterns

- Mapping (where possible) provides very valuable data. This is because:
    - Structural orientation data is of *very high* confidence
    - The key block-forming joint sets, their spacings and persistences can be accurately gauged

Example: A Large Underground Copper Mine



- Need to understand variability of geotechnical conditions across complex multi-level operation
- Identifying factors affecting stope performance for meeting revised production targets
- Identification of factors causing:
  - instability in development drives
  - instability/overbreak in stopes
  - generation of oversize blocking drawpoints

Context

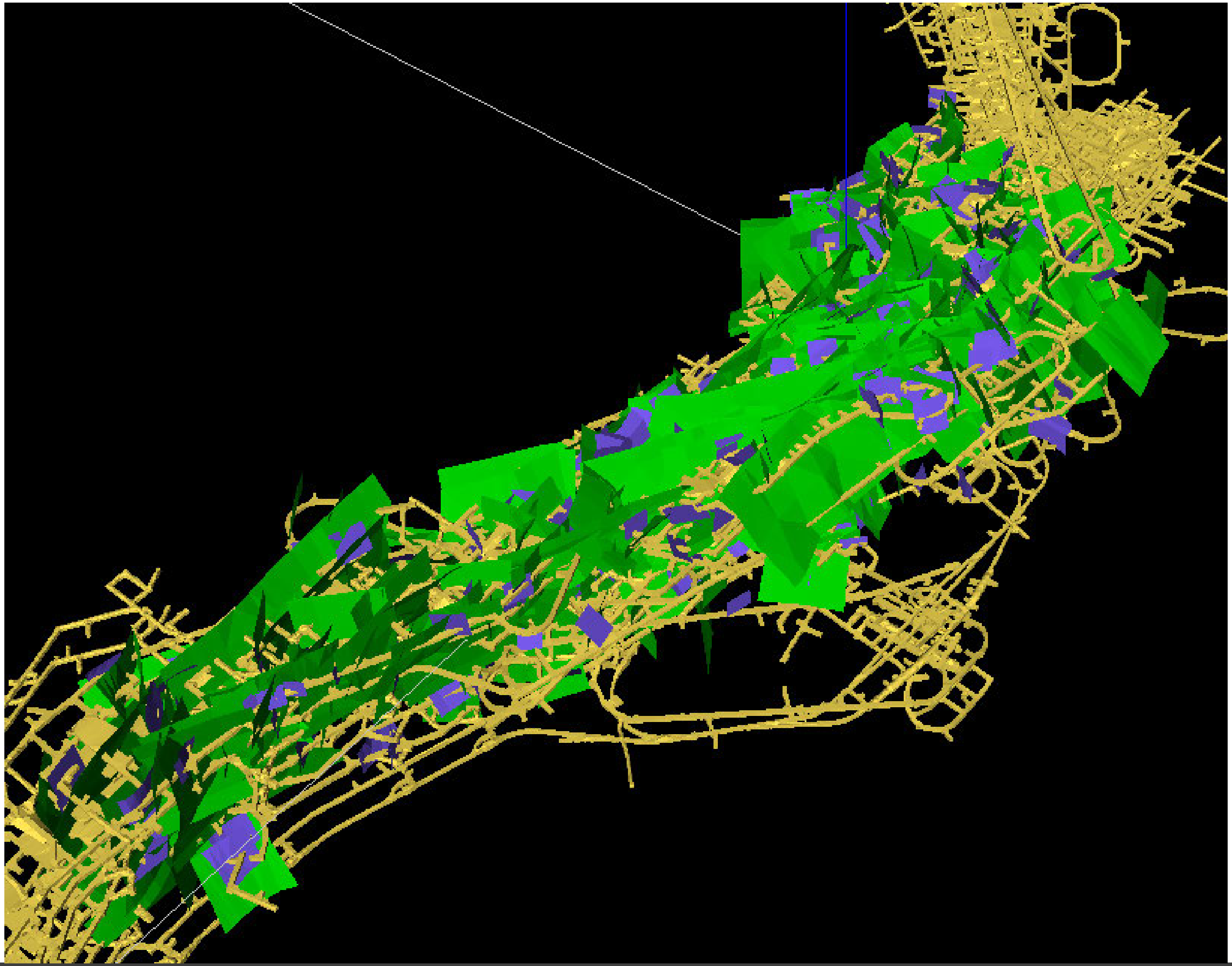
- No geotechnical drilling data from surface or underground drilling
- Large-scale rock mass characterisation to be made from face mapping, and collation of existing structural data
- Identify varying conditions and their controlling factors
- Construction of a Geotechnical Domain Model (GDM)

