SANIRE – COMREC Paper 3.4
Surface Mining Webinar

Introduction to Open Pit Slope Design

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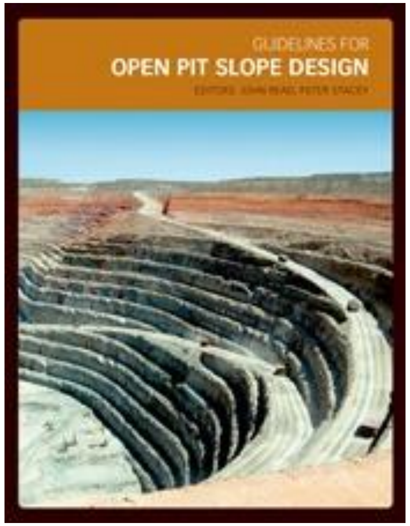
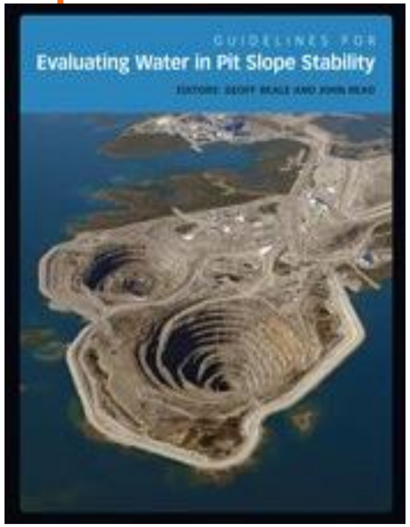
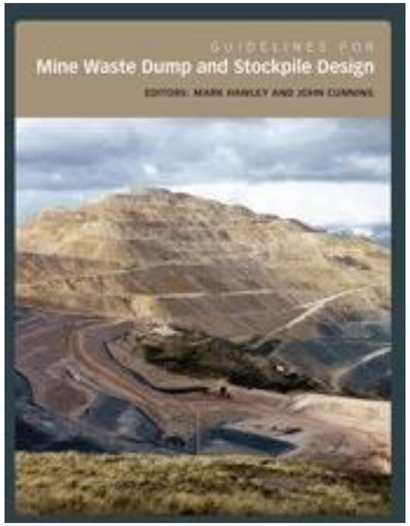
Open Pit Guidelines & Pertinent Texts



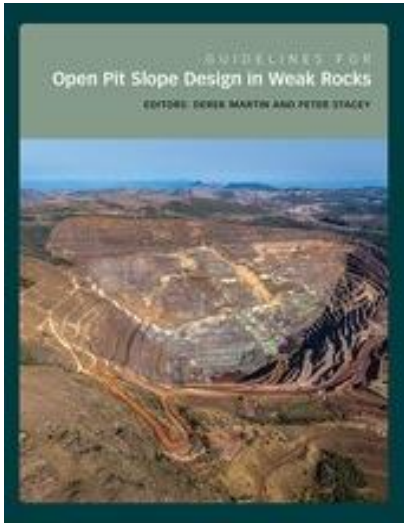
Guidelines for Open Pit Slope Design, 2009



Guidelines for Evaluating Water in Pit Slope Stability, 2013



Guidelines for Mine Waste Dump and Stockpile Design, 2017



Guidelines Open Pit Slope Design in Weak Rocks, 2018

Guidelines for Slope Performance Monitoring, 2020

https://www.lopproject.com/guidelines/

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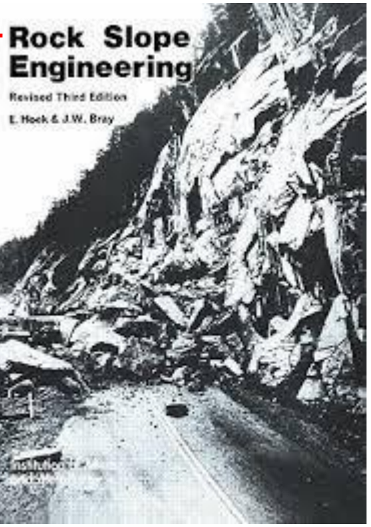

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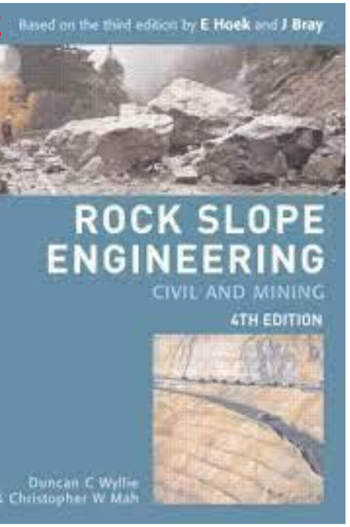


1. **Rock Slope Engineering, Hoek & Bray**
2. **Rock Slope Engineering for Civil and Mining, Wyllie & Mah (update on original Hoek & Bray)**

Agenda

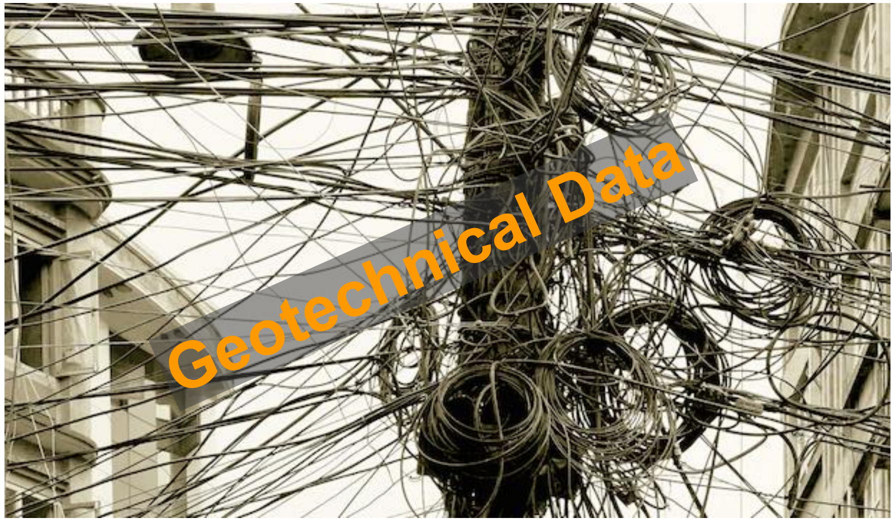
01

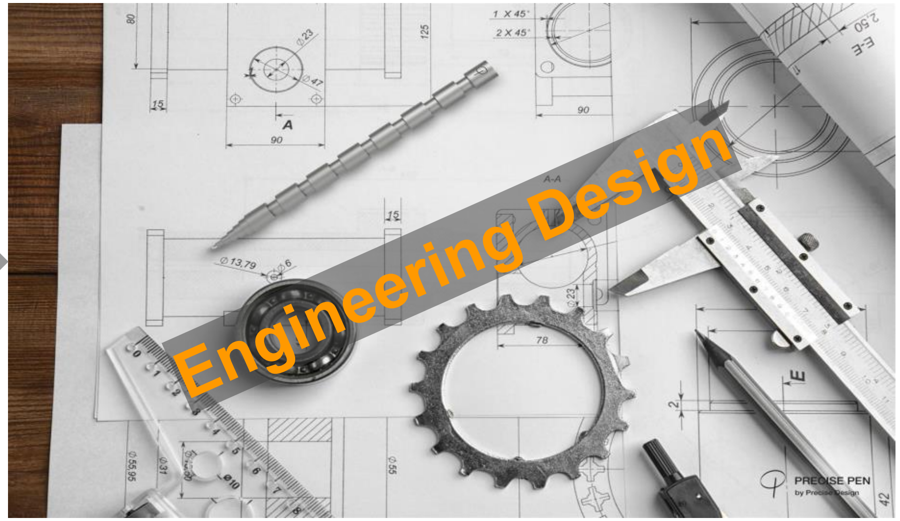
Introduction

Why do we need guidelines & a clear strategy?

Introduction

Why do we need guidelines and a clear strategy?



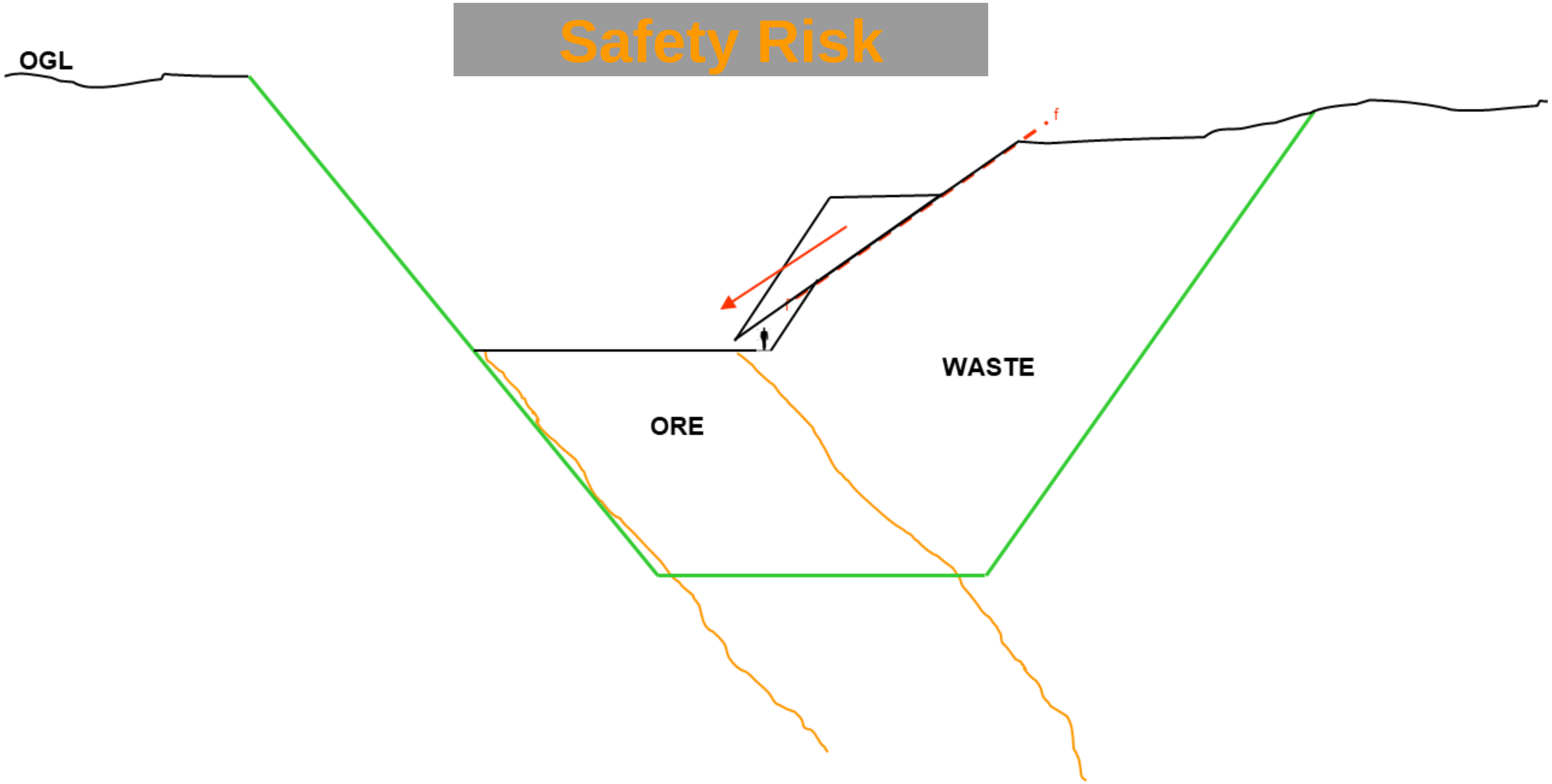


Bui, *et al*, 2020

Sunrise Dam Gold Mine, AngloGold Ashanti

Introduction

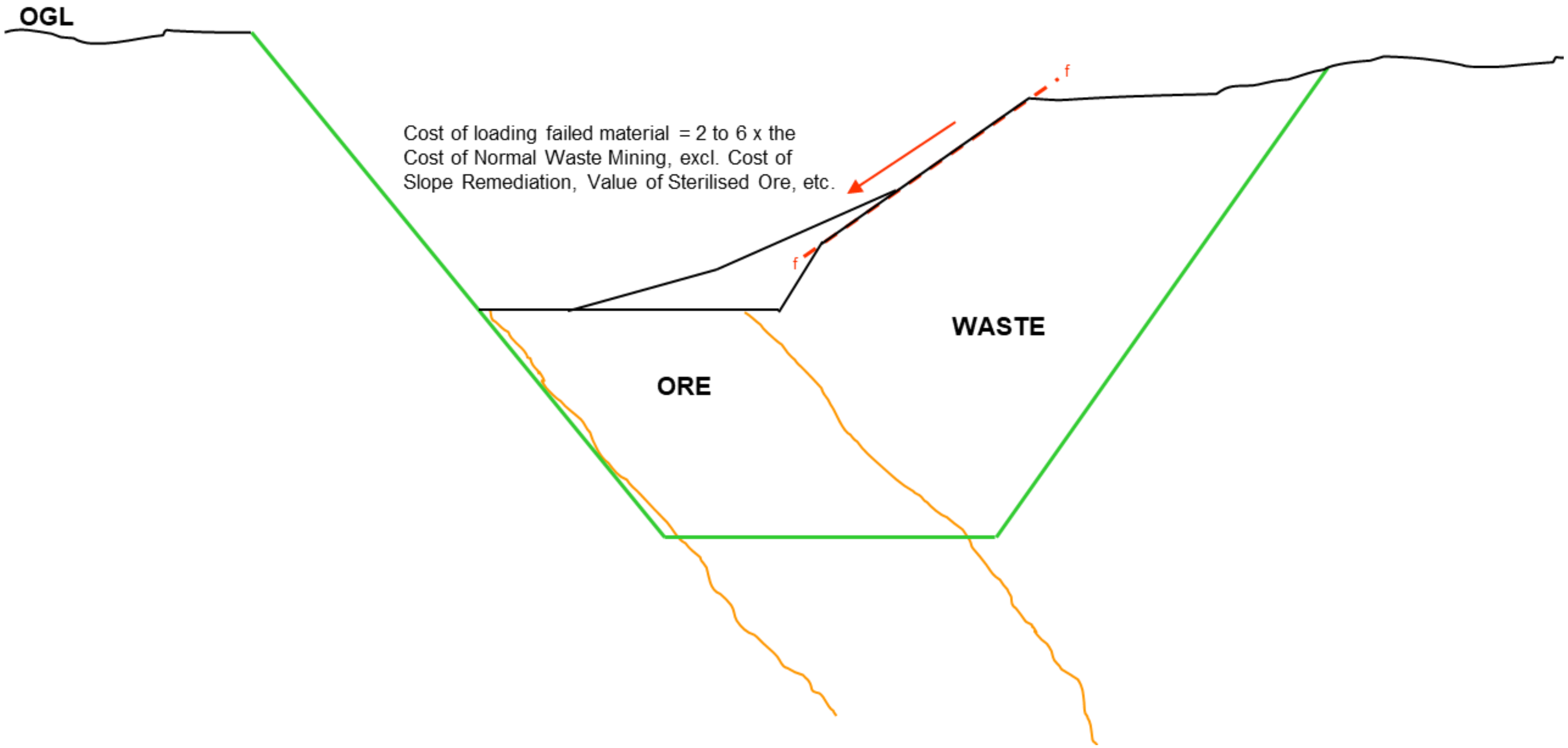
Why do we need guidelines and a clear strategy?



