Uncertainty in ground support design and implementation in underground mining

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Abstract

In underground mining, there are a number of uncertainties in the ground support design process and during implementation of ground support designs. The minimisation of geological uncertainty is one of the rock engineering principles outlined by Bieniawski (1992) and by Stacey (2004, 2009). Generally, there are two main types of uncertainty; uncertainty due to naturally variable phenomena in time or space and that due to lack of knowledge or understanding (Baecher and Christian, 2003). McMahon (1985) listed six types of geotechnical uncertainty: risk of encountering unknown geological conditions; risk of using incorrect geotechnical criteria; bias and/or variation in estimated design parameters is greater than anticipated; human error; design changes and excessive conservatism.

All of these types of uncertainty are encountered in the design of ground support. They occur in the form of uncertainties around the design block size; loading conditions; spatial variability of ground conditions; rock mass strength; shear strength; discontinuity spacing; discontinuity orientations, etc. Uncertainty is not only present in the design of ground support, but also in the implementation phase. This occurs in the form of variations in installation quality; adherence to patterns and spacing; human error in the application of the correct ground support standard; not identifying a change in ground conditions, etc.

Conventional deterministic and empirical design methods do not adequately cater for uncertainties in the design of ground support. Probabilistic design methods, such as the Point Estimate Method and Monte Carlo Simulation, can be applied to better understand the uncertainties in the design process. Limiting uncertainties in ground support implementation can be achieved by training of operators and supervisors; good supervision of implementation; and a well-considered and managed quality control programme. It is important to feed the results from the quality control and monitoring programmes back into the design.

In this paper, the various uncertainties with ground support design and implementation will be reviewed and discussed in context of McMahon (1985) and Baecher and Christian (2003). The application of probabilistic design methods in ground support design and feedback of quality control data will be discussed.

1 Introduction

Ground support is critical in ensuring the stability of underground mining excavations, thereby contributing to safety and uninterrupted production. A number of methods, including empirical, analytical and numerical, are applicable when designing ground support. Generally, a deterministic approach is applied, but probabilistic methods are also available. When designing ground support, it is important to consider the implementation phase. Designs should be practical to implement. There are a number of uncertainties when designing ground support schemes. When a conventional deterministic approach is applied, several uncertainties may be overlooked.

2 Ground support design and implementation processes

There are a number of well-documented design schemes for ground support design. Generally, they all require the following:

- Description of the rock mass and identification of likely failure mechanisms
- Assessment of support demand (block size, depth of failure, support pressure, etc.)
- Assessment of support capacity (element type, technical specifications for static and dynamic conditions, density, *in situ* performance, etc.)
- Design acceptance criteria (appropriate factor of safety related to excavation purpose).

The design philosophy used could be deterministic; limit state; probabilistic; or a combination of these. Generally, combinations of empirical and deterministic design methods are used to design ground support in mine development and stopes.

A simplified version of Terzaghi’s Observational Approach (design – implement – monitor – redesign) is generally applied in the design of ground support (Figure 1). Typically, this would involve estimating ground support requirements using an empirical method such as the Barton Q-System (Barton el al., 1974), the RMR System (Bieniawski, 1976), rules of thumb or analytical methods such as key block methods (Goodman and Shi, 1985). The ground support design is then implemented and monitored. Monitoring is usually done by means of observations, although in some cases, instrumentation is used. The ground support design is then modified or optimised based on performance observations.

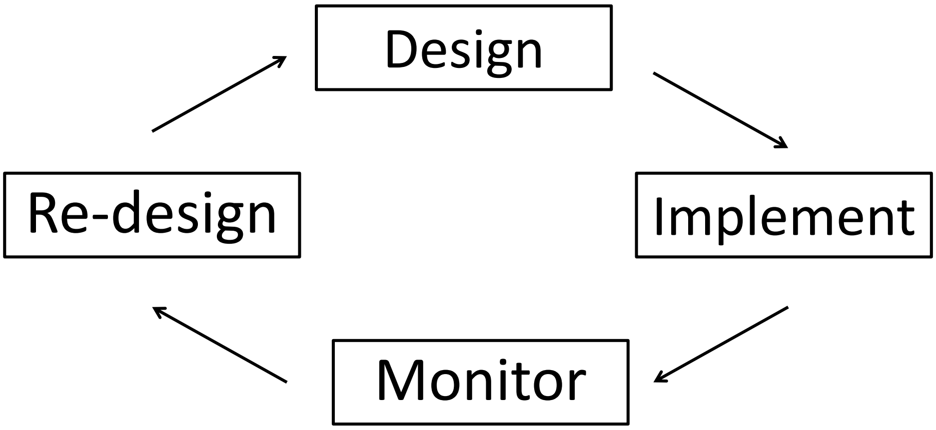

Figure 1: Modified observational design loop

Peck (1969) outlined eight steps in the application of the observational approach (Table 1) and the degree to which all these steps can be followed depends on the nature and complexity of the work. This approach can be successfully used in ground support design, although more often than not, a number of steps are omitted.

As with all design, ground support design needs a rational approach with clearly defined engineering objectives. Bieniawski (1992) provided a clear guideline on this and identified six design principles for rock engineering design (Table 1). Stacey (2004, 2009) suggested a distinction between defining and executing designs and outlined 10 steps for rock engineering design (Table 1). Steps 1 to 4 are about defining the design whilst steps 5 to 10 are about implementing the design.

In Table 1, the various steps outlined by Peck (1969), Bieniawski (1992) and Stacey (2004, 2009) have been loosely grouped to show similarities. All three authors outline the need for minimising uncertainty or considering unfavourable variations as well as there being a strong emphasis on monitoring and optimisation. It is important to understand that the implementation process is not divorced from the design process.