Fieldwork

A year of underground mapping including:

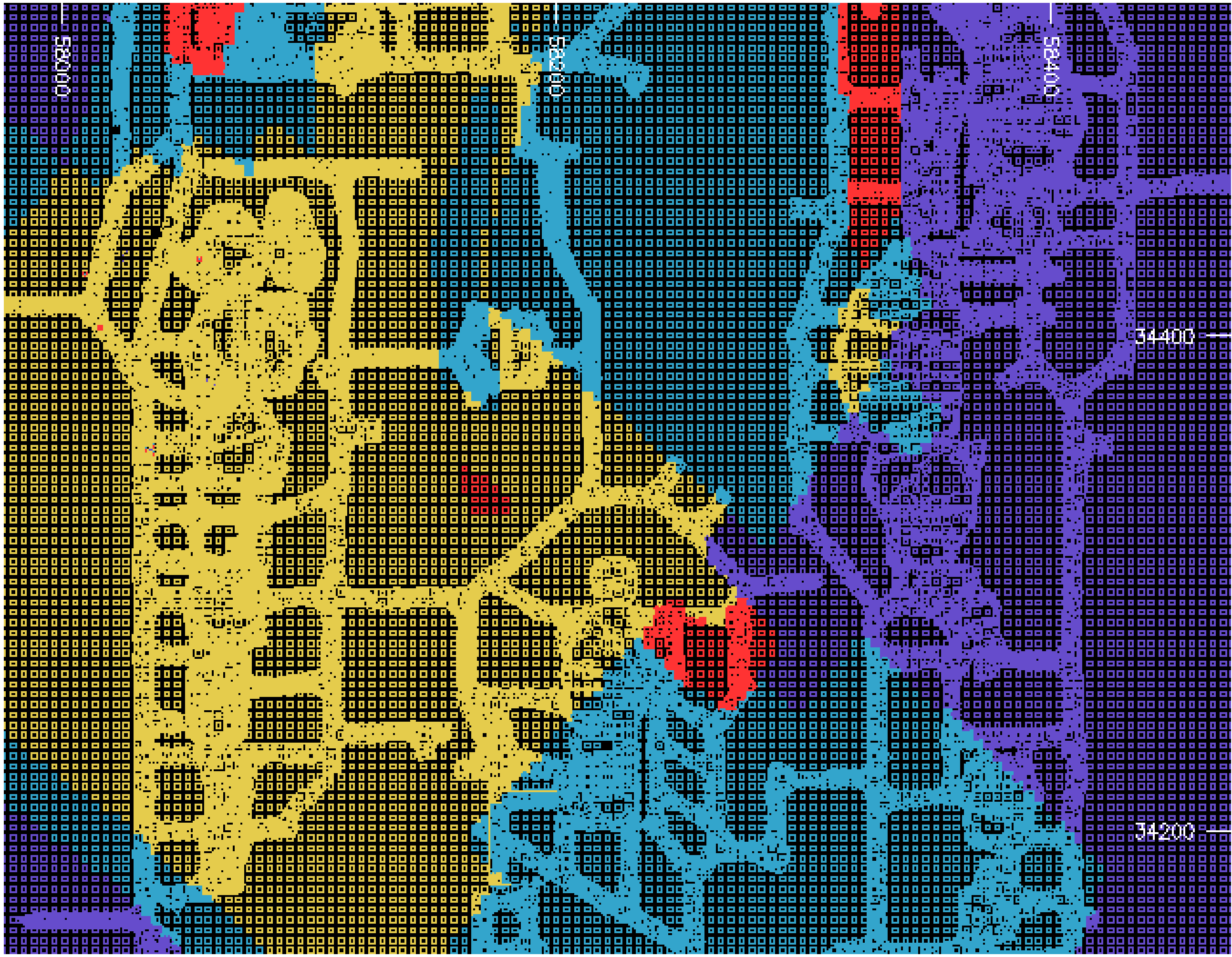
- Structural mapping / ground truthing of all accessible development (~150km)
- Window mapping (~350 windows)
- Continuous “blockiness” mapping of all accessible development (rapid, descriptive method for identification of rock mass “types”)