Introduction

Why do we need guidelines and a clear strategy?

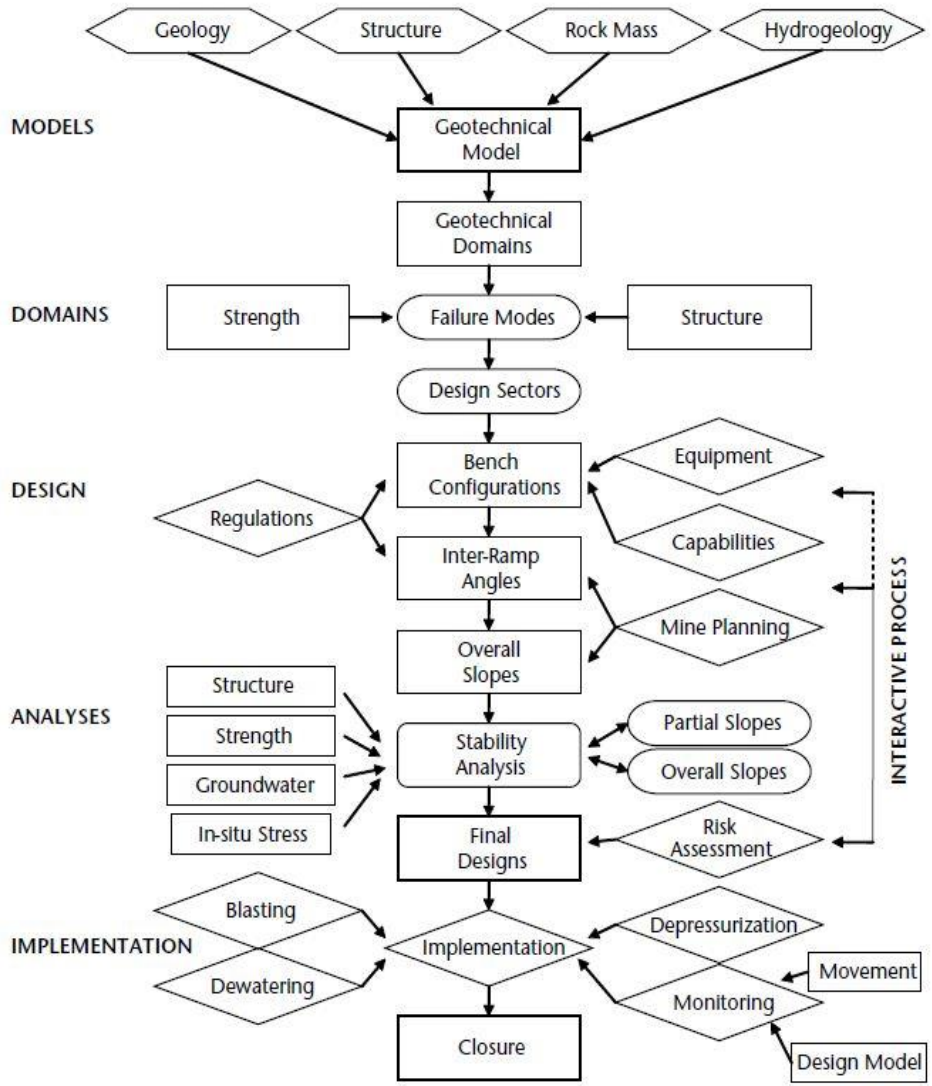
Economic Risk



Introduction

The slope design process

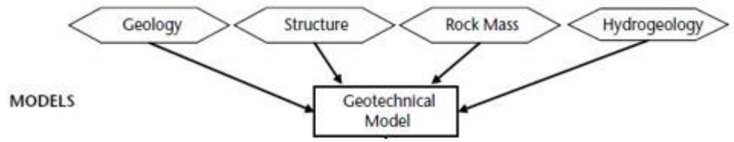
- Internationally accepted "Guidelines for Open Pit Slope Design", published CSIRO, 2009
- Compiled by the Large Open Pit Study Group
- Edited by Read and Stacey
- Logical, systematic guidelines for the design of open pit slopes, considering 5 main steps in a partly iterative process:
  - Data and models;
  - Geotechnical domaining;
  - Geotechnical design;
  - Geotechnical design analysis; and
  - Operational implementation.



02

Data & models

Constituents of the geotechnical model



Data & models

Field observation, face mapping, drilling, core logging, sampling & testing – field and laboratory

Geology model

- Main lithological contacts
- Weathering profiles
- Alteration surfaces/zones
- Geomorphology
- In-situ stresses
- Seismicity
- Preferably 3D (georeferenced)
- Lithology solids (wireframes)
- Not grade block model

Structural model

- Major structures
- Intermediate structures
- Minor structure/ fabric/jointing
- Bedding & foliation
- Correct tectonic history
- Structural environment defined (shear, fault blocks, folded, etc.)
- Preferably 3D (georeferenced)
- Structural solids (wireframes)

Rock mass model

- Hard rock vs. soft rock
- Intact strength
- Discontinuity strength
- Strength anisotropy
- Weathering type & clay content
- Rock mass ratings & classification
- Scale
- Back-analysis & laboratory testing

Hydrogeology model

- Groundwater
- Rainfall
- Surface water
- Phreatic surface
- Compartmentalised
- Perched
- Transient water
- Pore pressure
- Relative stress
- Porosity & Transmissivity
- Infiltration & recharge
- Flow direction & rates

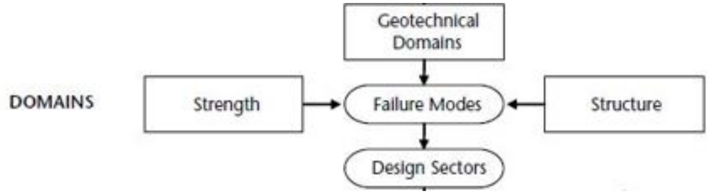
Geotechnical model constituents

Geotechnical model

03

Geotechnical domains

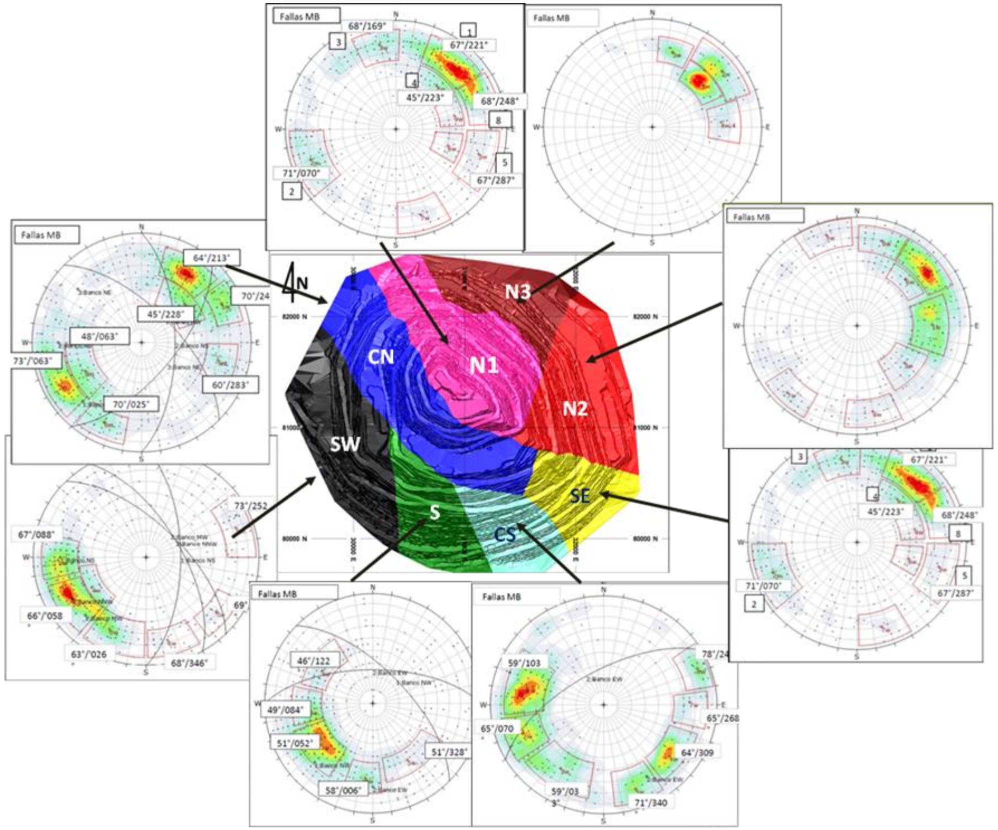
Fit-for-design



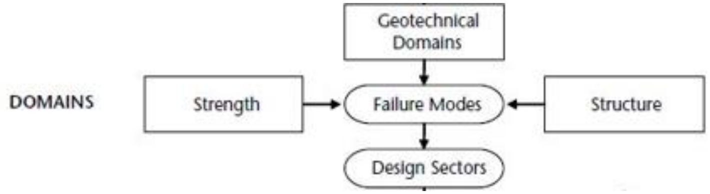
Geotechnical domains

Why do domaining?

- Open pits are large excavations, covering extensive areas and often containing multiple geological units and features
- The natural environment is highly variable – no one size fits all across the extent of an open pit
- "Slope design engineers often do not stop to assess the geological (incl. structural) and geotechnical context of a particular deposit, and that of the proposed pit to be developed." (Murphy & Barnett, 2018)
- Geotechnical domains provide design context related to the inherent variability in the physical properties of the rock mass in relation to the variability in the slope geometry, allowing fit-for-purpose design assumptions and analysis to be carried out



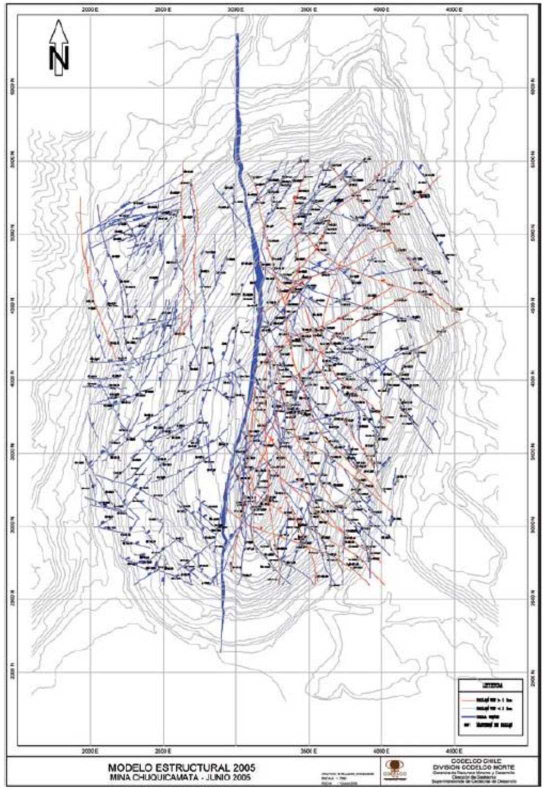
Typical domain model for a large open pit in Chile

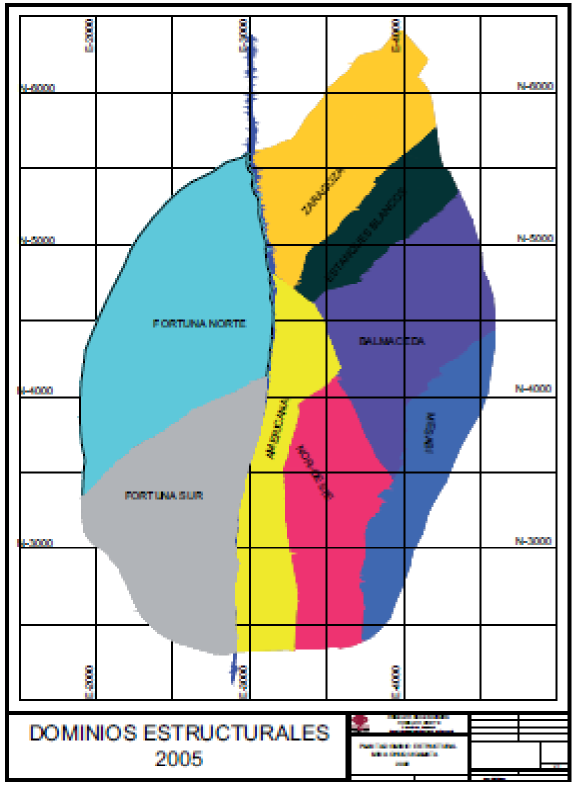


Geotechnical domains

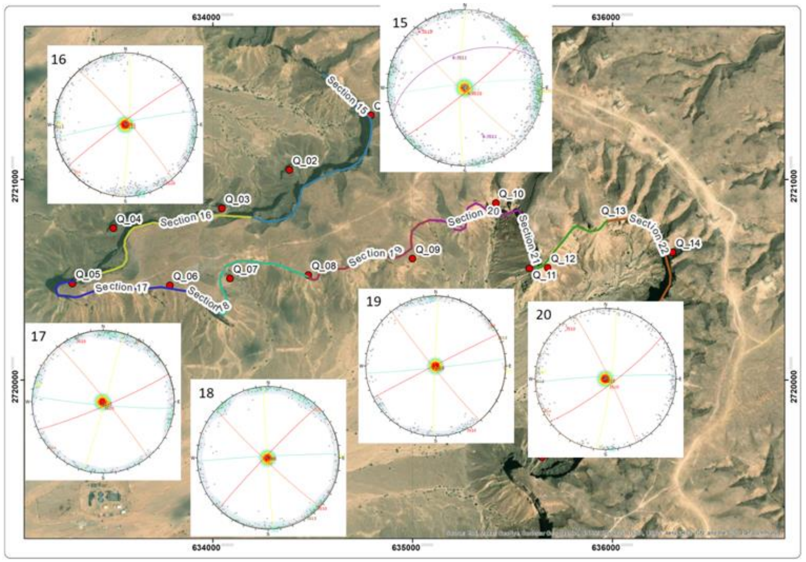
Geotechnical domain definition

- Similar structure – first step is to define structural domains
- Similar geology
- Similar material characteristics
  - Rock mass rating
  - Strength properties
  - Weathering
  - Alteration
- Slope orientation and failure mechanisms