Table 1: Comparison of design approaches and principles

Observational Design (after Peck, 1969)	**Design Principles (after Bieniawski, 1992)**	**Circle of Design Approach (after Stacey, 2004, 2009)**
Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.	Clarity of design objectives and functional requirements.	Statement of the problem (performance objectives).
		Functional requirements and constraints (design variables and design issues).
Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.	Minimum uncertainty of geological conditions.	Minimisation of uncertainty (collection of information, e.g. site characterisation, rock properties, groundwater, in situ stresses).
Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.	Simplicity of design components.	Concept formulation (geotechnical model).

Observational Design (after Peck, 1969)	**Design Principles (after Bieniawski, 1992)**	**Circle of Design Approach (after Stacey, 2004, 2009)**
Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.	State-of-the art practice.	Analysis of solution components (analytical, numerical, empirical, observational methods).
Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.		Synthesis and specifications for alternative solutions (shapes, sizes, locations, orientations of excavations).
Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.	Optimisation.	Evaluation (performance assessment).
Measurement of quantities to be observed and evaluation of actual conditions.		Optimisation (performance assessment).
Modification of design to suit actual conditions.	Constructability.	Recommendation.
		Implementation (efficient excavation and monitoring).

3 Uncertainty in geotechnical design

McMahon (1985) outlined six types of uncertainty encountered in geotechnical engineering Table 2. The first three types of uncertainty are due to geological or natural constraints, whilst the others are due to social or human nature. The term ‘uncertainty’ is loosely applied in geotechnical engineering. Baecher and Christian (2003) distinguish between uncertainty related to natural variations in time and space (randomness) and uncertainty related to lack of understanding or knowledge. These are referred to as aleatory and epistemic uncertainly respectively by Kiuregihain and Ditevsen (2009, in Hadjigeorgiou and Harrison, 2011).

Table 2: Types of geotechnical uncertainty (after McMahon, 1985)

Type	Description	Examples
1	Risk of encountering an unknown geological condition.	Unknown structures or weak zones. Unexpected presence of water. Application of in-cycle fibrecrete, making understanding of rock mass conditions difficult as mapping cannot be undertaken.
2	Risk of using the wrong geotechnical criteria.	Incorrect failure mechanism identified. Inappropriate numerical modelling applied.
3	Risk of bias and/or variation in design parameter being greater than estimated.	Material properties variability underestimated. Poor understanding of joint spacing and length.
4	Human error.	Poor quality data collected. Poor sampling practices.
5	Design changes.	Poor planning requiring redesign. Design changes made in the field without consultation.
6	Over conservatism.	Assuming full excavation width wedges. Applying discounting factors at all stages of the design.

Hadjigeorgiou and Harrison (2011) argue that uncertainty and sources of error are two different components of engineering analysis design and that understanding of both is important in geotechnical engineering. They also show that the two components overlap in some circumstances, and that not accounting for uncertainty can lead to substantial errors. In their discussion on the use of rock mass classification schemes, they identify two groups of errors. The first group consists of errors intrinsic to the classification scheme used, including errors of omission; errors of superfluousness; and errors of taxonomy. The second group of errors is associated with implementation, and includes errors of circumstance; errors of convenience; errors of ignoring variability; and errors of ignoring uncertainty. Most, if not all, of these errors occur in ground support design and implementation. Many of the errors that contribute to uncertainty could be classified as a Type 4 uncertainty as defined by McMahon (1985).

3.1 Uncertainty in ground support design

When designing ground support, various types of uncertainty and errors occur. These can be arranged into two groups. The first group deals with design inputs and consists of uncertainties and errors from variation in ground conditions due to natural variations in the geology; spatial variations due to lack of data; data bias; natural variations in material properties; uncertainty in material properties due to testing errors or insufficient testing; inability to conduct mapping due to the application of in-cycle fibrecrete, etc. The second group deals with design analysis uncertainties including choice of appropriate design methods; correct application of the design method; identifying relevant failure mechanism; defining design block size or depth of failure; understanding of acceptable risk and the choice of appropriate acceptance criteria (factor of safety or probability of failure).

Table 3 summarises some of the uncertainties and errors that are typically encountered when designing ground support and attempts to relate these to McMahon's (1985) classification and terminology used more recently by Baecher and Christian (2003) and Hadjigeorgiou and Harrison (2011). This list is by no means complete and serves to merely demonstrate that a wide range of uncertainties exist when designing ground support in mining. In many cases, the uncertainty could fall into a number of classes.

Table 3: Uncertainties in ground support design

Description of Uncertainty	Contributors and Influencers	Type of Uncertainty
Rock mass characterisation and classification.	Limitations of classification schemes.	Type 2
	Misapplication of classification schemes.	Type 4/epistemic
	Over reliance of classifications schemes.	Type 4/epistemic
Spatial variability in ground conditions.	Density and quality of the data.	Type 4/epistemic
	Unknown structures.	Type 1/aleatory
	Natural variability.	Type 1/aleatory
Rock and rock mass properties.	Testing methods.	Type 4/epistemic
	Sampling and number of tests.	Type 4/epistemic
	Natural variability.	Type 1/aleatory
Loading conditions – static, quasi-static and dynamic (mining induced seismicity).	In situ stress orientations and magnitude.	Type 3 and 4/epistemic
	Stress changes due to mining – increased stress and de-stressed conditions.	Type 2/type 3
	Dynamic loading – scaling relationships, distance from source, site response.	Type 3 & 4/epistemic
Failure mechanism.	Stress induced (static or dynamic).	Type 2/type 4
	Geology defined (structural).	Type 2/type 4
	Geology defined (weak zones).	Type 2/type 4
	Combination of stress and geology.	Type 2/type 4
Design block size.	Discontinuity spacing and length.	Type 2/type 3
Design block shape.	Discontinuity orientations and number of sets.	Type 2/type 3
Depth of failure.	Induced stress and rock strength.	Type 2/type 3