Structural (fault) Model



Geotechnical Model

Domain	Ground Conditions
A	Massive rock. Very few faults.
B	Massive to blocky rock. Widely spaced faults.
C	Blocky rock. Moderate Faulting.
D	Blocky rock Numerous intersecting faults.



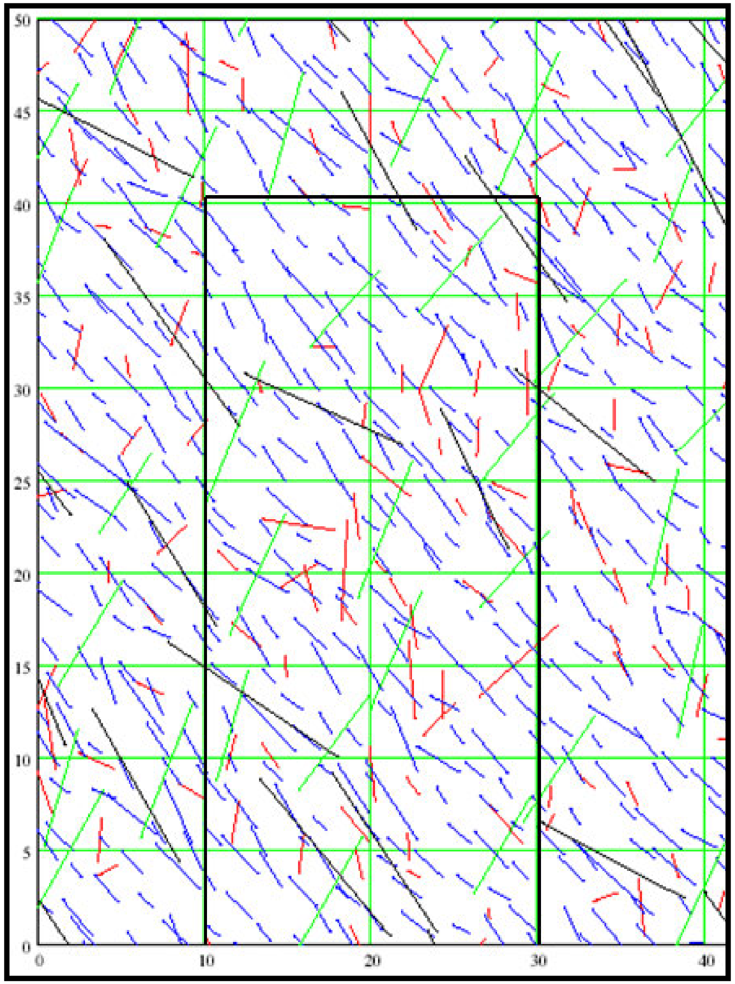
Prediction of Stope Performance

- Probabilistic recreation of rock mass fabric for each domain type
- Identifying kinematically unstable blocks in sidewalls and crowns of stopes
- Maximum depth and length of failure “blocks” measured
- Nature of failure blocks (intact or fragmented) noted
- Approximate block failure volumes calculated