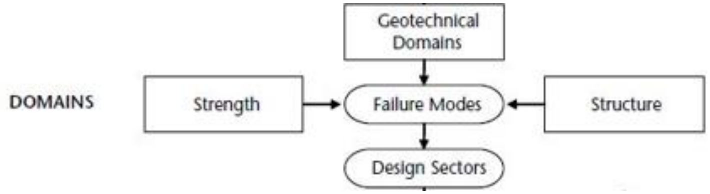




Structural model (left) and structural domains (right) at Chuquicamata Mine in Chile, 2005 (from Read & Stacey, 2009)



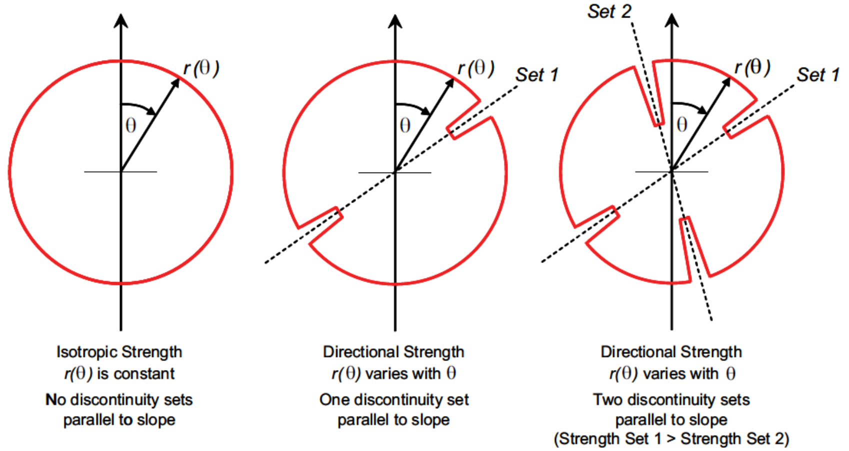
Structural orientation vs slope orientation – failure mechanisms in hard rock



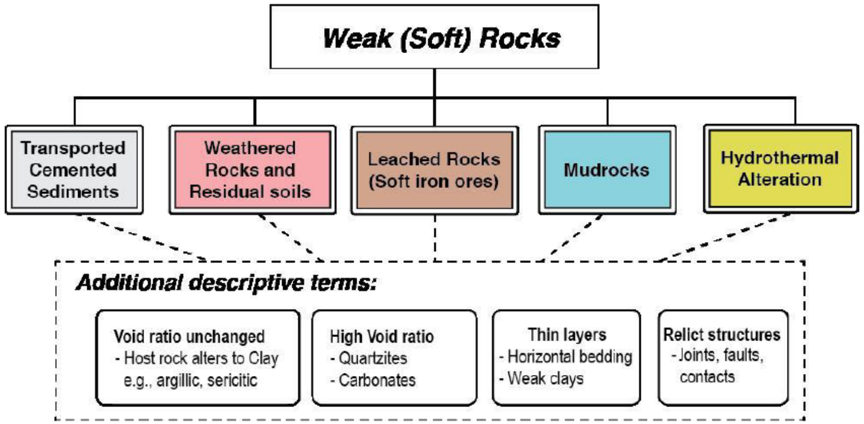
Geotechnical domains

Geotechnical domain definition - strength

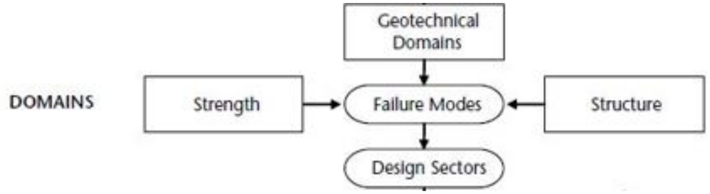
- Strength model – strong(hard) vs weak (soft) rock
  - Hard rock – discontinuity strength is dominant
  - Soft rock – rock mass strength is dominant
- Intact vs discontinuity strength
  - Intact – compressive vs tensile strength
  - Discontinuities – infilling, roughness & shear strength
- Directional strength & anisotropy
  - Influence of structural defects and orientation
- Weak rocks and residual soils (e.g.: saprolites & laterites)
  - Expect sampling bias
  - Back-analysis is critical
- Ensure appropriate investigation techniques
  - Mapping
  - Drilling & logging
  - Sampling
  - Field testing
  - Laboratory testing
  - Back-analysis



CSIRO, 2009



Martin & Stacey, 2013



Geotechnical domains

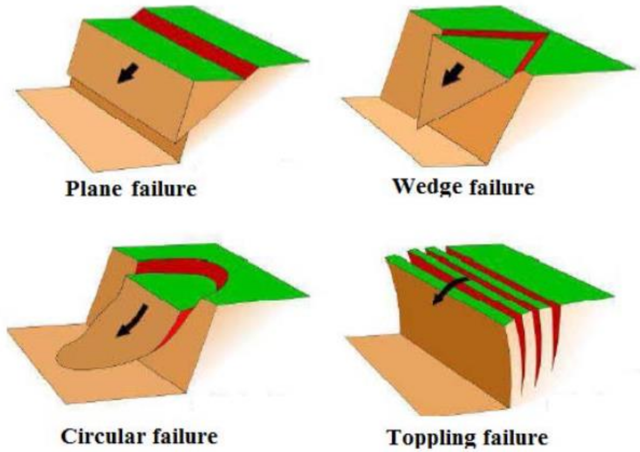
Geotechnical domain definition – failure modes

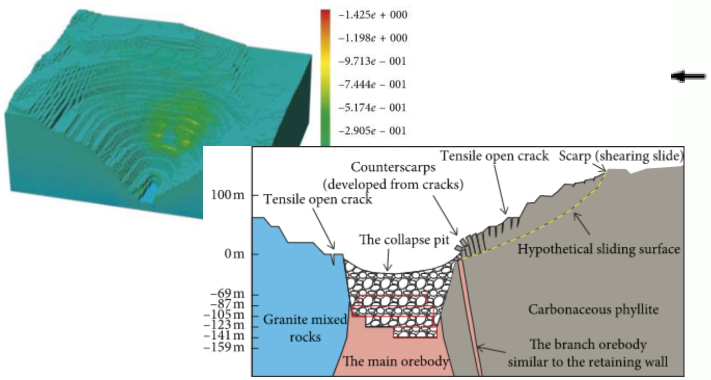
- 4 basic slope failure mechanism, defined kinematically
  - Planar failure
  - Wedge failure
  - Toppling failure
  - Circular failure

Structurally controlled (discontinuity shear strength) (Planar, Wedge and Toppling failure)

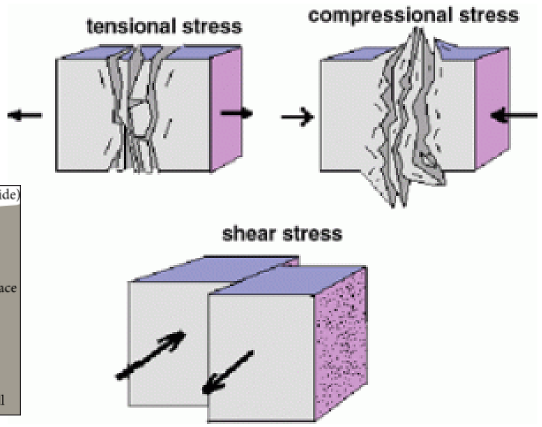
Material/rock mass strength controlled (Circular failure)

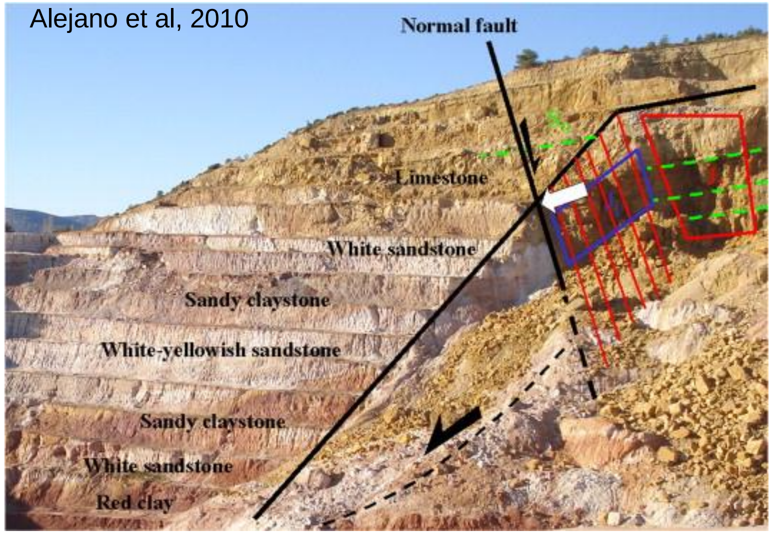
- Complex failure
  - Stepped path failure & rock bridging
  - Combination of one or more failure mechanisms
- Stress
  - Regional in-situ stress environment
  - Tectonism and stresses
  - Mining induced stresses

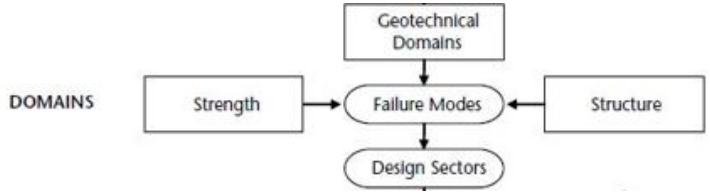




Yingpeng et al, 2019



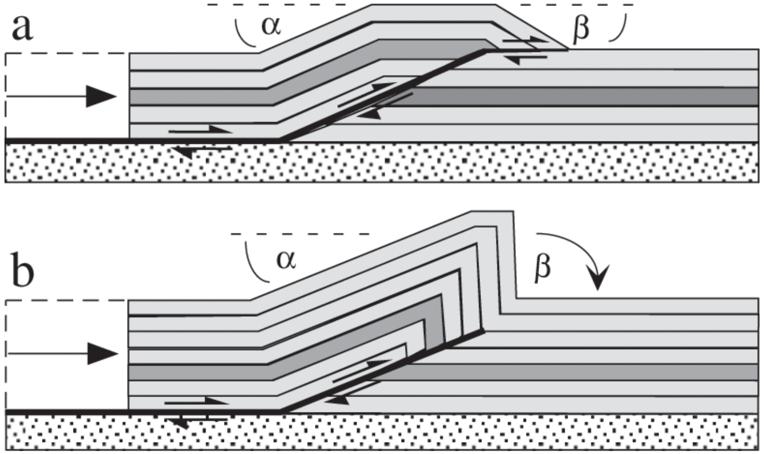




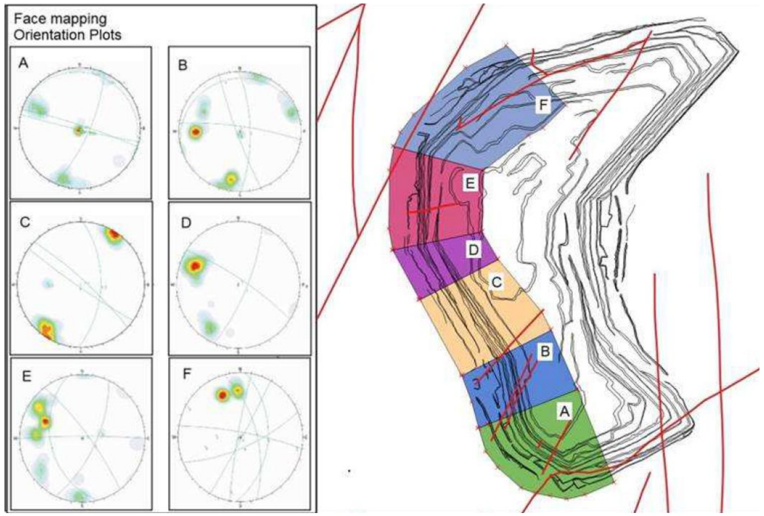
Geotechnical domains

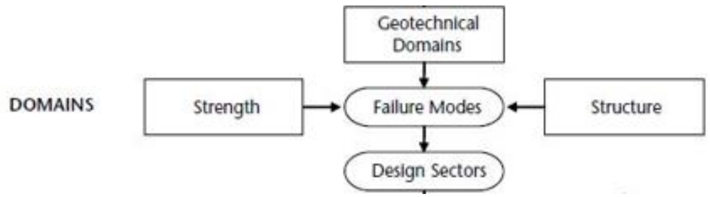
Geotechnical domain definition - structure

- Tectonic setting
  - Sheared, faulted, folded – tectonic history/chronology
- Critical structural set
  - Structure orientation vs slope orientation
- Structural interaction
  - Fabric – joint-joint
  - Fault-joint
  - Fault-shear/sheared contacts
  - Fault/joint contact
  - Folded environments, etc.
- Structure – slope interaction
  - Sub-vertical to sub-horizontal
  - Sub-parallel to slope
  - Self-supporting vs failure – when?
  - Influence on dominant failure modes