Description of Uncertainty	Contributors and Influencers	Type of Uncertainty
Numerical modelling.	Matching software to level of inputs.	Type 2 and 4/epistemic
	Model calibration.	Type 3/type 4
Analysis uncertainty.	Application of inappropriate methods.	Type 4/epistemic
	Incorrect application of a method.	Type 4/epistemic
Acceptance criteria.	Acceptable risk levels not defined.	Type 6
	Lack of understanding of uncertainty.	Type 4/type 6
	Over conservatism.	Type 6
Support specifications.	Manufacturing quality.	Type 3/type 4
Support performance.	Installation as per suppliers specifications.	Type 3/type 4

3.2 Uncertainty in ground support implementation

Uncertainty is not only present in the design of ground support, but also in the implementation phase in the form of variations in installation quality, adherence to patterns and spacing, human error in the application of the correct ground support standard, not identifying a change in ground conditions, inadequate resources etc. Many of the uncertainties in ground support implementation could be classed as Type 4 uncertainties and are essentially errors. Some of these uncertainties are summarised in Table 4.

Table 4 Uncertainty in ground support implementation

Description of Uncertainty	Contributors and Influencers	Type of Uncertainty
Installation quality.	Inadequate installation procedures.	Type 4
	Inadequate quality control systems.	Type 4
	Poor training and competence.	Type 4
Adherence to patterns and spacing.	Risk taking behaviour.	Type 4
	Production pressure.	Type 4
	Poor training and competence.	Type 4
	Convenience.	Type 4
Application of the incorrect ground support standard.	Poor communication of the requirements.	Type 4
	Design changes in the field.	Type 5
Not identifying a change in ground conditions.	Poor training and competence.	Type 4
	Lack of understanding and awareness.	Type 4/epistemic
Ground support performance.	Inadequate monitoring.	Type 4
	Inappropriate monitoring.	Type 2
	Performance results not fed back into design.	Type 4

4 Dealing with uncertainty in ground support design

As shown in Section 3.1, there are a number of uncertainties that have to be considered in ground support design. These uncertainties arise from: natural variability in the geological environment; lack of data; errors in collecting data; errors in testing; errors in analysis and interpretation, etc. In addition to the known uncertainties, there are likely to be several unknown uncertainties. Brown (2007) concluded that there are two general types of uncertainty:

- Parameter uncertainty – what we know we don’t know
- Conceptual uncertainty – what we do not know we do not know.

The addition of unknown uncertainties further complicates the ground support design process. When considering all the uncertainties, the designs process can appear rather daunting to the design engineer.

The first step to dealing with design uncertainty is recognising that it exists; and the second is recognising that it may not be possible to eliminate all uncertainty and that contingency plans are required. Once there is recognition of these facts, a design process that attempts to reduce uncertainty to reasonable limits can be defined.

4.1 Data collection to minimise design uncertainty

Hadjigeorgiou and Harrison (2011) outline sources of error associated with data collection and testing programmes, which ultimately result in uncertainty. Data collection is a critical step in the minimisation of uncertainty and includes field data collection and laboratory testing programmes. A comprehensive and well-designed field data collection programme is the backbone of reducing uncertainty. Unfortunately, these programmes are often limited by the resources available or by access (e.g. in-cycle fibrecreting). Either, the design engineer can motivate for additional resources (not always successful) or can attempt to focus the existing resources on what are considered the most critical components. Access issues can be addressed by using remote photogrammetric methods of structural data collection. In some cases, engineers have to proceed with limited information, so it is important to effectively communicate the assumptions and limitations of the design and ensure that the relevant parties understand the design confidence level, and that adequate contingencies are included in the implementation process.

Hadjigeorgiou (2012) provides a good overview of shortcomings in data collection and how data can be more effectively used in solving geotechnical problems. It is possible to minimise input data uncertainty by rigorously implementing the following principles:

- Understand what data is needed and the goals of the programme
- The spatial distribution of data needs to be sufficient to define geotechnical domains and identify critical structures or zones that could be problematic
- Use well defined data collection procedures and staff that have been adequately trained in standard geotechnical techniques
- Implement data collection quality control procedures
- Implement sound sampling procedures
- Use accepted testing procedures (ISRM, ASTM) and certified laboratories for material testing
- Use statistical methods to define minimum number of samples required for each material
- Develop statistical descriptions for all parameters used including indicators of variation (histograms are particularly useful for understanding data distributions)
- Ensure that data is stored in well-constructed and managed databases
- Make use of visualisation tools to view data in three dimensions and gain a better understanding of the spatial distribution of data.

4.2 Minimising uncertainty in analysis and design

In order to limit uncertainties in design, it is necessary to apply the correct design tools. This requires an understanding of likely failure mechanisms and confidence that the level of input information is commensurate with the design tools to be used. For example, it does not make sense to use top of the range high-level numerical modelling software when only very basic and limited input data is available.

Stacey (2008) and Pells (2008) have both been critical of a ‘cook book’ approach to geotechnical design. Design analysis should be well thought out and tailored to the particular environment and potential problems with due consideration given to accounting for uncertainty.

4.2.1 Design methods

A range of design methods can be applied including empirical; analytical; and numerical methods. The design method applied must be matched to the conditions and likely failure mechanism. Empirical rock mass classification systems are widely used in ground support design as they are reasonably easy to apply and can be very useful when applied correctly. Recently a number of authors (Pells, 2008; Ranasooriya and Nikraz, 2008) have recommended caution when using empirical classification systems for support design. When applying rock mass classification schemes in ground support design it is important to consider a range of values rather than a single value for various input parameters of the classification system.

Analytical methods such as closed form solutions and key block methods (Goodman and Shi, 1985) etc. are widely used. They are also relatively easy to use and are invaluable when correctly applied. These methods can be used relatively easily in conjunction with probabilistic methods and incorporated into spreadsheets.