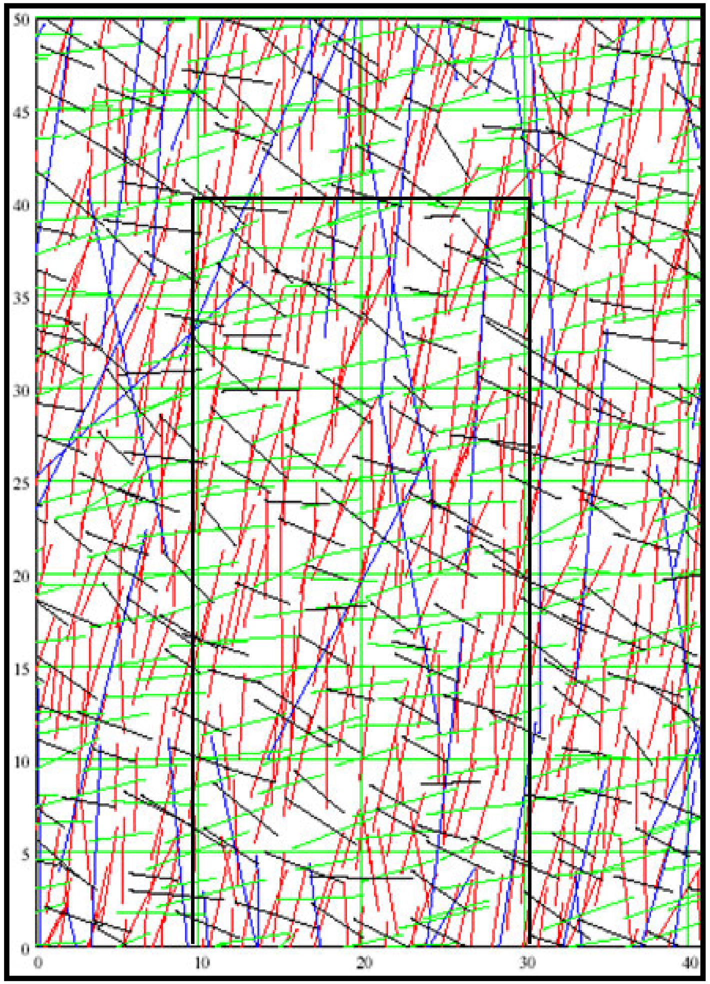
➢ Assessment of the potential for overbreak and oversize generation in stopes

Prediction of Stope Performance

Visualisation of rock mass for performance assessment



Vertical Section Domain A



Vertical Section Domain D

Prediction of Stope Perfomance

Domain	Ground Conditions	Volume of Overbreak	Frequency of Oversize	Volume of Failure (m^3)
A	Massive rock. Very few faults.	Low	Low	Up to 200 (infrequently up to 2000)
B	Massive to blocky rock. Widely spaced faults.	Low to medium	Low to medium	Up to 500 (infrequently up to 1100)
C	Blocky rock. Moderate Faulting.	Medium to high	Medium	Up to 20000 (infrequently up to 10000)
D	Blocky rock Numerous intersecting faults.	High	High	Up to 10000 (infrequently up to 50000)

Influence of Hydrogeology

Geotechs need a “working” understanding

Recommend geotechnical & hydrogeological investigations should be closely linked

- Often a key factor affecting stability
- Depressurisation may be required
- Dewatering and depressurisation not necessarily the same thing
- Conceptual hydrogeological model
    - o Groundwater levels
    - o Material properties (hydraulic conductivity etc.)