Schultz RA, 2019

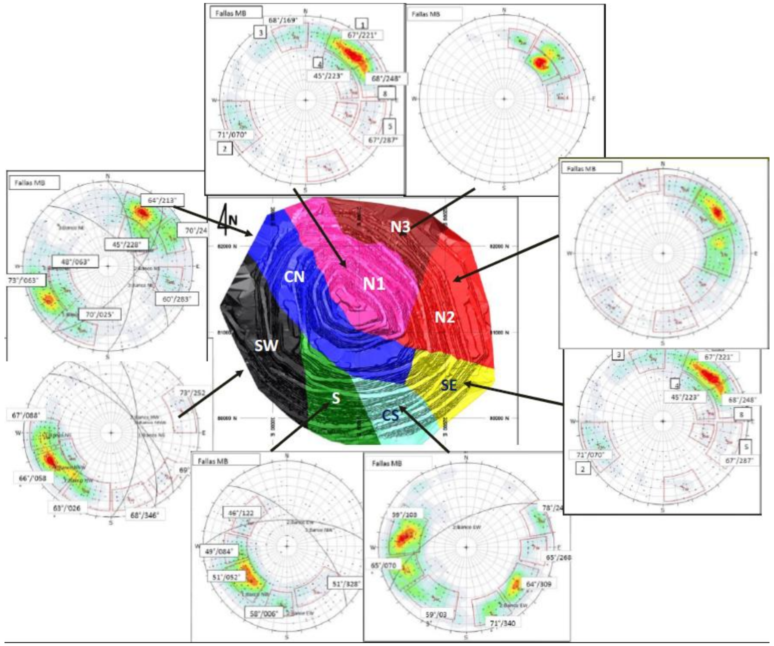


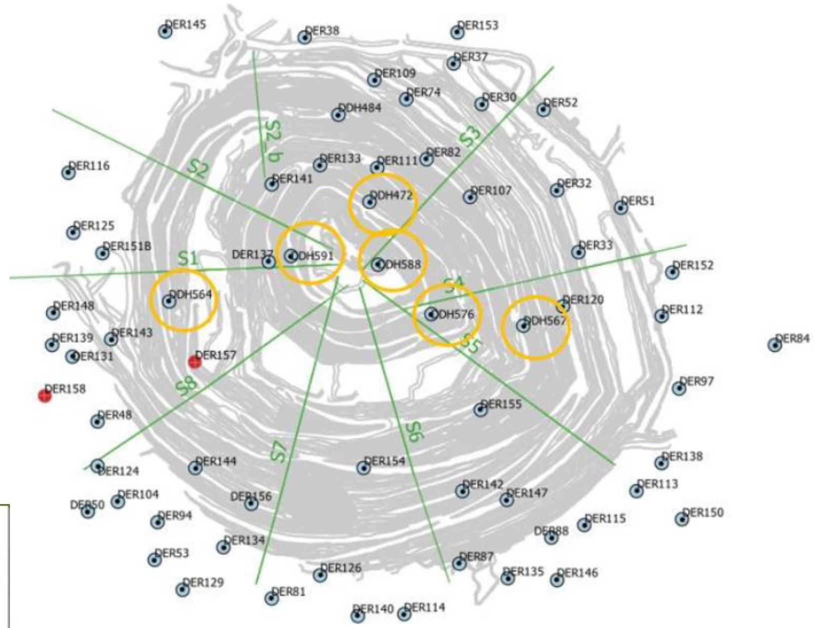


Geotechnical domains

Geotechnical domain definition – design sectors

- Design sectors can be subdivisions of geotechnical domains
  - Influence of pit slope orientation
  - Design acceptance criteria – infrastructure
  - Mining method – free dig vs drill & blast
  - Influence of neighbouring/adjacent mining activities (e.g.: pillar/crown pillar between pit and underground activities)
  - Existing instabilities





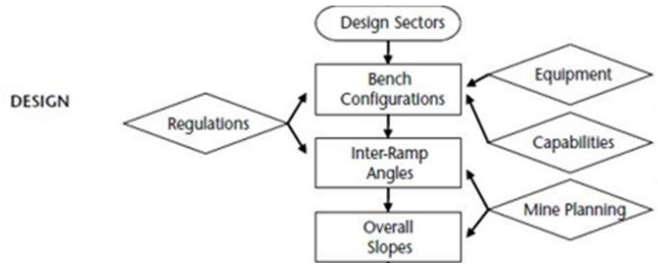
Structural domains vs design sectors for a large open pit in Chile

03

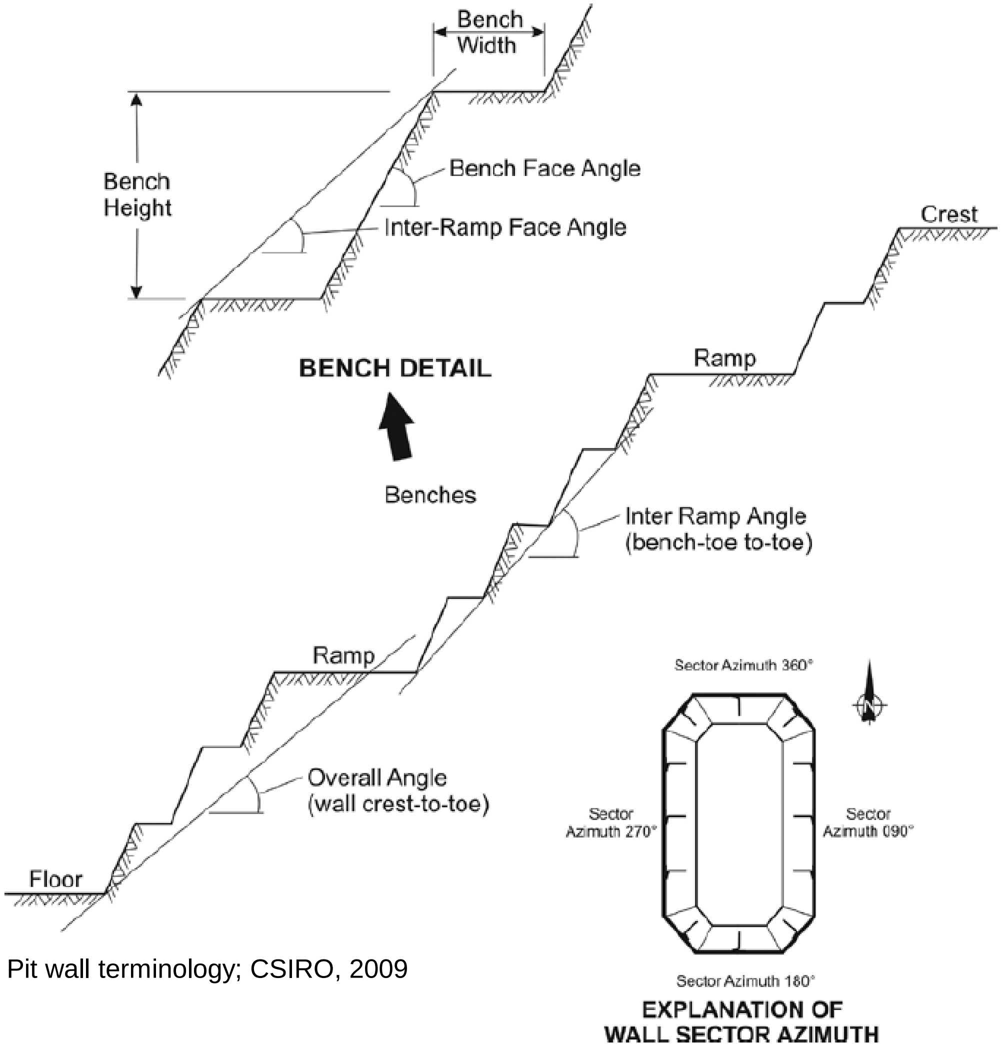
Design

Know where you are going

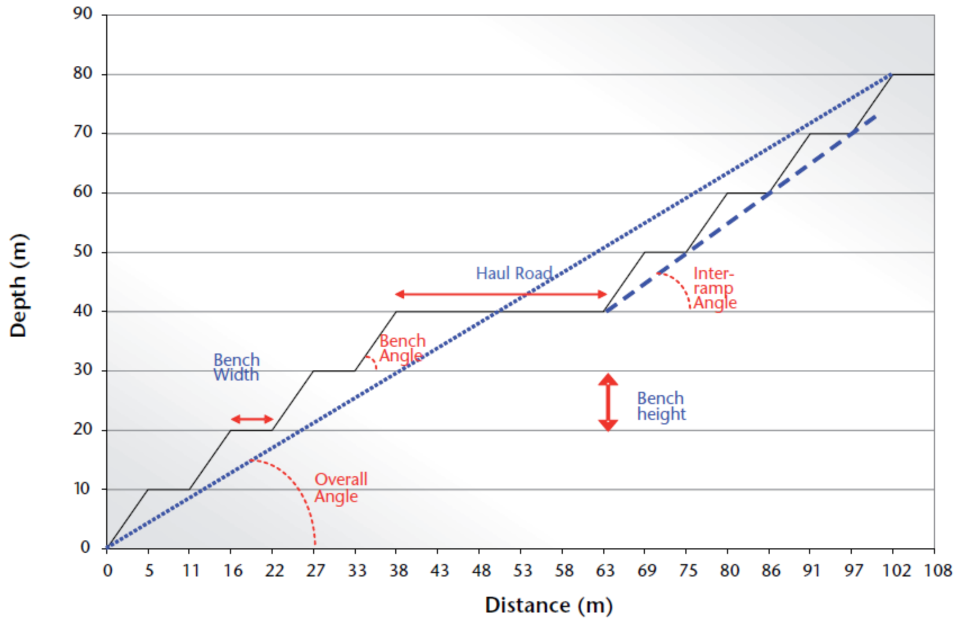
Design



Geotechnical design – nomenclature



Pit wall terminology; CSIRO, 2009

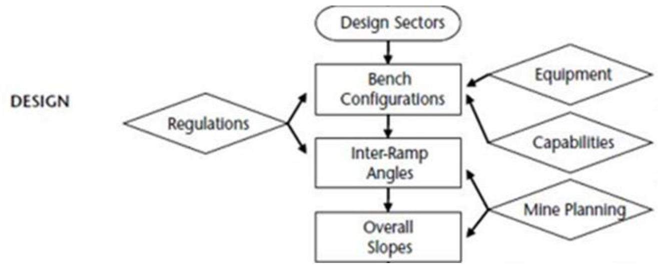


Slope angle, depth & distance; CSIRO, 2009

Note: **The horizontal portion of the bench is now commonly referred to as the berm/catchment berm, and its width as the berm width.**

The controlling angle for slope stability is the crest-to-toe angle, while the commonly applied angle for mine planning and mining engineering design is the toe-to-toe angle.

Design



Geotechnical design – design criteria

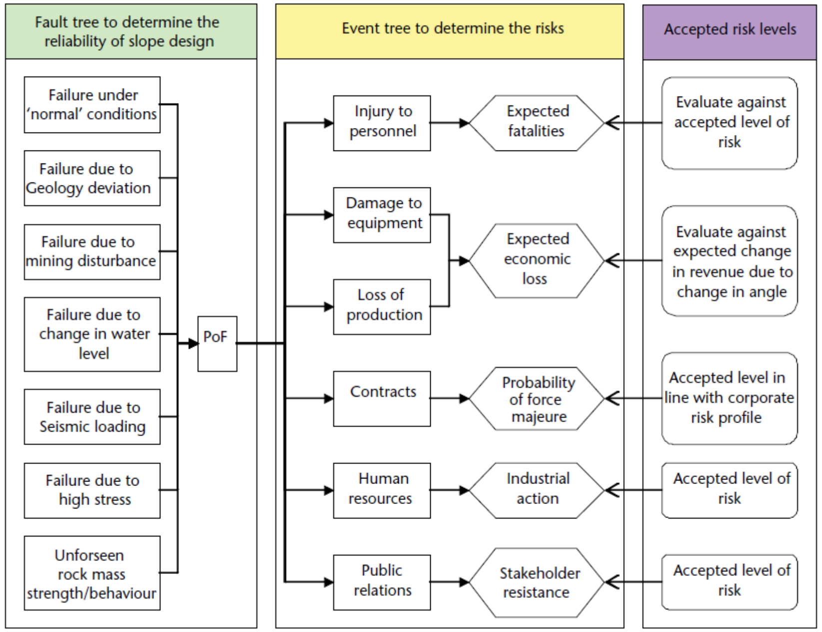
- FoS based – capacity (resisting forces)/demand (driving forces)
- PoF based – statistical probability that FoS ≤ 1
- Varying levels of acceptance depending on the importance of the slope
  - No critical infrastructure may be FoS = 1.2 – 1.3, PoF = 10 – 15%
  - Critical infrastructure (e.g.: ramps, crushers, portals) may be FoS > 1.5, PoF < 5%
- Consequences of instability or eventual failure may be more quantitatively assessed by applying a risk-based approach – incorporating safety and economic impacts, as well as societal views and legislative requirements/impediments

Commonly applied

		Acceptance criteria[a]		
Slope scale	Consequences of failure	FoS (min) (static)	FoS (min) (dynamic)	PoF (max) P[FoS ≤ 1]
Bench	Low–high[b]	1.1	NA	25–50%
Inter-ramp	Low	1.15–1.2	1.0	25%
	Moderate	1.2	1.0	20%
	High	1.2–1.3	1.1	10%
Overall	Low	1.2–1.3	1.0	15–20%
	Moderate	1.3	1.05	10%
	High	1.3–1.5	1.1	5%

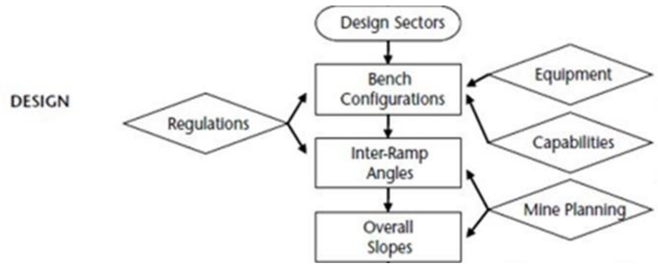
a: Needs to meet all acceptance criteria
b: Semi-quantitatively evaluated, see Figure 13.9

Modified from CSIRO, 2009



Steffen et al, 2006

Design



Geotechnical design – slope design controls

	Rock Mass Strength		
	Weak	**Moderate**	**Strong**
Slope Element			
Bench Face	Strength (structure)	Structure	Structure
IRA	Strength	Structure (strength)	Structure
Overall	Strength	Structure (strength)	Structure (strength)
Design approach	General Overall ↑ ↓ IRA ↑ ↓ Bench	By Sector Bench ↑ ↓ IRA ↓ Overall	By Sector Bench ↑ ↓ IRA ↓ Overall
	Major structures may impact Overall (and IRA)		

