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Suggested framework for design effort and acceptance criteria for underground mine excavations

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Abstract

It is generally accepted that a higher confidence and reliability is required for the design of underground mining excavations as it passes through the various study stages (conceptual, pre-feasibility, feasibility) and the implementation and operational phases. Often this is related to the amount and type of geotechnical data available to support the underground excavation design; however, many additional factors need to be considered. Many of these factors are interrelated and cannot be chosen or dealt with in isolation. This requires consideration of context, intent, consequences, uncertainty, and risk.

The design effort for underground mine excavations needs to consider the following:

- *Excavation design lifetime, use and criticality to continuing mining operations.*
- *Excavation hazard and risk (principally safety and economic, but also reputational and licence to operate).*
- *Anticipated failure mechanisms (scale, frequency, and predictability).*
- *Data availability (confidence, spatial distribution, representativeness, type, quantity, and quality).*
- *Appropriate design methods (related to risk profile and failure mechanisms).*
- *Design criteria which consider the excavation use and serviceability requirements.*

Only by understanding the risks associated with the excavation and its intended use, is it possible to determine the design effort and appropriate design criteria. The paper will discuss the aspects outlined above and propose a scheme that relates the design effort to the excavation risk. This approach has been useful for providing a framework, for alignment of consultants and internal stakeholders in prioritising design study and investigation area focus, and commensurate rigour in approach for recent projects.

Keywords: *design, acceptance criteria, uncertainty, risk*

1 Introduction

Various approaches can be adopted in the design of underground mining excavations. The design approach needs to consider the confidence level and reliability of the underlying geotechnical model and design inputs, as well as the excavation criticality to ongoing operations and the expected life of the excavation. The excavation design needs to consider the risk in terms of people, equipment and economics. The design will pass through various stages during mining study but an implementation design will ultimately be needed.

The level of design effort required in an implementation design is influenced by many factors but the most important are the level of uncertainty and variation associated with the geotechnical model and input parameters, criticality of the excavation, life and serviceability requirements, and the acceptable risk profile. A robust understanding of these factors and others will inform the level of design effort, design methodology and design acceptance criteria (DAC). This paper discusses these aspects and suggests a framework for developing underground mining excavation designs ready for implementation.

2 Design process and level of effort

A variety of design methods are used for underground mine excavation design. These can broadly be classed as empirical, observational, analytical and numerical methods (Dunn 2014, 2015, 2019). Irrespective of what design method is used and whether the design approach is deterministic or probabilistic, the reliability of the design is largely influenced by the reliability of input parameters.

The reliability of design inputs is a function of ability to reduce or minimise geomechanical uncertainty. Several authors (Peck 1969; Bieniawski 1992; Stacey 2004, 2008, 2009) have written significant papers on geotechnical design and all three authors outline the need for minimising uncertainty or considering unfavourable variations in design inputs. A review of the design principles described by these authors is provided by Dunn (2013) and will not be repeated in this paper.

The geotechnical model is generally the basis of a geotechnical design. Steffen (1997), Haile (2004) and Haines et al. (2006) have all provided guidance on the geotechnical data requirements and qualitative descriptions of the geotechnical model relative to the study or design stage. Read & Stacey (2009) provide guidance on target confidence levels required for geotechnical models necessary for large open pit slope design for different project stages. Cepuritis & Villaescusa (2012) outline the data and design reliability required for open stope span design, as well as what design methods should be applied for different project stages. The suggested reliabilities are similar to those proposed by Read & Stacey (2009) and are as follows:

- Conceptual: <50%.
- Pre-feasibility: 50–60%.
- Feasibility: 60–70%.
- Initial construction: 70%.
- Early to mid-life operations: 80%.
- Mature operations: 85%.

Cepuritis & Villaescusa (2012) also outline design reliabilities for each stage which are the same as the rock mass or geomechanical model reliabilities. The confidence of the design and design reliability can also be linked to the level of design effort.