Example: Ok Tedi West Wall Cutback

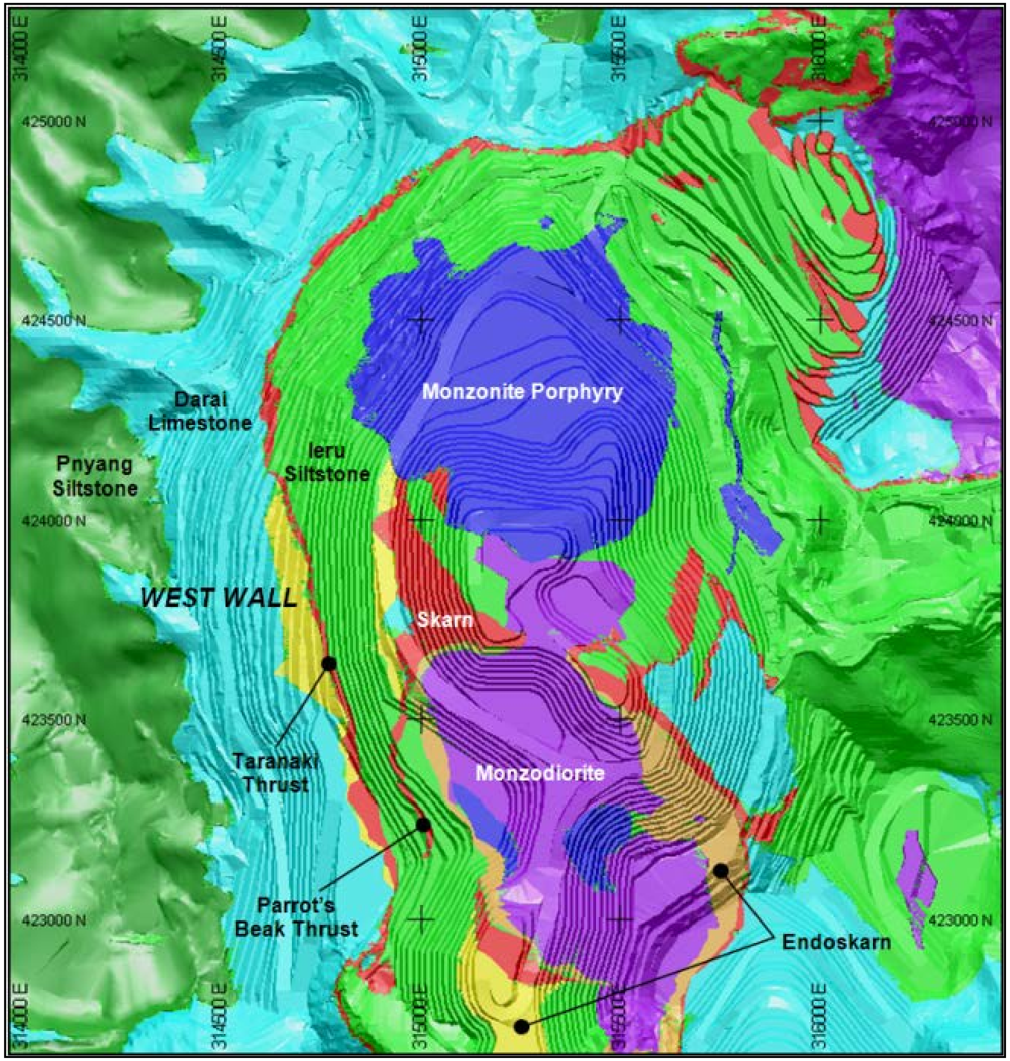
Background

- Ok Tedi is a copper-gold mine situated in the remote highlands of PNG
- Terrain around the pit is rugged, mountainous
- Annual rainfall 9 -11m, seismicity of 4-6 on Richter scale
- Cutback and deepening of the pit over 13 years
- Height of final cutback slope ~1000m
- Large thrust faults and normal faults
- Rock mass characteristics and groundwater conditions are complex