Numerical modelling can also be used for support design and is useful to determine likely loading conditions, changes in loading conditions and expected deformations. The models range from simple 2D elastic models to highly complex 3D non-linear models. The calibration of numerical models with observations or monitoring data (back-analysis) is vitally important to reduce uncertainties associated with models and input parameters and has been demonstrated by various authors (Beck *et al*., 2009; Graf and Basson, 2010).

Wiles (2006) proposed a methodology that allows the design engineer to reduce prediction errors (uncertainty) when using numerical modelling. A single representative coefficient of variation was defined which represents uncertainty. Essentially, it characterises how well the entire modelling procedure is performing and it includes contributions from the variability of the pre-mining stress and rock mass strength, material heterogeneity and errors introduced by the modelling procedure, e.g. elastic versus inelastic.

4.2.2 Deterministic analyses

It is common to apply a deterministic approach when using the methods outlined above. Typically, mean values are used in design analyses, although it is common to look at a range of values such as worst, expected and best cases. The use of worst case values can result in very conservative designs and this is commonly encountered when designing for full excavation width wedges, which rarely occur if discontinuity trace lengths and discontinuity spacing are considered (Diederichs *et al.*, 2000; Thompson and Windsor, 2007).

Cumulative curves and percentiles can also be used although engineering judgement must be used in determining what value should be used in design. This could be the 95% cumulative value for a particular parameter or using a percentile value, e.g. the 25th percentile – 75% of the data exceeds this value.

When using deterministic analyses, it is relatively common to conduct a sensitivity analysis on critical parameters. Figure 2 shows the results of a conventional sensitivity analysis using a Spider diagram. Values for each parameter are systematically varied around the mean value (reduced and increased) to assess the impact on factor of safety. This approach is commonly used for financial analysis.

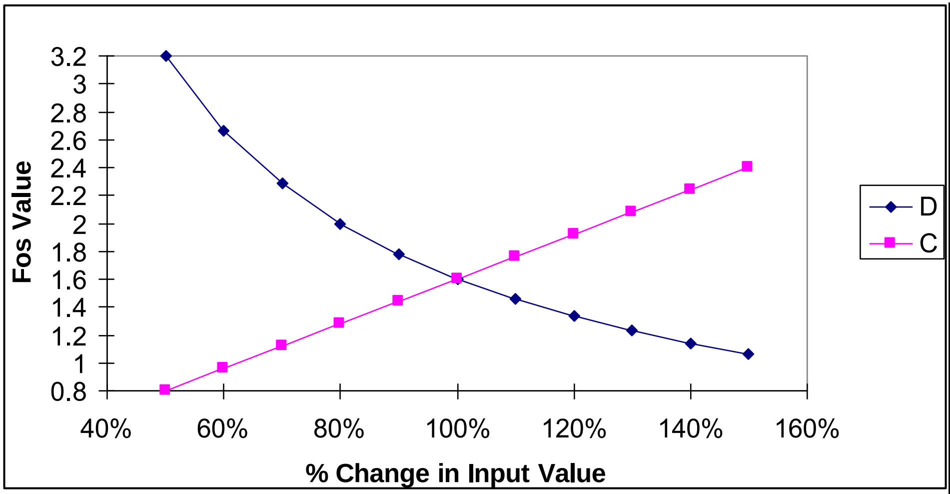

Figure 2: Sensitivity to variations in support demand (D) and capacity (C) (100% represents the mean value)

4.2.3 Probabilistic analyses

Probabilistic methods are quite frequently used in slope design analysis and can be used to account for uncertainty in ground support design. Esterhuizen (1993) showed that variability in rock mass properties and mining factors could be taken into consideration for hard-rock pillar design by statistical methods and the application of Rosenblueth's Point Estimate Method (Harr, 1987). A probabilistic approach has also been applied in the design of chromitite pillars (Wesseloo and Swart, 2000; Joughin *et al.*, 2000) with the application of the Point Estimate Method (PEM).

Pine and Thin (1993) evaluated various probabilistic analysis methods including Monte Carlo Simulation (MCS) or Latin Hypercube Sampling (LHS) and PEM for risk assessment in mine pillar design and concluded that PEM provides comparable results to MCS and LHS with much less computation. Probabilistic methods have also been applied by Tyler *et al.* (1991) and Beauchamp *et al*. (1998) in the design of ground support.

Probabilistic key block analyses using MCS has been applied to overcome some of the limitations of deterministic analyses (Estherhuizen, 1996; Esterhuizen and Streuders, 1998; Grenon and Hadjigeorgiou, 2003; Windsor, 1999; Dunn *et al.,* 2008). Dunn (2010) demonstrated the use of probabilistic key block methods and the PEM in ground support design.

Probabilistic methods can also be applied to rock mass classification schemes and empirical methods such as the Modified Stability Graph Method (Hutchinson and Diederichs, 1996).

Recent developments in the development of Phase 2 (™Rocscience) has included the incorporation of probabilistic analysis using the PEM. Valley *et a*l. (2010) evaluated MCS and PEM using Phase 2; they concluded that PEM is a time efficient probabilistic approach and provided results comparable with MCS. They noted that the PEM had some limitations, but was an attractive and efficient way of considering uncertainty in finite element modelling. Reusch and Beck (2007) indicated that mine scale 3D models do not lend themselves to MCS due to the large number of simulations required and used the Alternate PEM (Harr, 1989) to investigate shaft deflections.

The Response Surface Methodology (RSM) has been applied with complex numerical codes to conduct probabilistic numerical modelling for slope design and risk assessment (Tapia *et al.*, 2007). This approach could be applied to design ground support if using complex 3D numerical modelling is warranted, e.g. in high deformation environments such as block caving or where seismicity is a significant issue.