Silva et al. (2008), based on earlier work by Lambe (1985), describe the relationship between level of engineering design input including the underlying investigations and the Factor of Safety (FS) and Probability of Failure (PF), as shown in Figure 1. Whilst their work was predominantly on embankment slopes, the concept is valid for any geotechnical/geomechanics design. Four categories of design have been defined:

1. Category I – High failure consequences; facility designed, constructed and operated with a high level of engineering practice (best).
2. Category II – Ordinary facilities designed, constructed and operated with standard engineering practices.
3. Category III – Facilities without site specific design; temporary facilities with low failure consequences.
4. Category IV – Facilities with little or no engineering (poor).

This can be interpreted as meaning that if there is limited data and considerable uncertainty in the design inputs and limited design effort, it is necessary to consider a more conservative design (higher FS to satisfy an acceptable PF) to achieve an acceptable risk. This can be directly related to the choice of appropriate DAC.

An important component of the design effort is an understanding of what resources are needed to undertake the required design work at the appropriate level. This needs to consider the experience levels required; you cannot develop a Category I design without having access to highly skilled, competent and experienced geotechnical engineers. This is further complicated by the need to integrate varying degrees of experience between site, corporate and consultant resources and ensure that they are aligned with company goals.

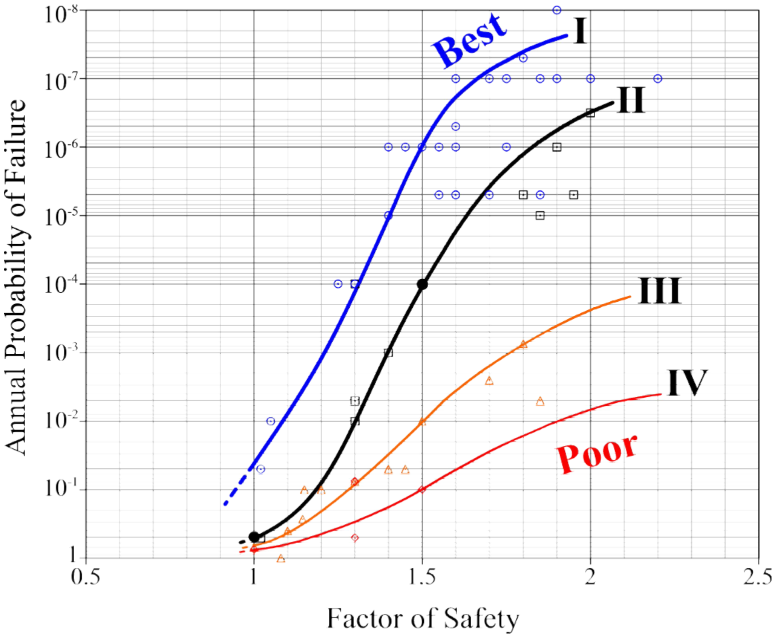

Figure 1 **Factor of Safety versus annual Probability of Failure for 'best' engineering design practices (Category I) and 'poor' engineering design practice (Category IV) (after Silva et al. 2008)**

3 Design considerations

The following section discusses some of the aspects that need to be considered in the design of underground mining excavations and the formulation of the design effort.

3.1 Excavation lifetime and criticality

The expected serviceable lifetime, use and criticality of continuing mining operations of an excavation will determine how much effort is required in the design of that excavation. The level of design effort required for shorter life production excavations such as ore drives will be less than that required for long-term excavations such as access portals, declines, shafts and underground infrastructure (pump chambers, crushers, workshops etc.). This influences both the data requirements and the level of design effort.

Prior to the design of an excavation, it is necessary to consider how critical an excavation is to ongoing operations. Failure of a mine access (decline or shaft) will generally bring production to a halt, although the presence of a second access will allow for people to be extracted if needed. Failure of large underground infrastructure such as a crusher will generally result in disruptions, although some limited production may be possible. The loss of a critical intersection may restrict access to areas of the mine. Prior to undertaking any design, it is important that risk assessments consider the vulnerability of the operation to the failure of specific excavation types.

3.2 Excavation hazard and risk

It is important to understand the hazards that are associated with underground excavations and the risks they may pose. This is related to the ground conditions (weak or competent ground, structures), loading conditions such as high stresses (depth, in situ stress field) and stress changes associated with mining, groundwater conditions, dynamic loads associated with mining-induced seismicity etc.