➢ Hydrogeological input crucial in assessing stability of Cutback Design

Pit Geology

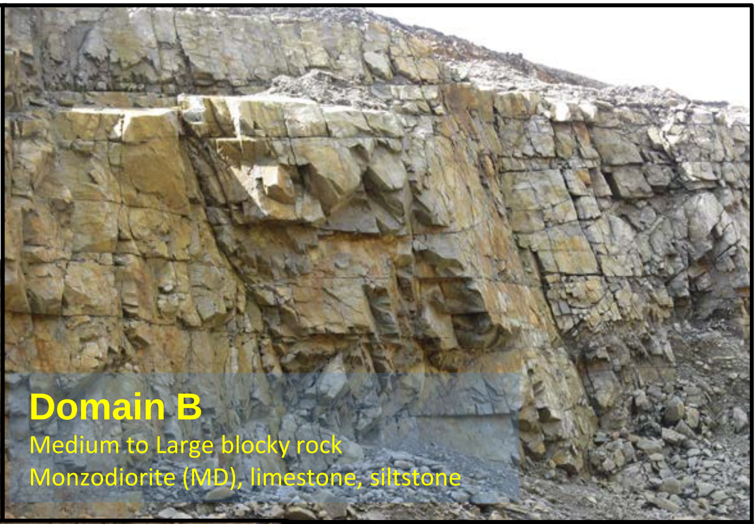
Plan view of geology superimposed on pit walls



