②

(3) Rock mass properties – define the physical characteristics of the rock mass from in-situ and laboratory testing of samples collected from drilling and in-situ sampling programmes. The rock mass consists of intact rock and discontinuities. Therefore intact rock testing and discontinuity strength testing must both be carried out. The main tests conducted are as follows: ①

- a) Uniaxial compressive strength.
- b) Triaxial compressive strength.
- c) Density.
- d) Shear strength tests: ~~Barg~~ ①
- e) Brazilian tensile strength tests.
- f) Base friction angle.

Additionally, in-situ definition of the rock mass is achieved by carrying out rock mass ratings, such as: ①

- a) Bieniawski RMR.
- b) Laubscher MRMR. ①
- c) Q tunneling index.
- d) GSI.

Of utmost importance is the determination of the joint/fabric characteristics, especially: ①

- a) Persistence / continuity.
- b) Orientation – dip/dip direction.
- c) ~~Rou~~ Surface roughness.
- d) Infilling type and thickness. ①
- e) Alteration
- f) Moisture condition.
- g) Surface expression / waviness.

These characteristics determine how the rock mass will react to mining and can be used in defining the relative influence of the intact rock vs. discontinuities in the rock mass. ①

(4) Groundwater – presence of pore water in the rock mass results in pore water pressure that exerts a force in the opposite direction to the cohesion of the rock mass. Effectively ① this results in a reduction of the relative stress in the rock mass and increases the likelihood ~~of~~ for instability. ① Additionally water contained along a structural plane may provide a lubricating effect, ① thereby reducing the frictional forces along the plane and increasing the likelihood of instability (sliding). ①

(5) Blasting – results in gradational damage to the rock mass from the energy wave ① (P, S and R-waves) that propagate back into the slope. ① This damage is both visible and at a micro scale in the rock mass fabric, resulting in a loss of integrity in the rock mass and increasing the likelihood for instability. ①

Question 2

a) Refer to attached stereonets.

There is potential instability (1) in the slope on 4 of 6 wedge intersections and 1 of 4 toppling planes. The toppling failure is considered unlikely due to the orientation of the slope to the ~~four~~ structural planes. Wedge failure is the likely failure mechanism (1) in this slope.

This potential is ~~mainly~~ on the intersection between ~~F2~~ ~~Fault 2 and Fault 1, and~~ Fault 2 and Joint set 1. (1) With some rock shearing, the intersection between Fault 1 and Fault 2 may also provide for wedge instability.

b) Instability = F2 and J1. ✓

∆ Dip = 40° (1) ∆ Dip direction = 130° (1)

(J1) Ratio A = 1,7 with $\theta = 25°$
(F2) Ratio B = 0,8 with $\theta = 20°$ (1)

$$FoS = A \tan \theta_A + B \tan \theta_B$$
$$= 1{,}7 \tan 25 + 0{,}8 \tan 20$$
$$= 1{,}08$$ (1)

(1)

The stability of the wedge is marginal with FoS of 1,0 equating to equilibrium. External influences such as rainfall or blast vibration may destabilise the slope.

c) The calculated FoS is true for the specific wedge analysed, but does not consider cohesion (1) or the effect of rock bridging (1) in the rock mass. Therefore, while kinematically true, (1) the wedge may be held in place by either of these factors, either permanently or for a period of time. This influence can only be determined by further analysis in ~~a~~ a programme such as Swedge, applying cohesion and/or rock mass strength in the wedge solution. (1) For this reason stereographic analysis provides a Probability of Occurrence for instability, defining the worst case scenario, and not a Probability of Failure. (1)

d) i) Visual inspection – to look for tension cracking and signs of water pressure, as well as evaluate blast damage. (1)

ii) Prism monitoring – to ~~det~~ measure the magnitude and direction of any ground displacement in the slope. (1)

iii) Radar monitoring – to give ~~stead~~ areal coverage and provide for early warning and alarming should any critical displacement occur. (1)

iv) Piezometer monitoring – to determine water pressures, only if water is present in the slope. (1)

v) Blast vibration monitoring – to determine the extent to which blasting may affect the slope. (1)