It is also necessary to consider the exposure of people and equipment within an excavation; main accesses will have high exposure for both, whilst some production excavations may have low personnel exposure but high equipment exposure.

When considering economic aspects, it is necessary to understand what impact a failure will have on an operation. Loss of access to a few stopes is likely a minor to moderate consequence, loss of a crusher chamber may be a major consequence, and loss of a main access might be a force majeure event with significant economic loss.

3.3 Anticipated failure mechanisms

Prior to undertaking design analysis, it is necessary to understand the likely failure mechanisms. These can be assessed from the geotechnical model (geology, structural, rock mass, intact rock etc.) and the expected loading conditions. Typically, the following is considered:

- Rock mass driven: weak rock mass, weak zones, deterioration over time, squeezing ground, unravelling.
- Structure driven: wedges, blocky ground, bedded strata, foliation, faults and lithological contacts.
- Stress driven: high stresses, changing stresses, lack of confinement.
- Dynamic loading: mining-induced seismicity.

In many cases it is a combination of geotechnical conditions and loading conditions. Generally, it is necessary to understand how loading conditions will change over time; for example, a tunnel may be subject to moderate stress during excavation, followed by high induced stresses as mining takes place, followed by a loss of confinement (lower stress) as mining progresses. This stress path will govern the type of failure that may occur. Initially, there may be moderate stress damage followed by an increase in stress driven damage and finally unravelling and gravity induced falls of ground as loss of confinement occurs.

Understanding the likely failure mechanism and how this may change over time is critical in choosing the appropriate design method and types of analyses needed. It is also necessary to understand the scale, frequency and predictability of the failure mechanisms as that would influence the DAC choice and required design effort.

3.4 Data availability and geotechnical model

The type, quantity, spatial distribution and quality of data available will determine the confidence and reliability of the geotechnical model and its underlying components. The required confidence level increases as the design progresses through the study lifecycle until the implementation stage. At this point, the geotechnical model is expected to be mature stage; however, it may be necessary to upgrade the model depending on the excavation type and criticality to the operation. When developing the geotechnical model, it is necessary to minimise uncertainty. This topic has been covered by various authors (Hadjigeorgiou & Harrison, 2011; Hadjigeorgiou 2012; Fillion & Hadjigeorgiou 2013).

Typically, the feasibility level study geotechnical model is sufficient for a decline or production ore drives, and cover drilling and appropriate ground support trigger action response plans (TARP) can cater for unexpected (but foreseeable) ground conditions for these small dimension (<6 m) excavations. In the case of portals, ventilation shafts, access shafts etc., location-specific geotechnical investigations are required as they are high exposure, long-life excavations. For large underground excavations such as crushers and main pump stations, specific geotechnical investigations are also required as these are long-life and wide-span excavations critical to ongoing operations.

3.5 Appropriate design methods

The design method and approach that will be applied is related to risk profile and the anticipated failure mechanisms, as well as whether the design approach is deterministic or probabilistic. In geotechnical engineering, a variety of design methods are used for underground excavation design. These can broadly be classed as empirical, observational, analytical and numerical methods and these are briefly described in this paper. Irrespective of what design method is used and whether the design approach is deterministic or probabilistic, the reliability of the design is largely influenced by the reliability of input parameters.

The choice of the design method is dependent on the design complexity. For example, empirical methods are often appropriate for standard dimension tunnels (<6 m wide) in reasonably competent ground; however, if these tunnels are expected to be developed in squeezing ground conditions, then a displacement-based criteria using three-dimensional (3D) numeral modelling is probably more appropriate.

3.5.1 Empirical methods

These include various rock mass classification systems such as the Q-system (Barton et al. 1974) and Bieniawski's (1976; 1989) rock mass rating, which are used both to classify the rock mass as well as for ground support design and excavation design. Laubscher's (1990) mining rock mass rating is widely used in cave mining designs whilst the modified stability graph method (Mathews et al. 1981; Potvin 1988) is widely used in open stope design. There are a number of empirically derived pillar design formulae (Hedley & Grant 1972; Lunder & Pakalnis 1997) as well as Carter's (2000) scaled span method for crown pillar design.