Notes

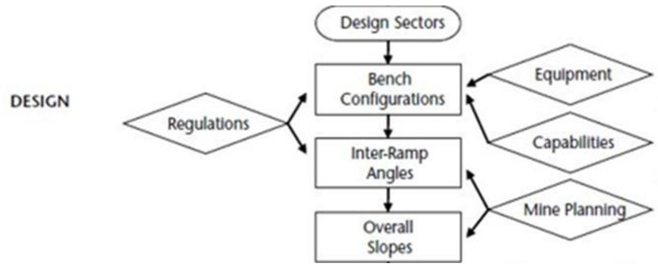
WEAK ROCKS

- Less susceptible to wall orientation unless major structures present
- Start by assessing Overall slope
- Fit bench configuration to Overall and/or IRA
- Bench height or angle may be controlled by strength
- Multiple benching (stacking) unlikely
- Water pressures likely to play major role

MODERATE TO STRONG ROCKS

- Sectorizallon required
- Structural control of BFAs
- Catchment design based upon anticipated failure quantity: minimum may be regulated
- Bench height controlled by equipment.
- Multiple benching (stacking) may be possible, especially in strong rock

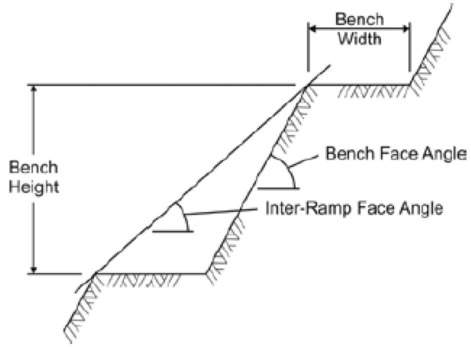
Slope design controls by rock strength, modified from; CSIRO, 2009



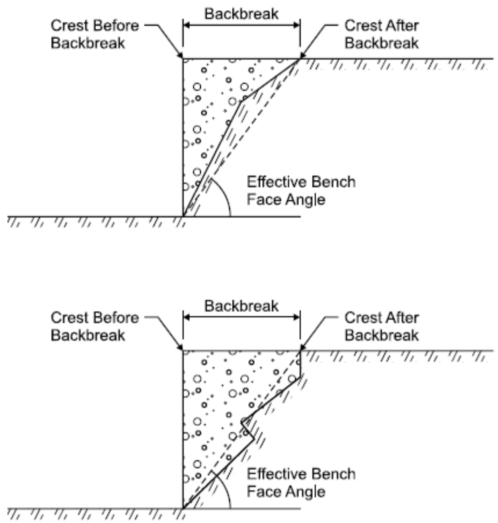
Design

Geotechnical design – bench-berm configurations

- Principal function of benches
  - Personnel safety (rockfall)
- Primary controls
  - Joint/structural geometry & shear strength
  - Capacity to contain rockfalls & spillage
  - Long-term access for slope monitoring & clean-up
- Design components
  - Bench height – vertical height between benches
  - Berm width – distance from toe of upper bench to crest of lower bench
  - Bench face angle – angle from crest to toe of immediate bench face
- Design methodology
  - Kinematic assessment
  - Spill/rockfall runout estimates vs berm width & catchment capacity
- Caveats
  - Structural geometry vs blasting & crest breakback



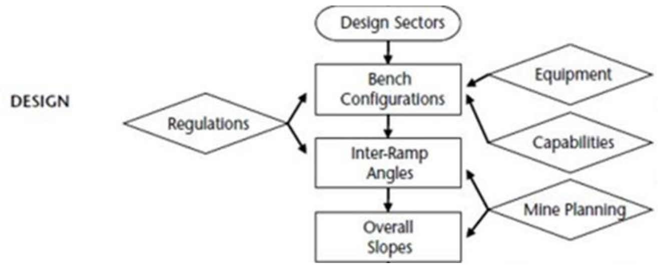
Components of a bench configuration; CSIRO, 2009



Breakback and effective bench face angle; Ryan & Prior, 2000

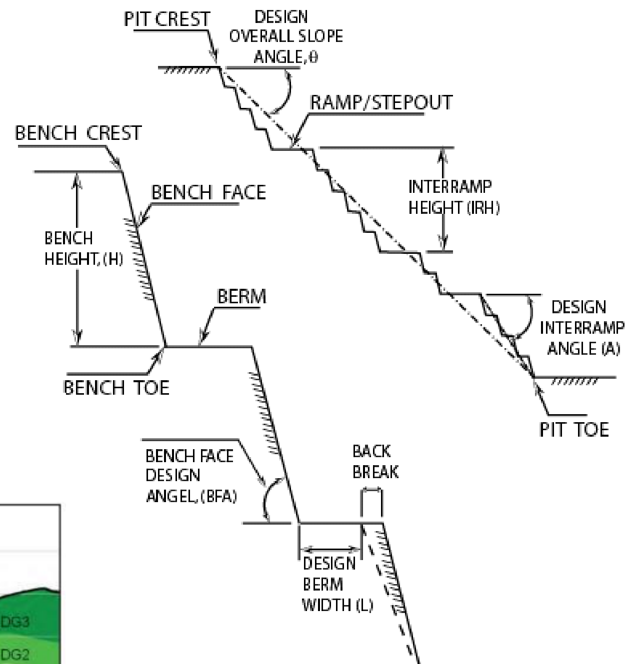
Bench design process; CSIRO, 2009

Design

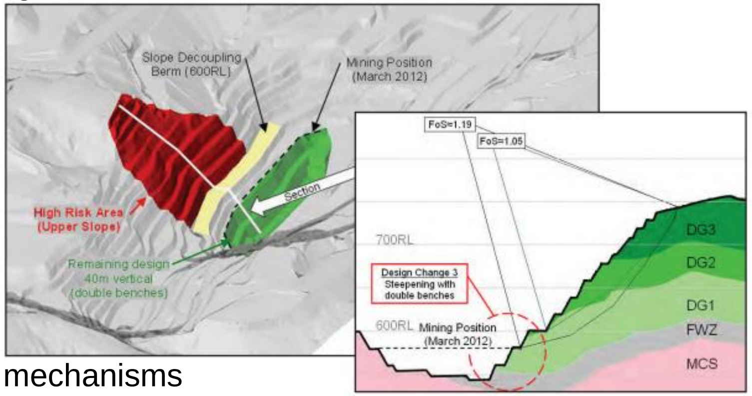


Geotechnical design – inter-ramp & stack slopes

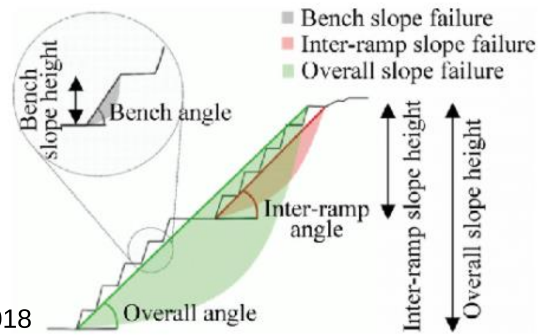
- Stack slopes
  - Combinations of benches separated by a larger geotechnical berm
  - There may be several bench stacks in an inter-ramp/overall slope
- Inter-ramp
  - Combinations of benches separated by a pit access ramp
  - Typically between 100 m and 200 m high
- Slope decoupling
  - Separate high from low-risk slopes
  - Control stress build-up in slopes
- Height & slope angle
  - Rock mass strength vs stress
  - Stress – strain relationship
- Failure mechanics
  - Inter-ramp scale generally = complex mechanisms
  - Combination of failure mechanisms and/or rock mass failure
- Consequence
  - More severe consequences
  - Larger failure volumes
  - Potential loss of access ramp, etc.
  - Rockfall



Abdul et al, 2009

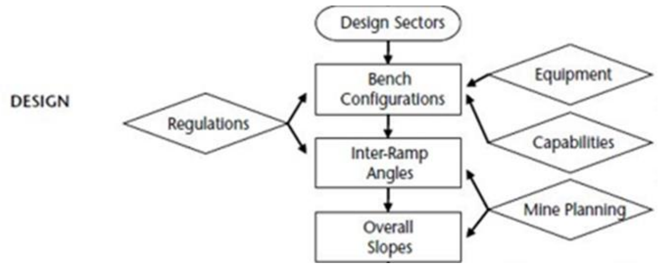


Bar, 2012



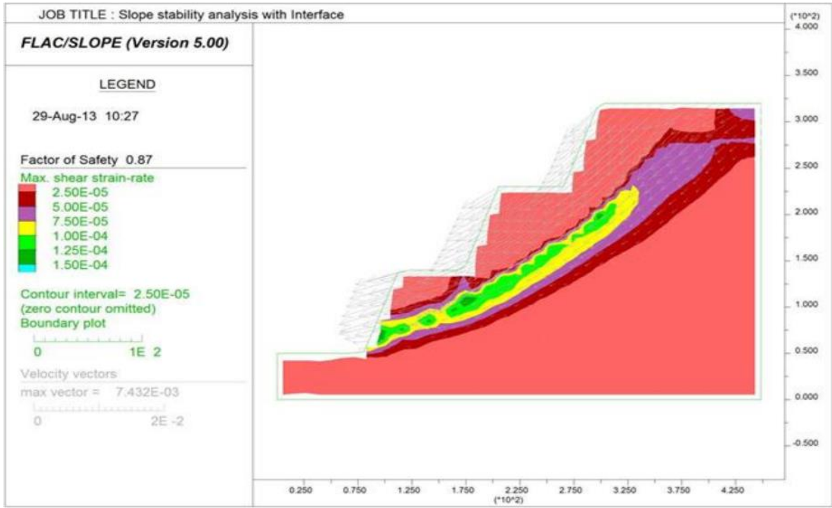
Dos Santos et al, 2018

Design



Geotechnical design – overall slopes

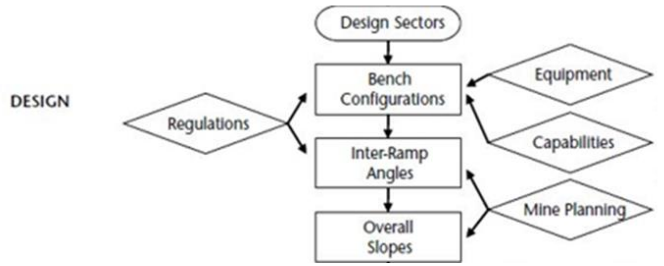
- Slope decoupling & stress management
  - Stacks & inter-ramp slopes
  - Stresses build as slope deepens, i.e., failure initiates at the toe, not the crest
  - Effect of structure
  - Risk management – separate high and low risk areas
- Height & angle
  - Driving vs resisting forces/rock mass strength vs stress
  - Safety aspects & perception
  - Legislative limits on berm widths & bench heights in some countries
  - Access ramps reduce slope angles – can be part of slope stability risk management
  - Economic aspects – stripping ratio
- Failure mechanics – generally complex
  - Complex failure & rock mass failure
  - Potential for interaction/coalescence of instabilities
  - Water pressure/effective stress
- Consequence & risk management
  - Awareness and exposure control – slope stability monitoring & training
  - Slope geometry & multiple access – limit risk



Soren et al, 2014

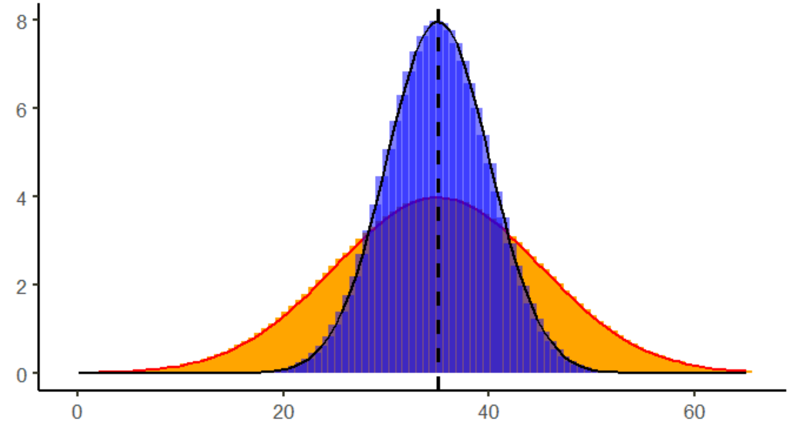
Courtesy, Rio Tinto, 2013

Design



Geotechnical design – integration

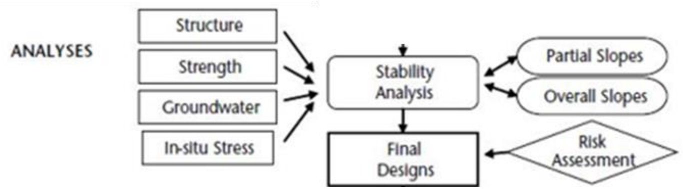
- Integrated open pit slope design
  - Iterative process between geotechnical & mine planning
  - Geological & structural input
  - Hydrogeological input
  - Rock mass/geotechnical input
  - Economic input – mine planning
  - Survey input – geospatial aspects
- Equipment capabilities
  - Greenfields - design should drive choice of equipment
  - Brownfields – often equipment limitations control aspects such as achievable bench height, single vs double benching, etc.
- Experienced vs unexperienced staff and operators
  - Recognition of ramp up period to ideal operations
  - Pit slope often start conservative and become more aggressive over time & with experience & added knowledge
- Data confidence
  - The greater the data confidence the less the risk of unknown instability & the more aggressive the design for a given rock mass
- Regulatory requirements
  - Licensing, staffing requirements, risk management, training, closure requirements, etc.