Rock Mass Quality

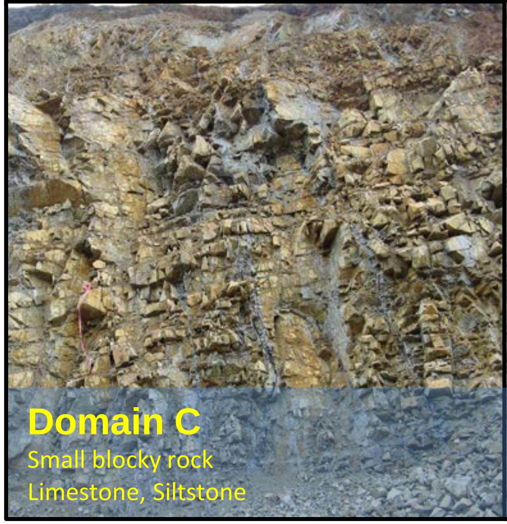
Domain A

Large blocky or Massive rock
Monzonite porphyry, magnetite skarn, monzodiorite



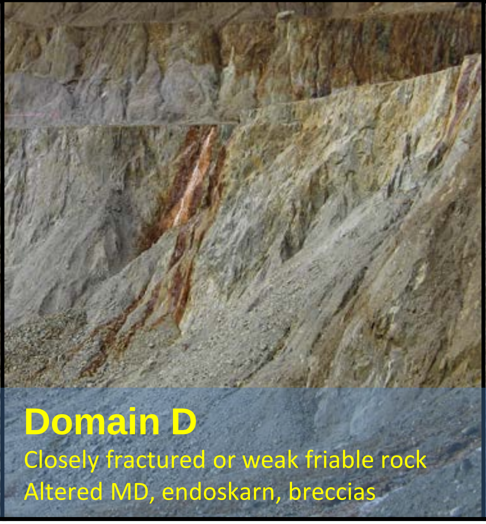
Domain B

Medium to Large blocky rock
Monzodiorite (MD), limestone, siltstone



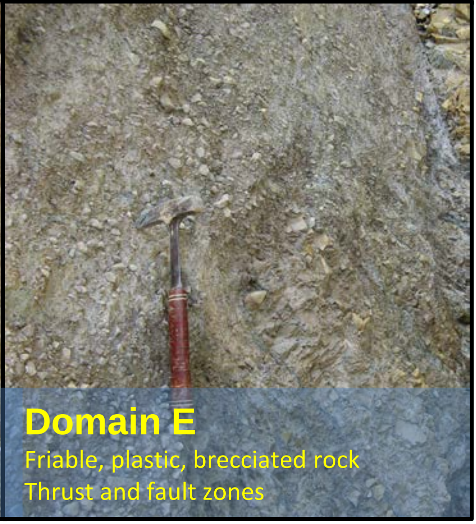
Domain C

Small blocky rock
Limestone, Siltstone



Domain D

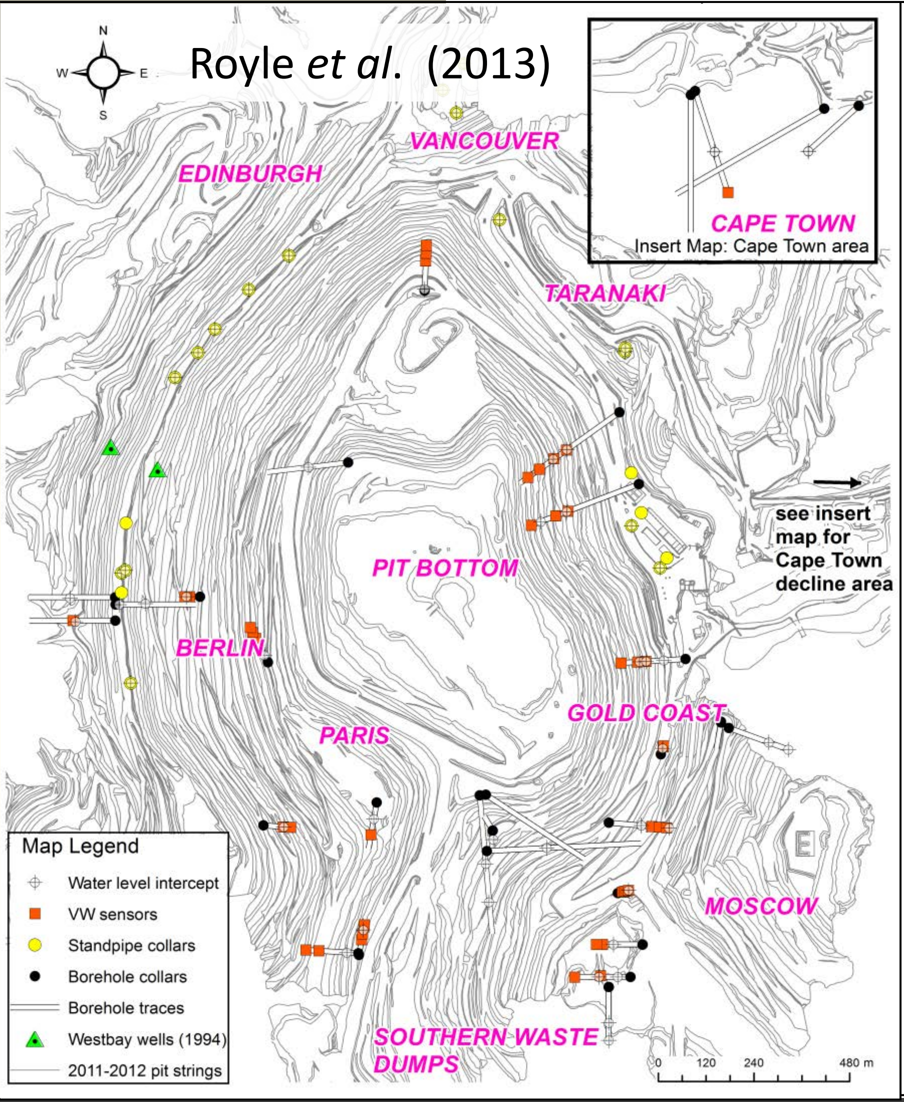
Closely fractured or weak friable rock
Altered MD, endoskarn, breccias



Domain E

Friable, plastic, brecciated rock
Thrust and fault zones

Investigation


Royle *et al.* (2013)

Hydrogeological Model

- Based on the current understanding of the slope geology and hydrological conditions (precipitation, infiltration, hydraulic conductivity, etc.)
- Major fault have been shown to have low permeability (clay gouge barriers)
- Complex distribution of multiple water tables, partly depressurised and dewatered slopes, and possibly confined (artesian) conditions in some deeper locations.