The above are just some examples of various empirical systems used in underground excavation design. It is worthwhile noting that some of these systems are used to classify the rock mass as well as developing design inputs and, in some cases, they are used as a design method.

3.5.2 Observational methods

These include the observational design approach as outlined by Terzaghi (Peck 1969) and systems such as the New Austrian Tunnelling Method, and observational cable bolt design (Hutchinson & Flamagne 2000).

3.5.3 Analytical methods

These include a variety of closed form solutions such as the Kirsch equations, beam theory (Beer & Meek 1982), key-block methods (Goodman & Shi 1985) etc.

3.5.4 Numerical methods

Numerical methods range from simple two-dimensional elastic boundary element analyses to more complicated two-dimensional analyses using tools such as RS2, FLAC and UDEC. 3D analyses range from boundary element analyses using codes such as Map3D (Wiles 2023) to more complicated elasto-plastic finite element (e.g. Abaqus), finite difference (e.g. FLAC3D) and distinct element methods (e.g. 3DEC). Large-scale, advanced 3D models are appropriate for assessing mine scale designs and complex geometries and interactions, whilst simpler two-dimensional models are suitable for assessing simple geometries such as tunnels.

Fundamentally, decisions on which analysis tool is most appropriate will depend on i) type, quality and quantity of data, ii) mode of instability/style of deformation expected, iii) scale and iv) geological and excavation geometry. Starfield & Cundall (1988) provide timeless and excellent guidance for an approach to developing numerical models for rock mechanics applications. Basson & Dunn (2009) provide practical guidance on numerical modelling for underground mines from the perspective of a rock engineering practitioner.

3.6 Design acceptance criteria

All designs require some level of DAC against which the design can be evaluated. Criteria such as FS and PF are commonly used. There are also approaches such as risk-based design (RbD) and performance-based design (PbD) which are closely linked to each other. When selecting DAC for underground mining excavations, it is necessary to consider the excavation use, serviceability requirements, criticality to the ongoing operations, design life and risk in general (safety, equipment, economic). The choice of DAC is linked to the risk tolerance and design effort.

There are multiple DAC for underground mining excavation and these include:

- FS and PF: typically used for ground support design, pillar design, crown pillars, backfill design, raisebore assessments etc. Could be replaced with PbD if the deformation and performance are well understood and there is tolerance for the anticipated deformation.
- Deformation limits: high deformation excavations where serviceability is the issue, i.e. you cannot stop the deformation but you can try and control it until you lose serviceability (squeezing ground, dynamic loading etc.) and need rehabilitation. This could be defined as a PbD or a RbD.
- Acceptable dilution: how much overbreak or underbreak can you accept (economic acceptance rather than safety)? This is another example of a PbD.
- Acceptable draw performance and recovery in cave mining.
- Shaft design covering ventilation, rock handling and personnel: FS or deformation limits applied to different components of the shaft system (e.g. lining, steelwork, histing cable etc.).
- Rock pass design: stability and wear; RbD.

The choice of DAC is closely associated with the degree of uncertainty (covers both not knowing and natural variability); high uncertainty means a more conservative DAC is likely needed. This can also be related to the concept of design effort described by Silva et al. (2008) which relates FS and PF to effort in data collection and design.

Hoek et al. (1995) suggest an FS of 1.3 is suitable for temporary mine openings whilst values of 1.5 to 2.0 are required for permanent excavations. However, the need to conduct sensitivity studies and understand the impact of input parameter variability is stressed. Hoek (1991) provides further guidance on acceptable rock engineering design.

Whilst FS and PF have their applications there are instances where they are not applicable; for example, how do you apply these to an environment where there is a high degree of deformation (e.g. squeezing ground, dynamic loading etc.). In these cases, an RbD or a PbD is more appropriate. This would also be applicable to stope and cave performance.

Defining DAC is critical to the design process and must be done; however, rather than applying a cookie-cutter approach, it is more sensible to develop an understanding of the following in formulating DAC:

- Uncertainty in design inputs.
- Likely instability mechanisms.
- Risk tolerance and a clear definition of what is acceptable.
- Design effort: related to uncertainty and risk tolerance.