05

Design analysis

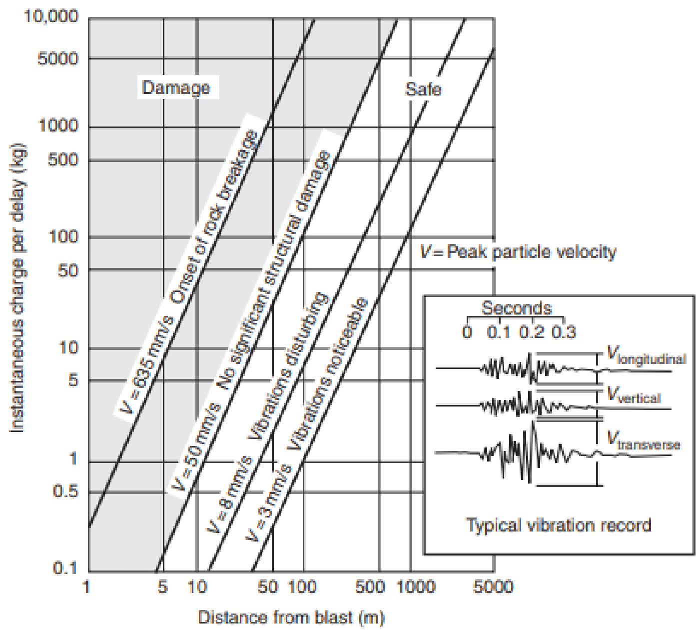
Failure criteria & modelling



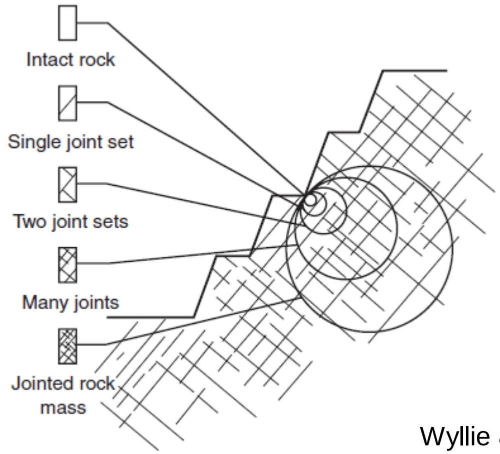
Design analysis

Instability interpretation

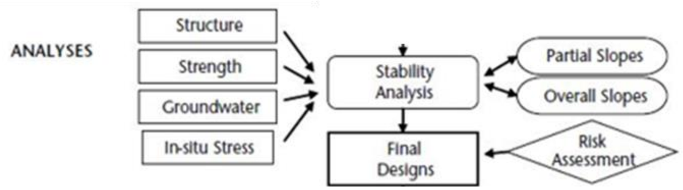
- Rock mass controls
  - Intact rock strength
  - Discontinuity strength/strength of structural defects
  - Directional strength/anisotropy
- Failure mechanism
  - Slope scale
  - Simple vs complex failure
- Failure criterion
  - Must be matched to rock mass characteristics & failure mechanism
  - Mohr-Coulomb
  - Hoek-Brown
  - Hoek-Brown, with Barton-Bandis applied
- Water
  - Phreatic water vs transient water
  - Surface water management - infiltration
- Blasting
  - Blast damage – cumulative effect
  - Charge mass per delay over scaled distance graphs (Hoek & Bray)
  - Good limit blasting & slope design
- Dynamic effects
  - Earthquake loading - seismicity



Wyllie & Mah, 2004 (modified from Hoek & Bray, 1974)



Wyllie & Mah, 2004

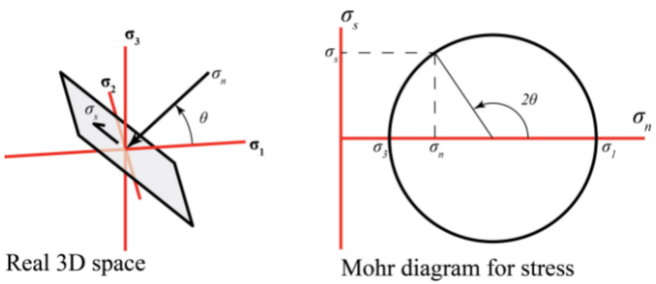


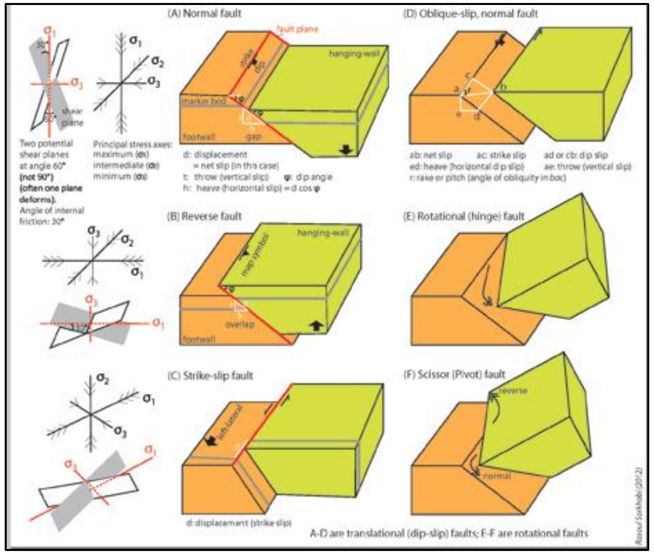
Design analysis

Model inputs

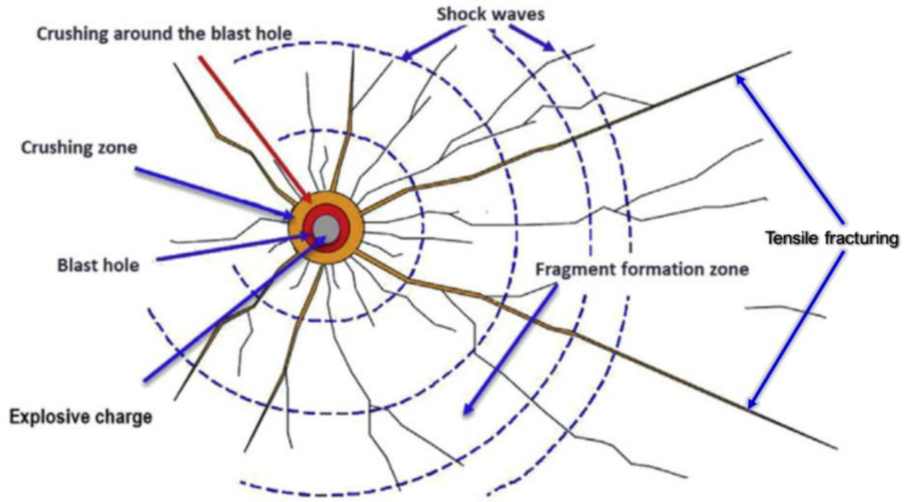
- Structure
  - Major, intermediate & fabric scale
  - Orientation
  - Strength of structural defects
- Rock mass strength
  - Intact strength
  - Discontinuity strength
  - Reliability of test data – sampling bias, scale effect, type of break
- Groundwater
  - Pore pressure grids vs phreatic surface
  - Transient water & Ru
- In-situ stress
  - Regional stress & relation to tectonic/structural environment
  - Stress direction – σ 1, σ 2, σ 3
- Blast damage
  - 'D' zone – damage & stress relaxation zone
  - Damage mechanism – blast damage is a cumulative effect

Calculating the stress on a plane at angle θ to σ_1



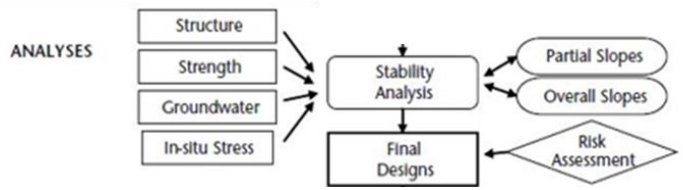


Sorkhabi, 2012



Schematic illustration showing formation of crushing zone, fracture zone and fragment formation zone.

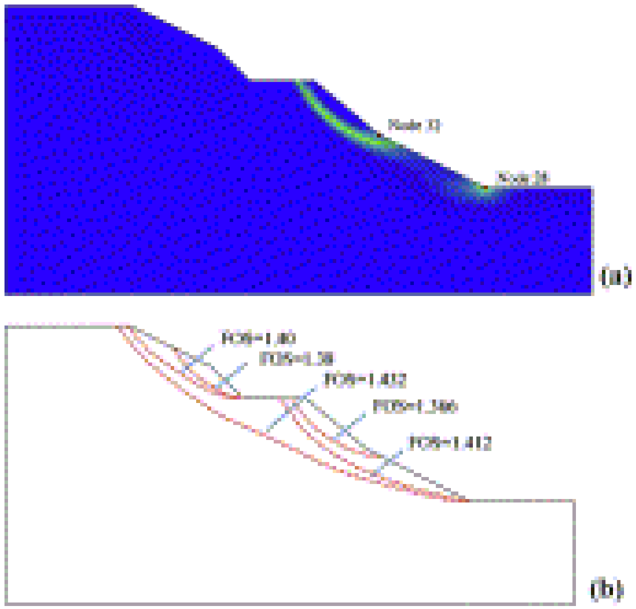
Kabwe, 2018



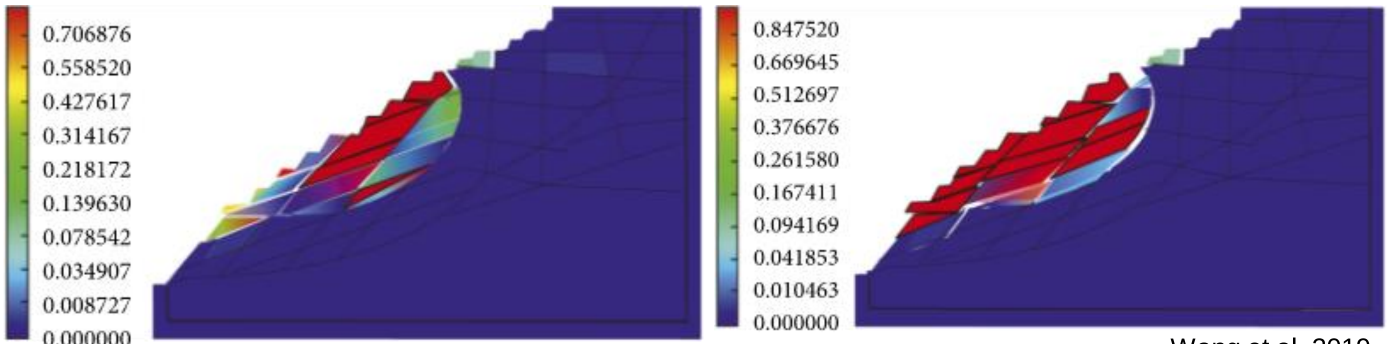
Design analysis

Slope modelling

- Partial slopes
  - Stack and inter-ramp slopes
  - Particular sections of a slope (e.g.: high risk areas)
  - Appropriate level of detail for rock mass, including structure & lithology
  - Groundwater model
  - Alteration & weathering
  - Strength model
- Overall slopes
  - Ramps
  - Economic impact
  - One of the main value levers in open pits
  - Appropriate level of detail for rock mass, including structure & lithology
  - Groundwater model
  - Alteration & weathering
  - Strength model



Liu et al, 2014

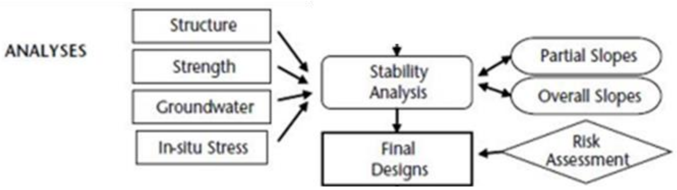


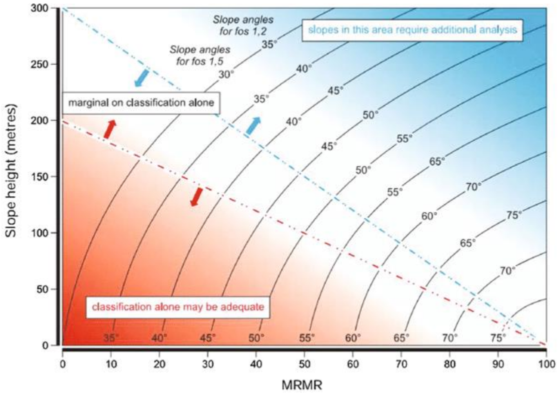
Wang et al, 2019

Design analysis

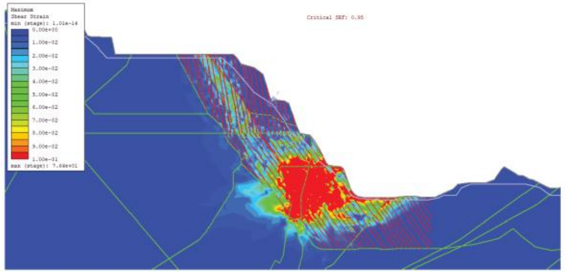
Stability analysis methods

- Empirical
  - Design charts (e.g.: Wedge stability charts, Haines & Terbrugge)
- Limit equilibrium methods (Slide, Slope/W, etc.)
  - Method of slices
  - Ensure analysis method (Janbu, GLE, Bishop, etc.) is suited to the problem
  - Always start with no failure limits applied, then refine afterwards as necessary
  - Limitations – limited to simple failure surfaces and mechanics, no stress evaluation
  - Relatively quick and easy
- Numerical methods (stress-strain behaviour analysis)
  - Continuum methods – FLACSlope, FLAC3D (limited joint modelling ability)
  - Finite element methods – RS2, RS3 (joints and anisotropy modelling)
  - Distinct element methods – UDEC, 3DEC (joints and structures)
  - Boundary element methods – Map3D (modelling of distinct blocks)
  - Time consuming and complex, especially 3D
- Fit-for-purpose
  - Know limitations and advantages of each method
  - Start simple and build complexity as understanding progresses