4.3 Design acceptance criteria

In geotechnical engineering design, as with any other engineering field, it is necessary to use some sort of criterion in deciding whether a design is acceptable. The most widely used acceptance criterion is factor of safety (FOS), although the use of probability of failure (POF) is increasing. These criteria are not mutually exclusive and are often used together in slope design; however, POF is not commonly used in ground support design in underground mining. Essentially the acceptance criteria capture the various uncertainties and errors associated with a design.

4.3.1 Factor of safety and probability of failure

FOS is a deterministic measure of the ratio between the resisting forces (capacity) and driving forces (demand) of the system in its considered environment (Wesseloo and Read, 2009).

FOS = capacity(C)/demand (D)

It is the most basic design acceptance criteria used in engineering and limiting equilibrium is achieved when the FOS has a value of 1.0 and the POF is about 50% for a normal distribution. Uncertainty about the likely performance of the system over a specified period under the proposed operating conditions usually results in the setting of a minimum design acceptance value for FOS based on experience. For underground support design, the degree of confidence in the capacity function depends on the: variability in the material properties; testing errors; installation practices; quality control procedures; etc. Similarly, the demand function includes factors such as removable block size; loading conditions; etc. In geotechnical engineering, the high variability in the system capacity and the uncertainty associated with determining loading conditions can result in considerable variations in FOS and POF (where FOS < 1).

In theory, the FOS concept is simple and widely used, but there are pitfalls when using FOS. It is for this reason that there has been a move away from a purely deterministic approach to a probabilistic approach, which takes into account the variability in capacity and demand. Furthermore, POF scales linearly while FOS does not.

The FOS value chosen indicates the risk tolerance and needs to consider the variation in capacity and demand. For example, an engineer might design using a FOS = 1.2, and this may be acceptable if the capacity and demand are well understood with limited variation; however, if there is a large variation then the POF (that proportion where FOS < 1) would increase. In this situation, it would be prudent to use a higher FOS. Figure 3 demonstrates the impact of uncertainty on the FOS distribution where a higher FOS actually has a higher POF (FOS < 1) due to the greater variability. This is a slope design example, but it is equally applicable to the design of ground support for underground mining.

The FOS value most often quoted is the mean value, which can be misleading. Sensitivity analyses are used to determine the impact of variability in the input parameters. The use of worst-case values can result in overly conservative FOS values and caution is recommended when using this approach.

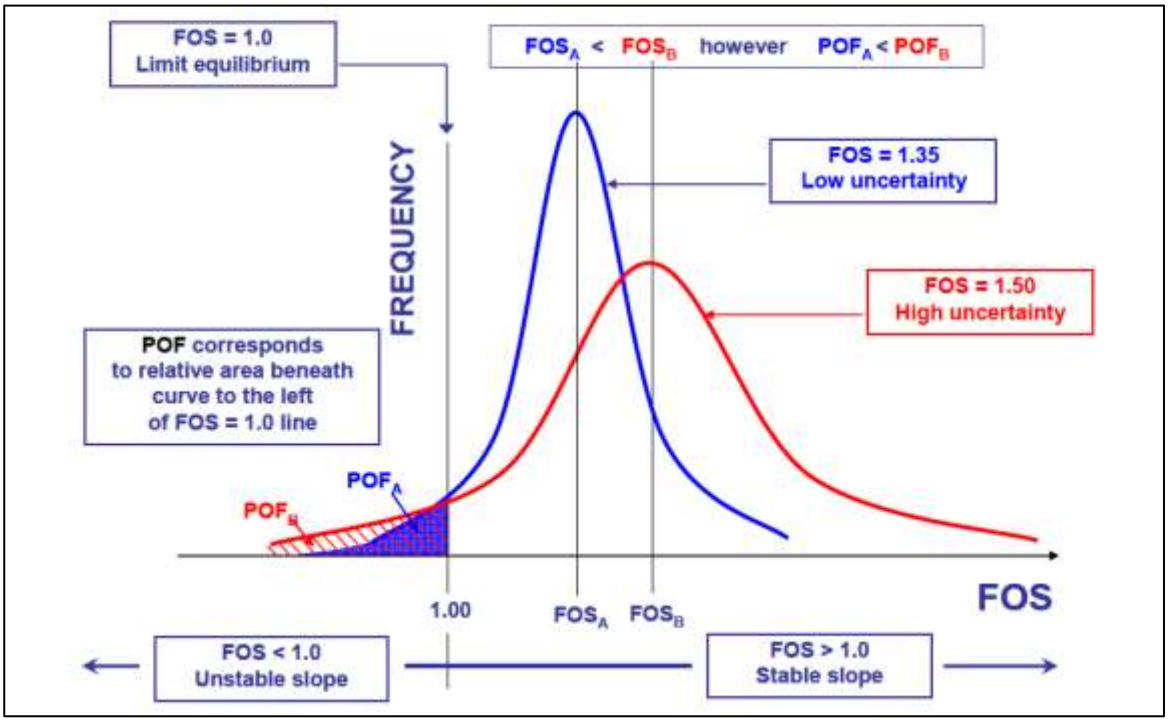

Figure 3: **Definition of POF and Relationship with FOS according to uncertainty magnitude (after Tapia et al., 2007)**

4.3.2 Determining factor of safety and probability of failure

Depending on the complexity of the design and the data available, different approaches can be used to assess the distribution of FOS. The simplest is a basic sensitivity analysis that considers a reasonable variation around the mean value.

In this case, the idea is to explore variation in parameters that could result in a lower FOS, for example a lower bolt capacity and a large design block. The point estimate method (PEM) is a useful method for assessing the expected value and variation of a system and can be applied when calculating FOS and POF (Harr, 1987). In complex cases, it may be appropriate to apply Monte Carlo simulation methods to determine the FOS and POF distributions.