The Method (simply put)

Groundwater pushback of approx. 250m required

Critical Factors:
- Timing
- Practicality
- Cost
  of measures

Problem?
- Assess slope stability using existing conceptual hydrogeological model (no drainage measures)

Solution
- Identify pore pressure distribution required to achieve target FoS / Pf for stability

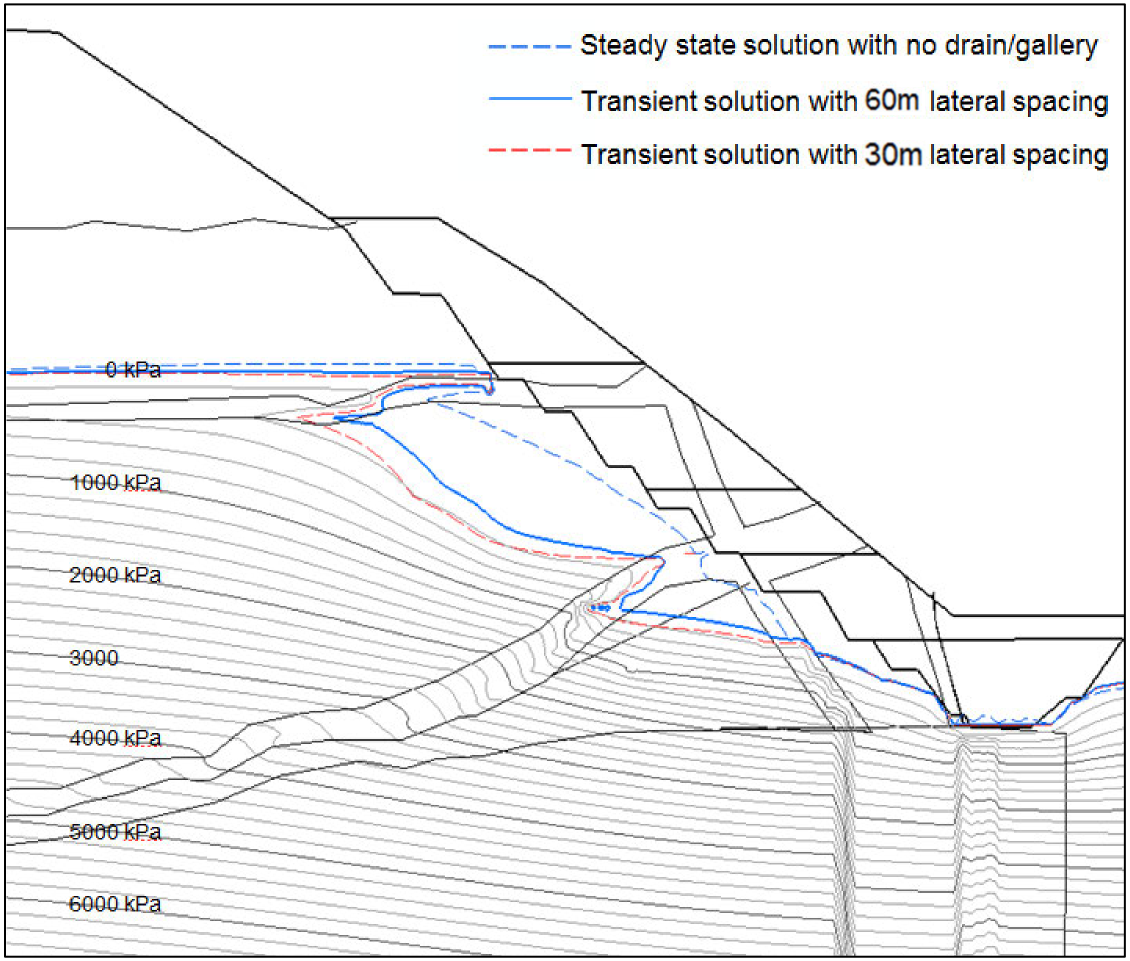
Requirement
- Identify drainage measures/configuration needed to achieve required pore pressure distribution – seepage analyses

Check
- Confirm stability of slope with the pore pressure resulting from the drainage design

Pore Pressure Prediction

Example section of final pwp predictions for a given scenario

- used as input to stability modelling



The Dark Art

Wise people have said:

> “It’s better to be approximately right than precisely wrong”

Thank You

Sometimes you just have to enjoy the view