(3) Rock mass model — is the constituent model of the intact rock and minor structure / structural fabric, such as, jointing, bedding, foliation, etc. The rock mass should define the intact rock strength and discontinuity strength for all rock units presents, as well as the relative influence of the intact vs. discontinuity strength. This is done by estimating the extent to which failure planes could propagate along structure vs. ~~through~~ shearing through intact rock. Therefore, the structural persistance is a key element of the rock mass model. This and other elements are determined from rock mass classification, while the intact and discontinuity strength are determined from laboratory and in-situ testing and/or from back analysis of ~~ext~~ existing slope instabilities. This information should be represented ~~of~~ per geotechnical domain, and is utilised in refining the geotechnical domaining. Minor structural orientations are a key parameter in the rock mass model.

(4) Hydrogeology model — represents the presence and extent of groundwater present in the rock mass. To some extent this includes rainfall and surface water management in as far as they affect infiltration rates and fluctuations in the water table. Groundwater that is not free flowing through the rock mass and out of the slope results in a pressure build-up in the available voids in the rock mass. This acts against the normal force, friction and cohesion in the rock mass and has a destabilising effect on a slope. The ~~dist~~ distribution and magnitude of these pressures must be defined in the hydrogeology model, as well as, the potential for flow rates and compartmentalisation of the groundwater along structural and lithological boundaries.

The structural and rock mass models provide the key input parameters for kinematic design analysis, with the rock mass model providing the key inputs for empirical design charts. All 4 constituent model that make up the geotechnical model provide key inputs for more detailed numerical design methodologies, such as, limit equilibrium analysis, finite element analysis, etc.

⑧

The blasting parameters, such as burden and spacing are calculated for the rock mass, according to the following rules:

Burden = 25 to 35 × hole diameter. ✓ 1/2
Spacing = 1 to 1,5 × burden. ✓ 1/2
Bench height = 2 to 1,5 × burden. ✓ 1/2
Subdrill = 0,2 to 0,5 × burden. ✓ 1/2
Stemming = 0,7 to 1,0 × burden. ✓ 1/2

✓ 1/2 The charge mass is calculated from the length of the blast hole vs. stemming length, and diameter and density of the explosives. The blast energy results from the charge mass detonated per timing delay, making single hole detonation timing crucial to achieving good limit blast results. ✓ ①

Ground vibration is measure as the Peak Particle Velocity (PPV) and is the main measurement for blast ~~damage~~ damage. ✓①
✓① The minimum distance for production blasting to the mining limit can be determined by considering the resultant PPV attenuation per charge mass detonated radiating away from the blasthole. This does not take into account the additional ~~E~~ energy dissipation from a pre-split, ① which can be factored in by taking ~~emp~~ empirical PPV measurements specific for the site at distances behind the pre-split line.

c) Qualitative blast ① measurement is achieved by visual inspection of the resultant muckpile, fragmentation, heave, backbreak line and remaining highwall once loading of the muckpile is complete. This can be reported semi-~~q~~ quantitatively by recording parameters such as: ✓①

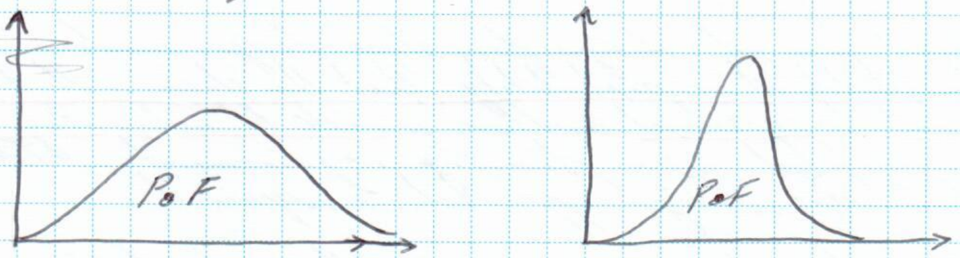
- half barrels present. ✓ 1/2
- hard toes present. ✓ 1/2
- extent of crest damage ✓ 1/2
- extent of face damage ✓ 1/2
- remaining bench catchment capacity. bench ✓ 1/2
- achievement of mining design lines (crest and toe). ✓ 1/2