4.3.3 Acceptable values

The FOS values commonly used are set by observation and trial-and-error experience over time, taking into account issues such as the reliability of the data, the types of analyses utilised, and the simplifying assumptions made. The choice of a particular value also indicates the level of risk that a design engineer or organisation are prepared to accept. Acceptable FOS values are often quoted for specific design areas such as slopes (Priest and Brown, 1983); pillars (Lunder, 1994); crown pillars (Carter and Miller, 1995) taking into account the use of the structures and its expected lifetime. Hoek *et a.,* (1995) suggest a FOS 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. This paper does not discuss appropriate acceptance criteria values but attempts to demonstrate the importance of understanding and accounting for uncertainty when defining design acceptance criteria.

4.4 Communicating the design

Effective communication of ground support design is critical to assist in the successful implementation of the design. This requires that the following aspects be comprehensively dealt with.

4.4.1 Design confidence level

Management and those responsible for implementing ground support designs need to understand the limitations of design input parameters and that expected conditions might differ, affecting the design reliability. Contingencies must be defined for when conditions change or the performance varies beyond acceptable limits.

4.4.2 Design specification

Ground support designs must be communicated in a clear and unambiguous manner. This is best done using a clearly annotated scaled drawing (often termed ‘Ground Support Standards’). This should clearly indicate for what dimension of excavation the design is applicable and the specifications for the individual ground support elements must be indicated. For example, it is not acceptable to simply specify Split Sets, specifications should include the length, diameter and whether they should be galvanised or not. Ground support designs should be formally approved by mine management.

4.4.3 Clarity on where the design should be applied and trigger levels for design changes

When or where specific ground support regimes or standards are applicable should be clearly defined (i.e. each geotechnical domain has a specific Ground Support Standard). Depicting this visually is an effective way of communicating ground support requirements. Trigger levels for when the design is not applicable should be listed and communicated to those implementing the design.

4.4.4 Quality assurance and monitoring

Quality control (pull testing, grout testing, support audits etc.) and monitoring requirements must be clearly defined in the design documentation. Acceptance values and limits for both quality control and monitoring must be defined, as should frequency of these activities. Specific requirements in terms of quality, performance and monitoring that will be fed back into the design loop must be outlined. Quality control and monitoring aspects should be included in contracts.

5 Dealing with uncertainty in ground support implementation

Uncertainties in ground support implementation are essentially due to human error (Type 4). They can also be compared to the errors of implementation outlined in Hadjigeorgiou and Harrison (2011). In some cases, it could be argued that these uncertainties or errors are due to a lack of knowledge and understanding. The following are needed to reduce uncertainties in ground support installation:

5.1 Training

Supervisors and operators need to be trained in ground control and ground awareness. They need to understand why support is installed; as well as the correct installation or application of different types of support. It is also necessary to understand what drives ground conditions and to be able to identify changes in ground conditions.

5.2 Ground support patterns and installation procedures

Ground support patterns must be clearly communicated as well as being practical to implement. Consideration must be given to the capabilities of the equipment available and the excavation dimensions. Installation procedures should be detailed and clearly defined. They must be assessed in the field to ensure that they are practical.

5.3 Supervision and quality control systems

Good quality supervision is a key part of quality control. A formal quality control system is required to ensure that support is installed as per the design. The quality control system should focus on activities during installation (e.g. standard operating procedures, training, spot inspections/task observations) as well as post installation (e.g. inspections, audits, testing). The requirements for support quality control are well defined in Potvin and Nedin (2003) and by Szwedzicki (2004).

5.4 Change management procedures

Procedures should be in place to ensure that ground support designs are not modified without consultation with the geotechnical engineer. It is acceptable to install additional support if conditions merit it, but support should never be reduced without proper consultation and design analysis. Ultimately any support design change needs to be done in a formal manner. This is an opportunity to feed back into the design and optimise it.

5.5 Trigger action response plans (TARPS) and contingencies

Plans need to be formulated to respond to situations where conditions are different to what was anticipated or when there have been significant deviations from the ground support design. If contractors are to be used then TARPS and contingency plans should be included in contract documents.

5.6 Performance monitoring

Some performance monitoring is conducted as part of the quality control process in the form of pull tests, shotcrete and grout sample UCS testing etc. Additional monitoring is required to assess the effectiveness of support designs. This can include visual observation, closure monitoring and extensometers. This data should be captured on a regular basis and should be fed back into the design so that it can be optimised.

6 Conclusions

Uncertainty is a reality in both the design of ground support and the implementation of ground support. The first step to dealing with uncertainty is recognising that it exists; and the second is recognising that it may not be possible to eliminate all uncertainty and that contingency plans are required. It is also important to recognise what types of uncertainty need to be dealt with. Once there is recognition of these facts, design and implementation processes that attempt to reduce uncertainty to reasonable limits can be developed.

In the design phase, it is possible to limit uncertainties by ensuring quality data capture and testing programmes are implemented that are based on accepted industry standards. Good design procedures are needed to ensure rigour. The use of descriptive statistics for input parameters and the use of probabilistic methods can be used to understand the design uncertainty. A variety of probabilistic tools exist that can be applied to empirical, analytical and numerical modelling design methods.

Understanding variability and the impact it can have on FOS or POF is important and must be factored in when choosing acceptance criteria for ground support design.

Ground support designers should not lose sight of the implementation phase, which has its own associated uncertainties. Measures have been outlined in this paper to assist in reducing uncertainty during the implementation phase.

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References

Baecher, G.B. and Christian, J.T. (2003) Reliability and Statistics in Geotechnical Engineering, Wiley, 618 p.

Barton, N., Lien, R. and Lunde, J. (1974) Engineering classification of rock masses for the design of rock support, Rock Mechanics, Vol. 6, pp. 189–236.

Beauchamp, K.J., Carvalho, J., Castro, L. and Morrison, D.M. (1998) Probabilistic Analysis for Ground Support for Underground Mines, Canadian Institute of Mining, Montreal.