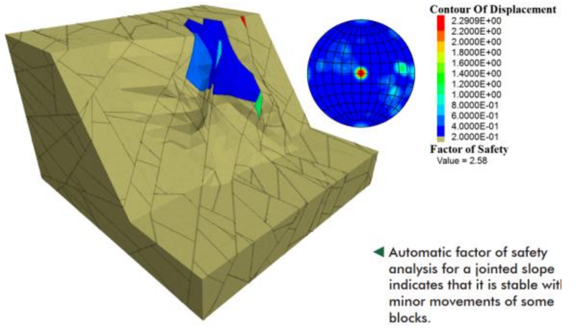




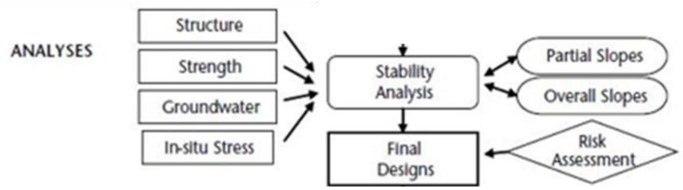
Haines & Terbrugge, 1991



Kabuya et al, 2020



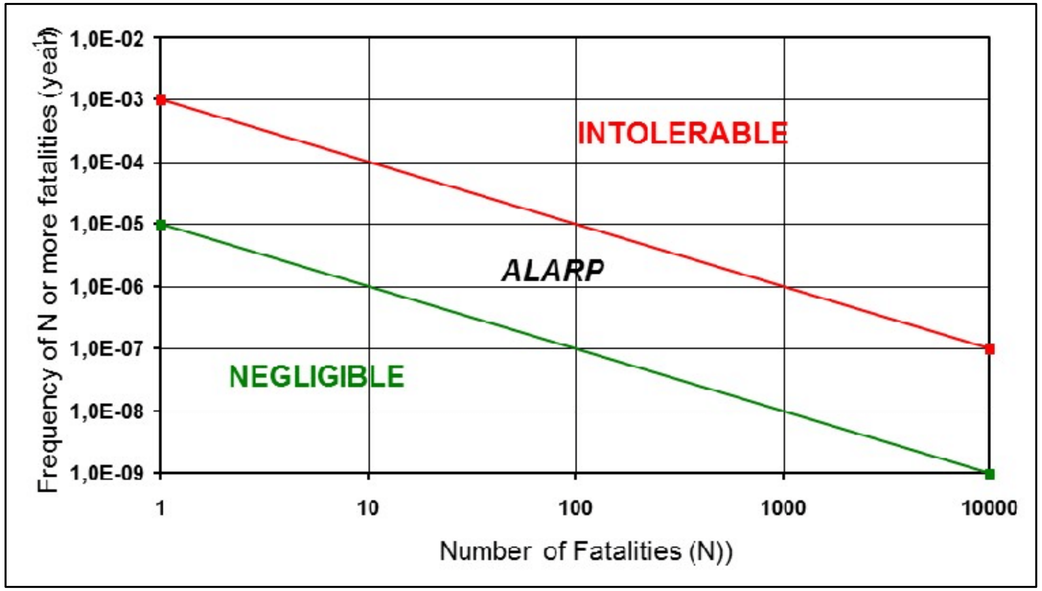
3DEC v5.2 Brochure, Itasca



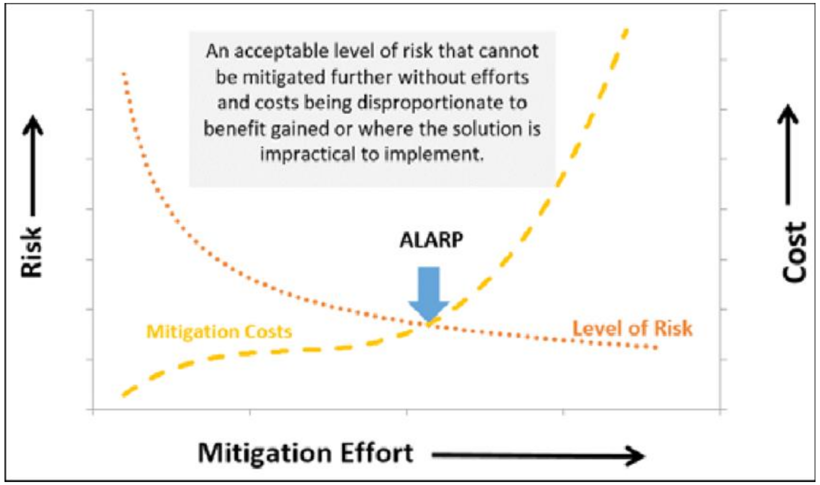
Design analysis

Final slope designs

- Iterative process
  - Geotech provides slope design parameters, mine planning carries out practical pit design, Geotech validates stability of pit design – and revise as necessary, then repeat process
- Risk assessment
  - As low as reasonably practicable (ALARP)
  - Risk matrices
  - Risk = likelihood x consequence
  - Likelihood = probability x exposure
  - Inherent vs residual risk
  - Inherent risk = given slope risk determined by geology, structure, rock mass
  - Residual risk = managed risk – depressurization, slope stability monitoring, rockfall mitigation, SOPs, GCMPs, CoPs, oversight & assurance, etc.



Dias Silveira et al, 2015

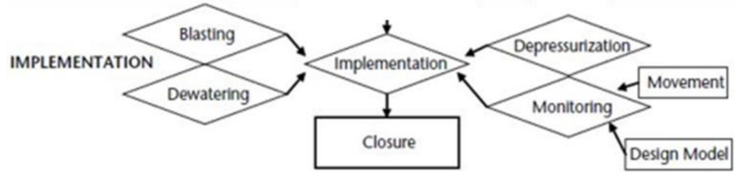


Campbell et al, 2016

06

Implementation

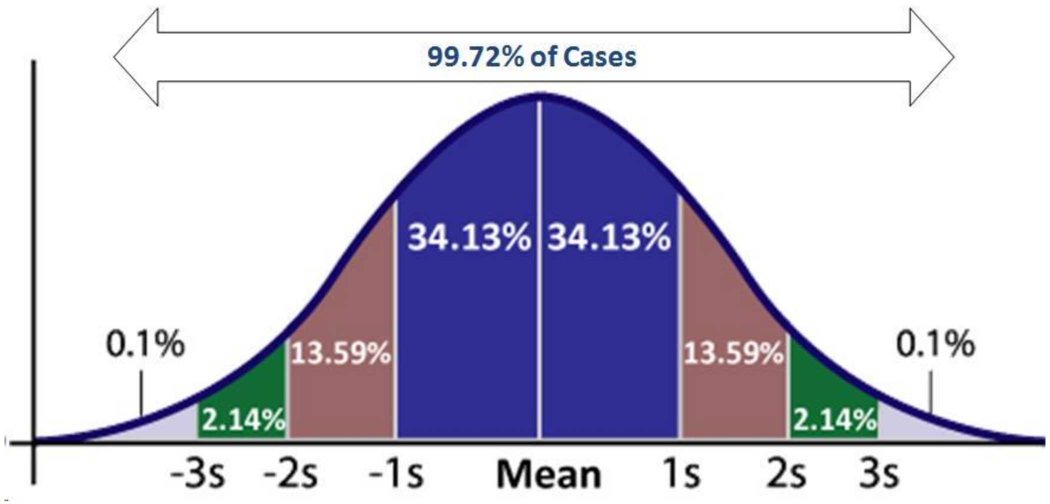
Where practice meets design



Implementation

Design vs operational risk – are they the same?

Design Risk

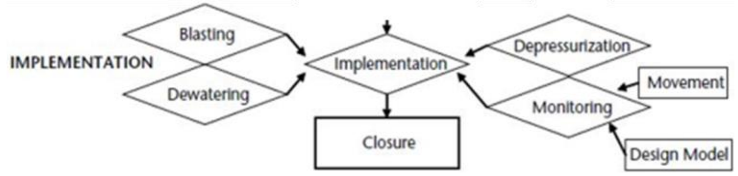


Wikimedia

Operational Risk

Kayesa, 2006

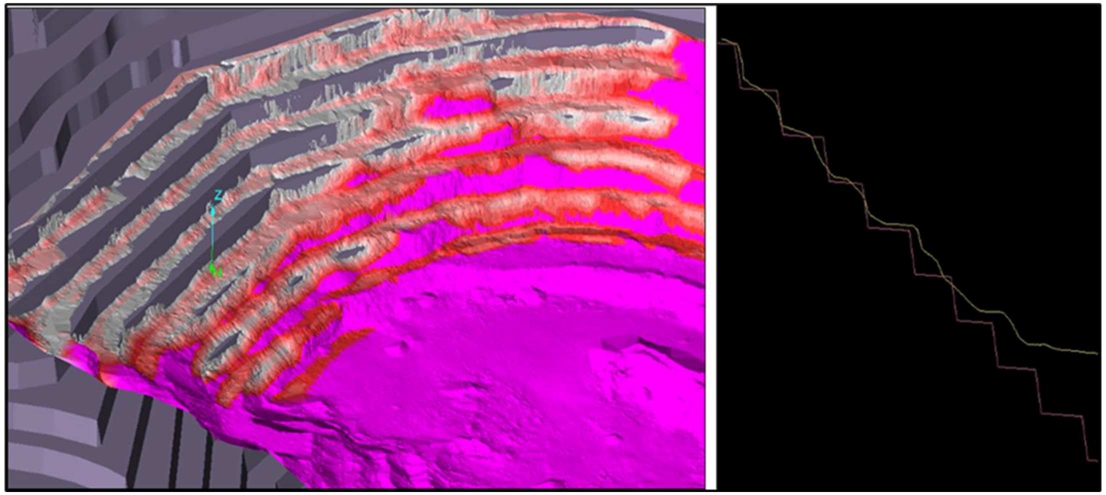
- Deals with making sense of variability in data and data acquisition methods to define design confidence
- Deals with variability in nature and human behaviour when implementing an imperfect design



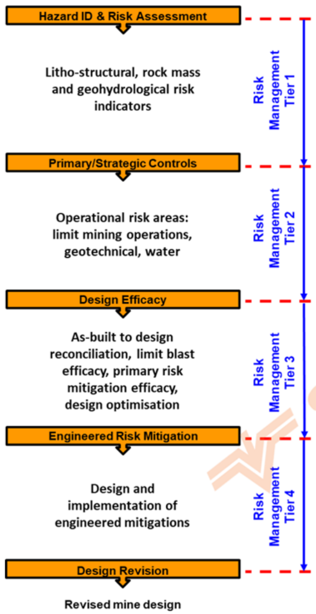
Implementation

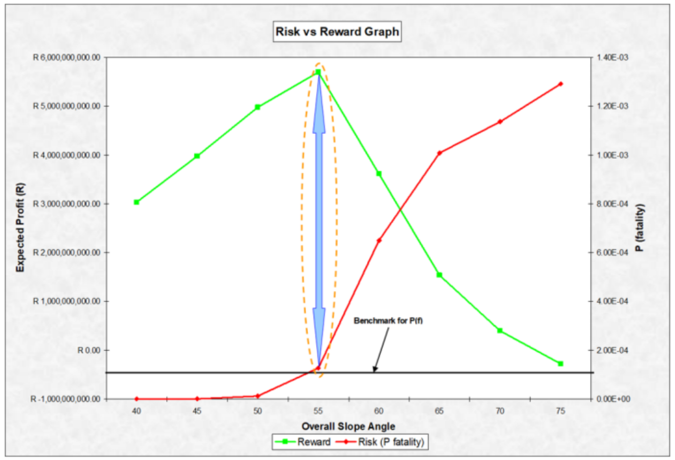
Reconciliation – design vs actual

- Bench positions
  - Achievement of the planned design line
- Bench faces
  - Actual vs design bench face angle
  - Face condition
  - Rockfall risk ratings
- Berm width
  - Actual vs design catchment capacity & rockfall risk ratings
  - Crest breakback
  - Hard toes & toe clean-up
- Slope angle
  - Impact of actual rockfall risks from face conditions and catchment retention
  - Actual vs design overall, inter-ramp & stack slope angles
  - Potential impact on minable reserves
- Geotechnical risk
  - Actual vs design risk profile
  - Required mitigation implementation & management
  - Oversight & assurance

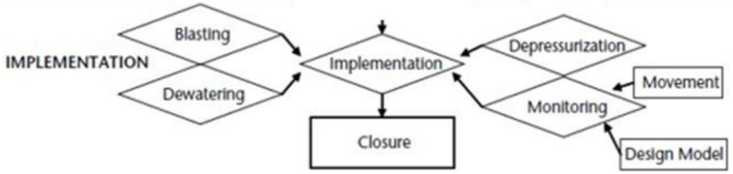


Bester et al, 2012





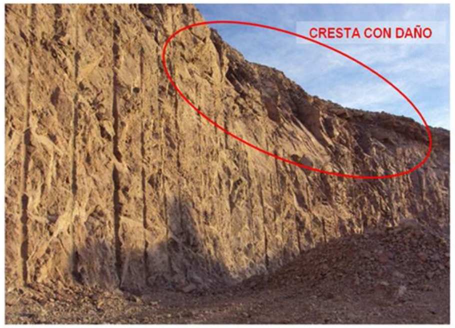
Mossop, 2004

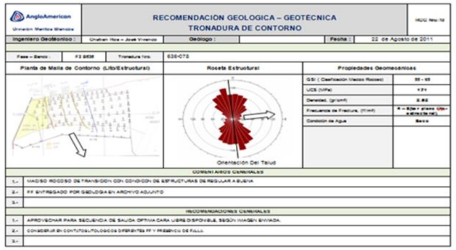


Implementation

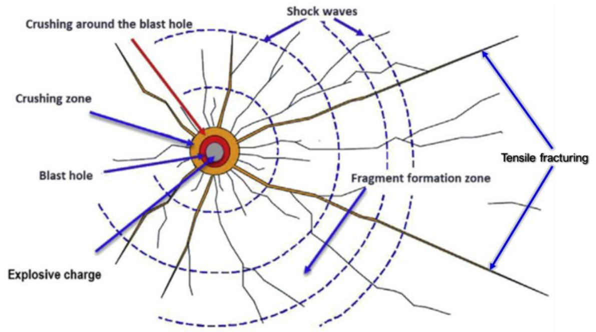
Blasting

- Blast damage mechanisms
  - Compressive
  - Tensile
  - Shock wave\high pressure gasses
  - Cumulative effect
- Blast design elements
  - Charge mass per delay
  - Burden, spacing, stemming, initiation, timing, direction, explosives, powder factor, explosive distribution in hole, etc.
- Good limit blast practice
  - Pre-split, buffers & trim
  - Safety – clean faces
  - Limits energy propagation into the unexcavated rock mass
- Limit blast assessments
  - Face assessment – face damage, pre-split half-barrels, crest breakback, etc.
- Continuous improvement
  - Record of inspections, design parameters, rock mass parameters & results
  - Inform future designs



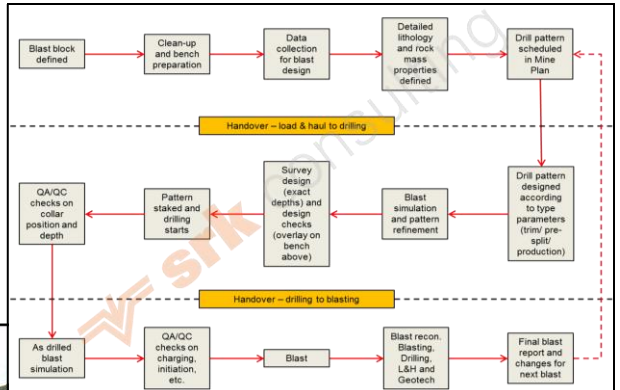


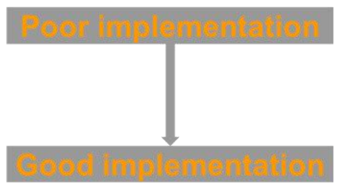
Anglo American, 2012



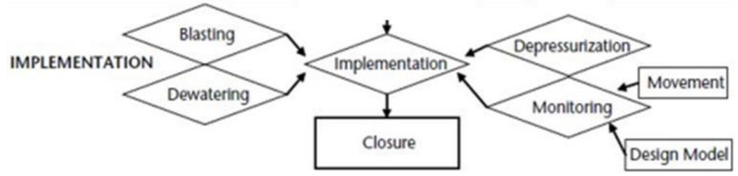
Schematic illustration showing formation of crushing zone, fracture zone and fragment formation zone.