Quantitative blast monitoring can be achieved by applying technology to directly measure blast performance parameters, such as: ✓ ①

✓① - high speed videography to measure initiation timing, heave, flyrock, site blasting constants for velocities.
✓① - PPV measurement to determine blast vibration, dissipation, blast damage, preferential energy propagation.
✓① - fragmentation measurement to determine explosives ~~eff~~ efficiency and rock breakage.
✓① - Radar slope displacement monitoring to determine elastic and ~~permanent~~ residual slope displacement resulting from the blast.
✓① - Measurement of achieved slope and face angles to determine design compliance.

- Density
- GSI
- m_i
- RMR

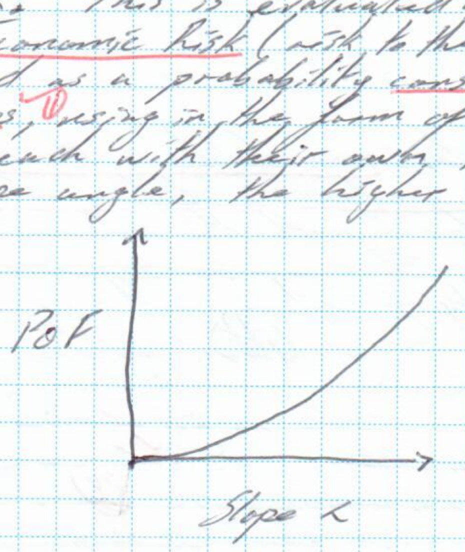
The effect of the level of data confidence on the design can be expressed as follows:



Low data confidence. High data confidence.

The higher the data confidence, the lower the variability in the design analysis outcomes, and the higher the design confidence and likelihood of success. This relates to a lower likelihood of encountering unexpected ground conditions. It stands to reason that the higher the degree of geological and structural complexity in the rock mass, the greater the design data requirements for a probabilistic design approach.

Risk based design then considers the PoF as the residual design risk and seeks to enable reliable management of this risk. This is evaluated as Safety Risk (risk to personnel) and Economic Risk (risk to the business), and can again be expressed as a probability considering several slope design scenarios, using in the form of a range of design slope angles each with their own PoF. Generally the steeper the slope angle, the higher the PoF (often exponential).



These results are then assessed for safety and economic risk respectively via the application of Fault and Event Tree Analysis to determine ~~an acceptable~~ a tolerable risk profile for the pit design. This relates to the level of risk in which there is confidence in the operator's ability to manage. ~~The results are expressed graphically as:~~ Mitigation measures are then applied to the safety and business risks to determine inherent and residual risk profiles for the range of slope designs. The results can be expressed graphically as:

Continued overleaf.

(3) Slope depressurisation may require perimeter wells around the pit, in-pit wells and/or horizontal drain holes. Piezometer holes for monitoring water pressures in the slopes are generally required.

(4) Implementation of an appropriate slope stability monitoring programme linked to stability alarms and pit emergency procedures is crucial. This should be controlled via integrated software at the pit control room and geotechnical offices, and may include:

- Visual inspection
- Crack meters and/or extensometers.
- Survey prism monitoring (preferably automated).
- Laser scanning.
- Photographic records from fixed points.
- Radar slope monitoring.
- Aerial LiDAR
- InSAR satellite monitoring.
- Piezometers.
- Borehole inclinometers.
- Tiltmeters.
- Blast vibration monitoring.

(5) On-going geotechnical data acquisition in support of the slope design is crucial. This is achieved by on-going geotechnical and structural mapping programmes, and on-going geotechnical drilling, sampling and laboratory testing programmes. This allows validations of design input parameters as the mine progresses.

(6) Reconciliation of the actual (excavated) pit limits to the design closes the loop on the design vs. operational performance, as well as the design vs. actual risk profile from both a safety and economic point of view.

These initiatives must be supported by sufficient geotechnical staffing and equipment resourcing, as well as on-going training of technical and operational staff in terms of geotechnical hazard recognition, risk management and operational requirements.