Beck, D.A., Pfitzner, M.J., Arndt, S.M. and Fillery, B. (2009) Estimating rock mass properties and seismic response using higher order, discontinuous, Finite Element models, in Rock Engineering in Difficult Conditions, in Proceedings Third Canada–U.S. Rock Mechanics Symposium and 20th Canadian Rock Mechanics Symposium, M. Diederichs and G. Grasselli (eds), 9–15 May, Toronto, Canada, 12 p. (on CD-ROM).

Bieniawski, Z.T. (1992) Principles of engineering design for rock mechanics, in Proceedings 33rd US Symposium on Rock Mechanics, J.R. Tillerson and W.R. Wawersik (eds), 3–5 June 1992, Santa Fe, USA, Balkema, Rotterdam, pp. 1031–1040.

Bieniawski, Z.T. (1976) Rock mass classifications in rock engineering, in Proceedings Symposium on Exploration for Rock Engineering, Z.T. Bieniawski (ed), Cape Town, South Africa, Balkema, Rotterdam, Vol. 1, pp. 97–106.

Brown, E.T. (2007) Block Caving Geomechanics, Second edition, JKMRC, Brisbane, 696 p.

Carter, T.G. and Miller, R.I. (1995) Crown-pillar risk assessment – planning aid for cost-effective mine closure remediation, Trans. IMM (Sect. A), 104, pp. A41–A57.

Esterhuizen, G.S. and Streuders, S.B. (1998) Rockfall hazard evaluation using probabilistic keyblock analysis, Journal of the South African Institute of Mining and Metallurgy, March/April 1998, pp. 59–63.

Esterhuizen, G.S. (1996) JBlock User's Manual and Technical Reference.

Esterhuizen, G.S. (1993) Variability considerations in hard rock pillar design, in Proceedings Symposium on Rock Engineering problems related to Hard Rock Mining at Shallow to Intermediate depth, 4–5 March 1993, Rustenburg, South Africa, South African National Group on Rock Mechanics, South Africa, pp. 48–54.

Diederichs, M., Espley, S., Langille, C. and Hutchinson, D.J. (2000) A semi-empirical hazard assessment approach to wedge instability in underground mine openings, in Proceedings International Conference on Geotechnical and Geological Engineering, GeoEng 2000, 19–24 November 2000, Melbourne, Australia, Technomic Publishing, Lancaster.

Dunn, M.J. (2010) The application of probabilistic keyblock methods for support design in blocky rock masses, in Proceedings 2nd Australasian Ground Control in Mining Conference, P. Hagan and S. Saydam (eds), 23–24 November 2010, Sydney, Australia, The Australasian Institute of Mining and Metallurgy, Sydney, pp. 106–112.

Dunn, M.J., Earl, P. and Watson, J. (2008) Support design using probabilistic key block methods, in Proceedings 6th International Symposium on Ground Support in mining and civil engineering applications, T.R. Stacey and D.F. Malan (eds), 30 March–3 April 2008, Cape Town, South Africa, The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 623–636.

Goodman, R.E. and Shi, G. (1985) Block Theory and its Application in Rock Engineering, Prentice-Hall, 338 p.

Graf, C.C. and Basson, F.R.P. (2010) Managing Stress and Ground Condition Changes with Increasing Depth at Callie Underground Mine, in Proceedings 2nd Australasian Ground Control in Mining Conference, P. Hagan and S. Saydam (eds), 23–24 November 2010, Sydney, Australia, The Australasian Institute of Mining and Metallurgy, Sydney, pp. 106–112.

Grenon, M. and Hadjigeorgiou, J. (2003) Open stoping using 3D joint networks, Rock Mechanics and Rock Engineering, Vol. 36(3), pp. 183–208.

Hadjigeorgiou, J. (2012) Where do the data come from? In Proceedings Sixth International Seminar on Deep and High Stress Mining, Y. Potvin (ed), 28–30 March 2012, Perth, Australia, Australian Centre for Geomechanics, Perth, pp. 259–277.

Hadjigeorgiou, J. and Harrison, J.P. (2011) Uncertainty and Sources of Error in Rock Engineering, in Proceedings 12th ISRM International Congress on Rock Mechanics, Harmonising Rock Engineering and the Environment, Q. Qian and X. Zhou (eds), 18–21 October 2011, Beijing, China, CRC Press, Leiden, pp. 2,063–2,067.

Hoek, E. (1991) When is a design in rock engineering acceptable? Müller Lecture, in Proceedings 7th International Congress on Rock Mechanics, 16–20 September 1991, Aachen, Germany, Balkema, Rotterdam, Vol. 3, pp 1,485–1,497.

Harr, M.E. (1989) Probabilistic estimates for multivariate analysis, Applied Mathematical Modelling, Vol. 13.

Harr, M.E. (1987) Reliability based design in civil engineering, McGraw-Hill, New York, 290 p.

Hoek, E., Kaiser, P.K. and Bawden, W.F. (1995) Support of Underground Excavations in Hard Rock, Balkema, Rotterdam, 300 p.

Hutchinson, D.J. and Diederichs, M.S. (1996) Cabelbolting in Underground Mines, BiTech, 406 p.

Joughin, W.C., Swart, A.H. and Wesseloo, J. (2000) Risk based chromitite pillar design - Part 2: Non-linear modelling, in Proceedings South African National Institute of Rock Engineers Symposium: Keeping it in the Bushveld and Advances in Support Technology, 10–11 October 2000, Rustenburg, South Africa, South African National Institute of Rock Engineering.

Kiureghian, A.D. and Ditlevsen, O. (2009) Aleatory or epistemic? Does it matter? Structural Safety, 31, pp. 105–112.

Lunder, J. (1994) Hard rock Pillar strength estimation an applied empirical approach, MSc thesis (unpublished), University of British Columbia, Canada.