Kabwe, 2018





Mossop, 2014



Implementation

Dewatering & depressurisation

- Dewatering vs depressurisation
  - Only part of the natural geotechnical environment that can be mitigated by engineering the problem away
  - Dewatering – lowering the groundwater table
  - Depressurisation – relief of excess pore pressure (increase effective stress in slope)
  - Primary vs secondary and tertiary structures & water
- Surface water management
  - Good surface management = less infiltration
  - Aims to reduce transient water effects
- Methodologies
  - Pit perimeter wells and pumps
  - In-pit wells and pumps
  - Sub-horizontal drainholes
  - Sumps
  - In-pit and pit perimeter drainage canals
- Monitoring
  - Open wells – water levels
  - Vibrating-wire piezometers
  - Rainfall measurement – often variable across pits

CSIRO, 2009

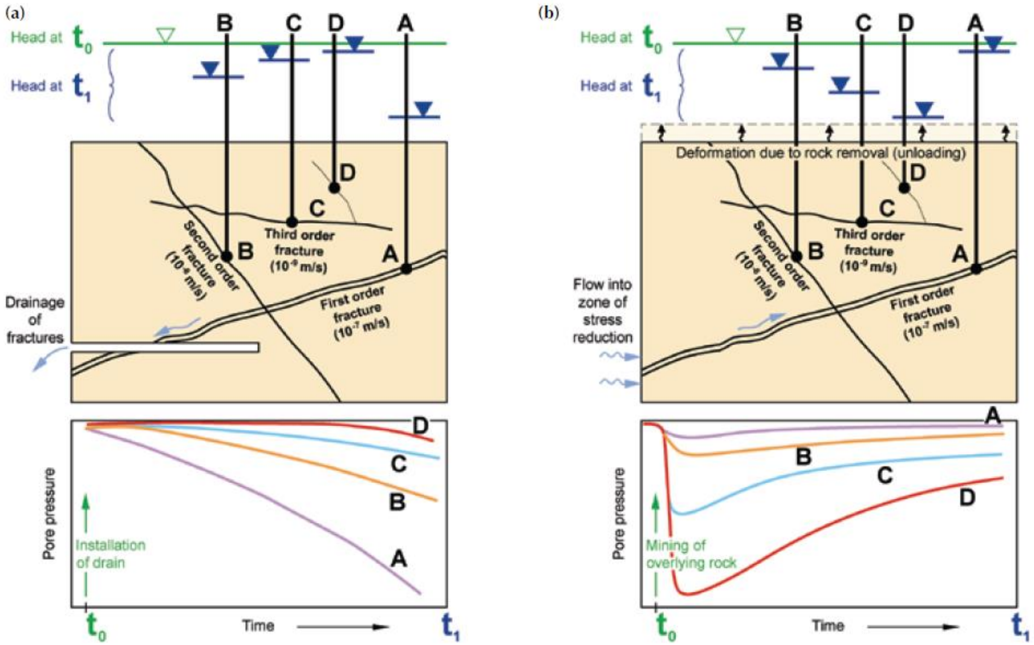
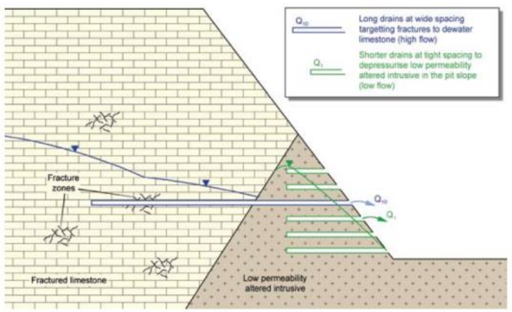
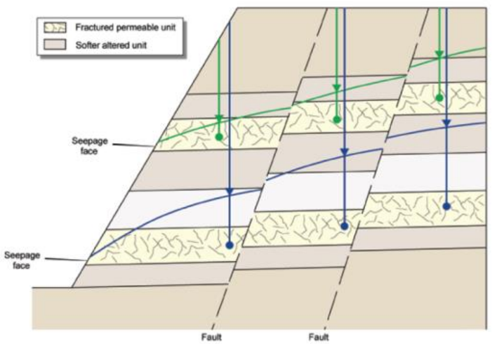
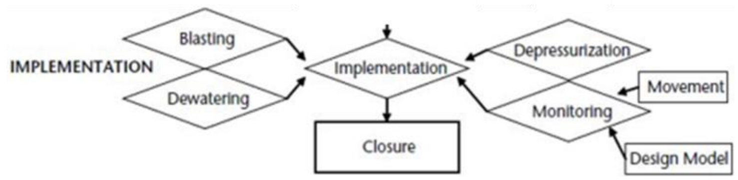


Figure 6.25: (a) Fracture-controlled (dual-porosity) drainage response due to groundwater flow; (b) unloading response in a fractured medium





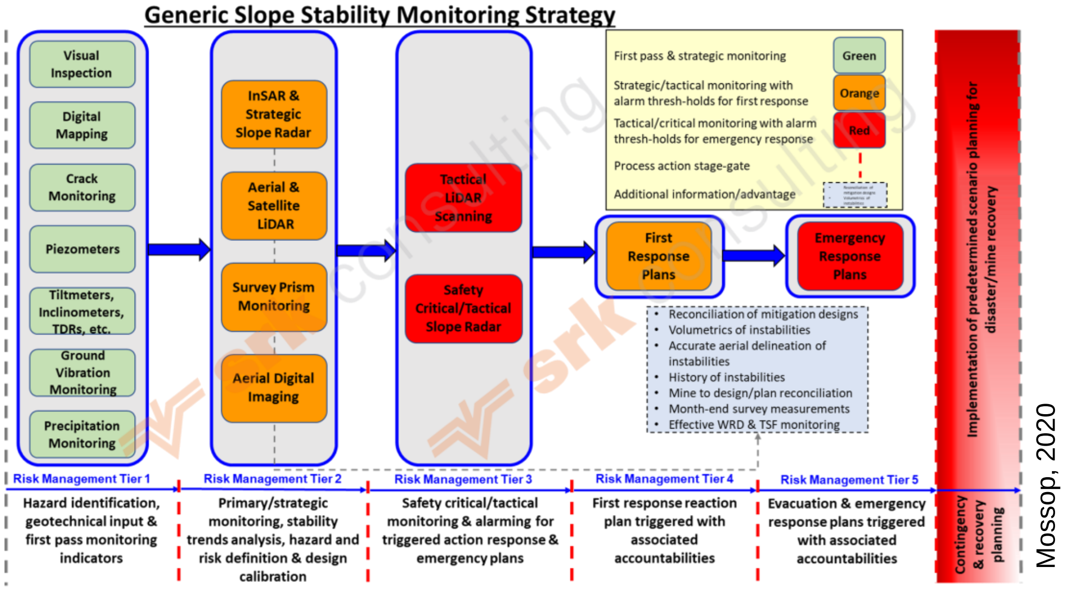


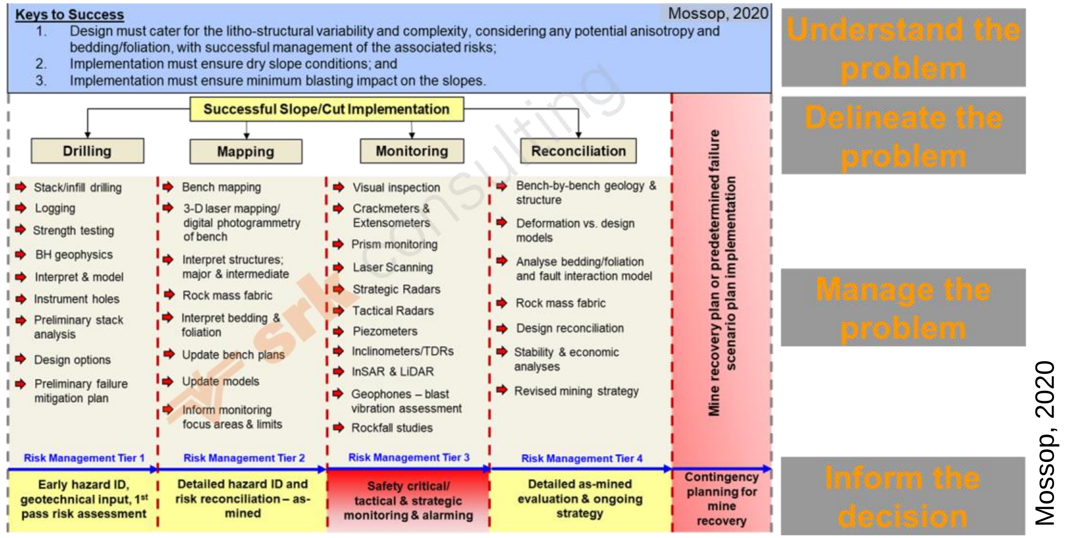
Implementation

Slope stability monitoring

- Purpose of slope stability monitoring
  - Safety – managing personnel & equipment exposure
  - Economic – slope design reconciliation & back-analysis
- Surface vs sub-surface monitoring
  - Surface monitoring systems = reactive in terms of ground deformation, but proactive in terms of safety risk management
  - Sub-surface systems = proactive in terms of ground deformation
- Monitoring methods
  - Satellite & terrestrial radar, laser, survey prisms, GPS, crackmeters, wireline extensometers – surface
  - Borehole extensometers, inclinometers, TDRs, micro-seismic sensors, piezometers – sub-surface
  - Aerial coverage vs point coverage
  - Must be suited to failure mechanism & slope risk profile
- Regulatory
  - Effective ground deformation monitoring is a requirement of the MHSA (1996)

> *"17(7) The employer must ensure that –*
> *(c) where ground movement, as a result of mining operations, poses a significant risk, an effective ground movement monitoring system is in place."*

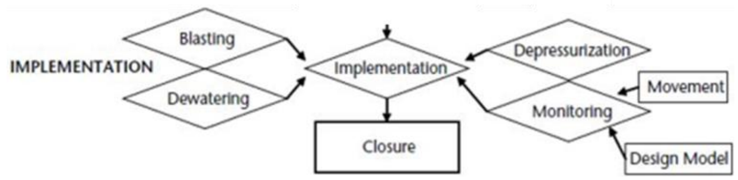




07

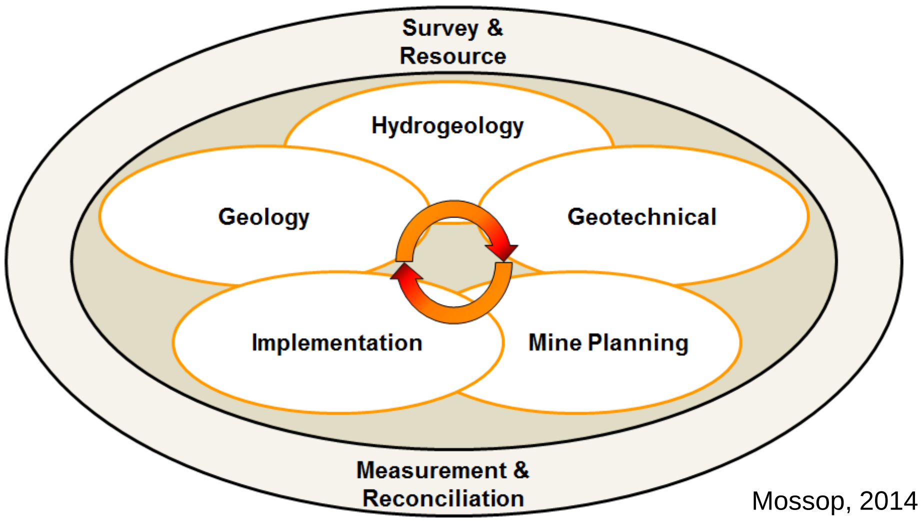
Closure

Responsible mining

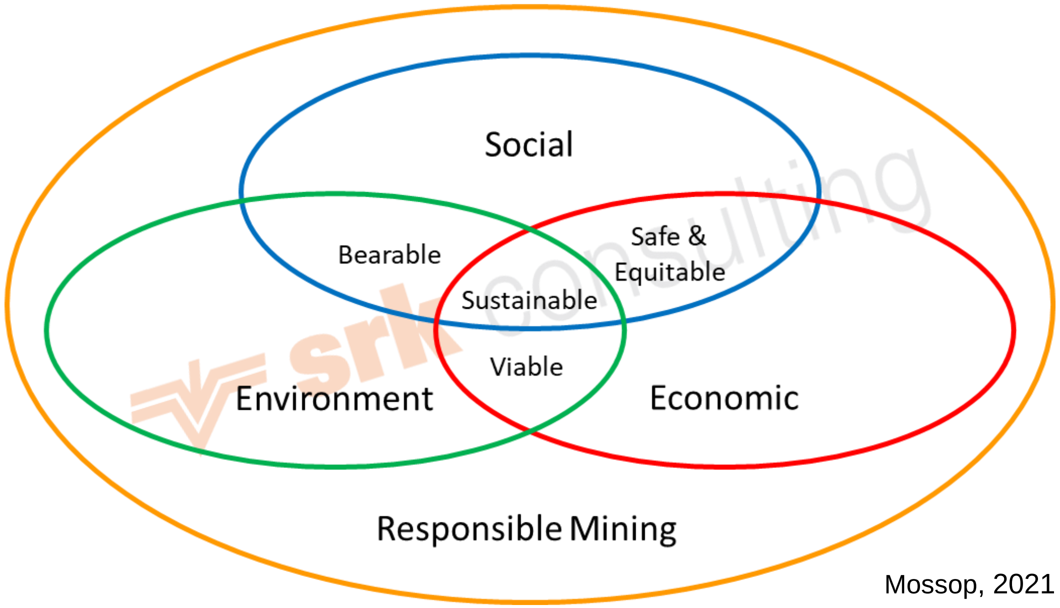


Closure

Where do we go from here – Responsible Mining



Mossop, 2014



Mossop, 2021

- Pillars of Sustainability, applied in an integrated approach define a viable, sustainable mining implementation by being socially bearable, safe and equitable, economically equitable and viable, and environmentally viable and bearable
- Only when all these factors have been satisfied can a mining operation claim to be responsible
- **Geotechnical and Survey input are value enablers across the mining cycle and value chain and are critical facilitators of Responsible Mining Practice, through to Mine Closure Planning & Implementation**

Thank-you