By clearly articulating these, specific DAC can be defined for different excavations. This is a critical step in assessing the design effort required.

4 Excavation design effort scheme

A range of factors that need to be considered in the design of underground mining excavations have been outlined, although it is noted that the list is not exhaustive. These technical factors need to be incorporated into the larger governance framework in place in many mining companies and this is demonstrated later in the paper.

For various reasons, misalignment between the demands and availability of both internal and external resources often requires careful prioritisation and focused effort to ensure that both tactical and strategic design objectives are satisfied. This challenge is often compounded by separate teams, with different accountabilities needing to harmonise design deliverables (e.g. site technical services team responsible for operational design changes and corporate or life of mine teams responsible for long-term or special project designs – often with consultant support). In alignment with an RbD approach and in support of consistent corporate assurance and governance processes, a framework was needed for prioritising design work, providing consistent guidance on minimum location-specific input data, level of analysis rigour, and level of review and design approval required. These factors can be related to the design effort framework defined by Silva et al. (2008).

The process has clear business risk abatement objectives but is also critical to achieving corporate safety commitments as well as preserving the intent to safely deliver maximum possible production. Central to this is a rigorous risk assessment of each design element and must consider safety and business plan risks.

It is important that this assessment includes not just perceived consequence outcomes, but also the knowledge base confidence level (design uncertainty). This should reflect the reasonably foreseeable occurrence but be aligned with credible occurrences. Credible modes of instability and inherent risk are assessed based on a confidence–consequence approach. Central to this workflow is a failure modes effects and analysis check which involves: hazard screening, risk assessment, and risk appetite, tolerance and capacity. The steps in this process are as follows:

1. Gather data for analysis.
2. Identify failure effects and causes.
3. Assess occurrence and severity.
4. Assess asset criticality.
5. Evaluate risk mitigation options/actions.
6. Analyse mitigation effectiveness.
7. Document findings.

The confidence–consequence concept, as applied to geotechnical mine DAC, is discussed by Adams (2015), and Macciotta et al. (2020) for open pits, Hawley & Cunning (2017) for waste dumps, and de Graaf et al. (2019) and Carter et al. (2022) for mine closure. There is opportunity to review and expand this concept to underground excavation design. In the interim, rather than adjusting the DAC, minimum data confidence levels (quantity and quality) are defined to ensure that the risk is adequately addressed.

Design projects are rated based on:

- Whether these are ‘out of ordinary’ conditions (i.e. not already covered with); ‘business as usual’ standard design classes and existing design TARP.
- Size and geometry of planned excavation.
- Availability and quality of location-specific geotechnical input data (model confidence).
- Design service life (expected design demand changes during this period): differentiating between primary orebody access, and short-term accesses.
- Business consequences of not achieving design objectives.

Table 1 is an example matrix with four main categories defined. Minimum data requirements, typical analysis techniques, and minimum review and assurance expectations are linked to increasing business risk class. The philosophy is an increased design effort relative to the assessed risk, for example an elevated or high risk would require a Category I or Category II design.