McMahon, B.K. (1985) Geotechnical design in the face of uncertainty, Austalian Geomechanics Society E.H. Davis Memorial Lecture.

Peck, R.B. (1969) Advantages and Limitations of the Observational Method in Applied Soil Mechanics, Ninth Rankine Lecture, Geotechnique 19, No. 2, pp. 171–187.

Pells, P.J.N. (2008) Assessing parameters for computations in rock mechanics, in Proceedings First Southern Hemisphere International Rock Mechanics Symposium (SHIRMS), Y. Potvin, J. Carter, A. Dyskin and R. Jeffrey (eds), Vol. 1 – Mining and Civil, 16–19 September 2008, Perth, Australia, Australian Centre for Geomechanics, Perth, pp. 39–54.

Pine, R. and Thin, I. (1993) Probabilistic risk assessment in mine pillar design, in Proceedings International Congress on Mine Design, Innovative Mine Design for the 21st Century, W.F. Bawden and J.F. Archibald (eds), 23–26 August 1993, Kingston, Canada, Balkema, Rottedam, pp. 363–373.

Potvin, Y. and Nedin, P. (2003) Management of Rockfall Risks in Underground Metalliferous Mines, Minerals Council of Australia.

Priest, S.D. and Brown, E.T. (1983) Probabilistic stability analysis of variable rock slopes, Transactions of the Institution of Mining and Metallurgy, Section A: Mining Industry, IMM, Vol. 92, January 1983, pp. A1–A12.

Ranasooriya, J. and Nikraz, H. (2008) Tetrahedral rock wedge stability under empirically derived support, in Proceedings First Southern Hemisphere International Rock Mechanics Symposium (SHIRMS), Y. Potvin, J. Carter, A. Dyskin and R. Jeffrey (eds), Vol. 1 – Mining and Civil, 16–19 September 2008, Perth, Australia, Australian Centre for Geomechanics, Perth, pp. 619−632.

Reusch, F. and Beck, D. (2007) Simulating Shaft and Crusher Damage in Deep Mines, in Proceedings Fourth International Seminar on Deep and High Stress Mining (Deep Mining 07), Y. Potvin (ed), 7–9 November 2007, Perth, Australia, Australian Centre for Geomechanics, Perth, pp. 65–79.

Stacey, T.R. (2009) Design—a strategic issue, The Southern African Institute of Mining and Metallurgy, Vol. 109, pp. 157–162.

Stacey, T.R. (2008) Are Design Codes Appropriate in Mining Rock Engineering?, in Proceedings First Southern Hemisphere International Rock Mechanics Symposium (SHIRMS), Y. Potvin, J. Carter, A Dyskin and R. Jeffrey (eds), Vol. 1 – Mining and Civil, 16–19 September 2009, Perth, Australia, Australian Centre for Geomechanics, Perth, pp. 129–136.

Stacey, T.R. (2004) The link between the design process in rock engineering and the code of practice to combat rock fall and rockburst accidents, The Journal of The South African Institute of Mining and Metallurgy, pp. 29–34.

Szwedzicki, T. (2004) Quality in ground support management, in Proceedings Fifth International Symposium on Ground Support, Ground Support in Mining and Underground Construction, E. Villaescusa and Y. Potvin (eds), 28–30 September 2004, Perth, Australia, Balkema, Rotterdam, pp. 483–489.

Tapia, A., Contreras, L.F., Jefferies, M. and Steffen, O. (2007) Risk Evaluation of Slope Failure at the Chuquicamata Mine, in Proceedings International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering (Slope07), Y. Potvin (ed), 12–14 September 2007, Perth, Western Australia, Australian Centre for Geomechanics, Perth, pp. 477–495.

Thompson, A.G. and Windsor, C.R. (2007) Block formation around excavations using deterministic and probabilistic methods, in Proceedings 11th ISRM Conference, The Second Half Century of Rock Mechanics, 9–13 July 2007, Lisbon, Portugal, Taylor & Francis Group, London, Vol.1, pp. 183–186.

Tyler, D.B., Trueman, R. and Pine, R.J. (1991) Rockbolt support design using a probabilistic method of key block analysis, in Proceedings 32nd US Symposium on Rock Mechanics, 10–12 July 1991, Norman, Oklahoma, Balkema, Rotterdam, pp. 1,037–1,047.

Valley, B., Kaiser, P.K. and Duff, D. (2010) Consideration of uncertainty in modelling the behaviour of underground excavations, in Proceedings Fifth International Seminar on Deep and High Stress Mining (Deep Mining 2010), M. Van Sint Jan and Y. Potvin (eds), 6–8 October 2010, Santiago, Chile, Australian Centre for Geomechanics, Perth, pp. 423–436.

Wesseloo, J. and Read, J. (2009) Acceptance criteria, Guidelines for Open Pit slope Design, P. Stacey and J. Read (eds) CSIRO, Australia, pp. 221–236.

Wesseloo, J. and Swart, A.H. (2000) Risk based chromitite pillar design - Part 1: Application of locally empirically derived pillar formula, in Proceedings South African National Institute of Rock Engineers Symposium: Keeping it in the Bushveld and Advances in Support Technology, 10–11 October 2000, Rustenburg, South Africa, South African National Institute of Rock Engineering.

Wiles, T.D. (2006) Reliability of numerical modelling predictions, International Journal of Rock Mechanics and Mining Sciences, Vol. 43, pp. 454–472.

Windsor, C.R. (1999) Systematic design of reinforcement and support schemes for excavations in jointed rock, in Proceedings International Symposium on Ground Support and Reinforcement Practice in Mining, E. Villaescusa, C.R. Windsor, A.G. Thompson (eds), 15–17 March 1999, Kalgoorlie, Western Australia, Balkema, Rotterdam, pp. 35–58.