Table 1 Design complexity: design rigour guideline matrix

Level of complexity		**Class I**	**Class II**	**Class III**	**Class IV**
Overall risk class description		**Low risk**	**Moderate risk**	**Elevated risk**	**High risk**
Description (conditions)	Any of these conditions exist (combined risk assessment outcome)	Routine conditions; existing designs; low personnel and equipment risk exposure; low consequential failure risk; short-term design life (<24 months); excavation width and height <6 m	Moderate deviation out of tolerance for standard (existing) design; short- to medium-term lifespan (<36 months); moderate personnel and equipment risk exposure; excavation width and height <6 m, or exceeds overbreak tolerance	Moderate-sized excavations (>6 m wide and high); long-term ore passes, vent raises (>36 months' service); no significant stress change anticipated; significant (elevated) personnel and equipment exposure risk consequence; >36 months' design service life. General stope design/minor adjustment to mine sequencing	Large excavations (>8 m wide and high); long-term service (>36 months); significant (high) personnel (safety) and equipment exposure risk; probable stress change effects over life of service. Life of mine strategy, mining method review/evaluation
Generalised process	Responsible and consulted resource to approve (agree to) process components at outset of design process (acceptability of empirical methods; extent of data characterisation)	Existing design TARP; empirical design checks; generalised domain rock mass properties; deterministic DAC	Empirical design review: location-specific mapping and characterisation (focus on joint set characterisation – condition, spacing and continuity); kinematic analysis (Unwedge); deterministic DAC	Empirical design review; local mapping and characterisation; additional (proximal) drilling data – may require targeted drillhole; kinematic analysis (Unwedge); deterministic DAC; 2D numerical analysis; monitoring; small-scale project management	Detailed characterisation (site specific); upfront planning and scheduling (planned additional drilling); combination (holistic) design approach: basic (empirical) through to advanced (kinematic, numerical, 2D (checks), 3D designs, deterministic and probabilistic; monitoring and risk management; full project management
Case examples		Ad hoc support recommendations for minor alterations to standard excavations within conditions as described by TARP	Limited span excavations (<6 m), ad hoc support requirements not explicitly addressed within current design; conditions within known ground classes and current design; loading bays; workshops	De-gritting stations, loading bays, silo chambers, long lifespan workshops and loading bays, dams, long shafts (>500 m), wide diameter (>4.5 m) ore and vent passes (also dependent on excavation method)	Crusher chambers, shafts (men and materials), LOM sequence review/mining method/strategy changes

An important consideration is the level of review and sign-off needed for higher risk excavations. For example, moderate and elevated risk (geotechnical/operation/business risk) would require review and sign-off by a principal geotechnical engineer (PGE); whereas a high risk might require review by a geotechnical review board (GRB).

It is also necessary to have a mechanism to deal with new, revised, and ad hoc non-standard excavation designs that affect any development for the life of the mine and principal infrastructure. Given the combined upfront effect on costing, execution timing, long-term safety and reliability, particularly for the extended life of the project, the consequences of these designs and recommendations are significant. It is therefore suggested that all such designs and recommendations are technically ratified at an appropriate level before issue for implementation. Table 2 outlines an example responsibility, accountability, consulted and informed (RACI) matrix for undertaking, reviewing, and approving significant designs.

The assurance engagement and input process should be governed by the combination of discrete scheduled processes including internal inputs and outputs reviews, annual discipline health audit and other audits, routine operational and design reviews undertaken at a PGE level, as well as external assurance reviews such as GRB and third-party audits.

Table 2 Generalised design, review, approve RACI (responsible, accountable, consulted, informed)

	Corporate/ consultant PGE	**Site geotechnical manager**	**Senior geotechnical engineer**	**Geotechnical engineer**	**Technical service manager**
Data collection	C	C	R	R	A
Characterisation	C	C	R	R	A
Geotechnical model	C	R	R	R	A
Design	C	R	R	–	A
Peer review	C	R	–	–	A
Technical review	R	A	–	–	I

5 Conclusion

The design of underground mining excavations is a multifaceted task that needs to consider many technical factors as well as corporate requirements in terms of safety and economic risks, ongoing operations, and governance. Depending on the complexity of the design and criticality of the excavation, different levels of design effort may be required.

When assessing the level of design effort, it is necessary to consider the following:

- Uncertainty associated with geological and geotechnical models.
- Likely instability mechanisms.
- Hazards and risks (safety, equipment and economic) associated with the excavation.
- Required design serviceable lifetime.
- Criticality of the excavation to ongoing operations (versus available redundancy).
- Corporate risk tolerance.

Only once there is a clear understanding of these factors can an appropriate design program and design level of effort be defined. This includes the development of DAC that are aligned with the excavation lifespan, criticality, likely instability mechanism and risk tolerance. Once this has been done, the design program can be defined on terms of level of effort for defining data requirements, design analyses complexity and methods, resources required and corporate governance and assonance requirements.

None of these aspects can be dealt with in isolation therefore a holistic view is needed to define an appropriate level of the design that meets the corporate risk and governance expectations.

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