Geotechnical Models and Data Confidence in Mining Geotechnical Design

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Abstract

The geotechnical model is the cornerstone of any mining geotechnical design and as such the confidence level and reliability of the geotechnical model is paramount. The geotechnical model confidence level needs to be commensurate with the level of design that is being applied or study that is being undertaken. The geotechnical model is made up of several components and the reliability of the data underlying these components ultimately determines the reliability of the geotechnical model.

Data reliability is linked to the quantity of data collected, the spatial distribution of the data collected, quality of the data collection and the interpretation of the data. In a typical project, there is an opportunity to improve data reliability through the scoping, prefeasibility, feasibility, and final design and implementation stages.

Currently very little quantitative guidance exists in the literature on assessing the confidence level of geotechnical studies, although there have been attempts by various authors (Haile, 2004; Haines, Swart and Kruger, 2006; Read and Stacey, 2009; Dunn, Basson and Parrott, 2011) to qualitatively describe what level of geotechnical data is required. Recently a number of authors (Read, 2013; Fillion and Hadjigeorgiou, 2013; Thomas, 2013) have outlined methods that could be applied to assess the reliability of some types of geotechnical data that are used in the development of geotechnical models.

This paper briefly discusses some of the factors influencing data reliability and the geotechnical model confidence and some of the tools available.

Introduction

The geotechnical model is the cornerstone of any underground or open pit mining geotechnical design. The geotechnical model provides the basis for developing geotechnical domains and analyses inputs. This means that the geotechnical model is directly linked to the design confidence and reliability. The geotechnical model is also linked to the project life cycle, from the study stages (scoping through to feasibility) through to implementation and operations stages. In a mining project there is also a link between the geotechnical model and the declaration of resources and reserves. This paper will explore some of the links between the geotechnical model and the project life cycle and the various factors influencing data uncertainty and the geotechnical model.

Geotechnical Model

The term geotechnical model is broadly used and can mean different things to different people. In simple terms, the geotechnical model is an amalgamation of the geological, structural, hydrogeological and rock mass models (Read and Stacey, 2009). Typically the level of confidence of each component varies; and depending on the geotechnical environment the relative importance of each component varies. The geotechnical model thus needs to be fit for purpose in both complexity and for the project life cycle stage.

Geological model

The geological model generally consists of the lithology, alteration, weathering, mineralised zones and the in situ stress state. The reliability of boundaries between zones is a key issue.

Structural model

The structural model consists of the major structures (large faults, bedding and folds) and minor structures or fabric (joints and minor faults). The reliability of the location of major structures is a key issue as these often play a significant role in controlling instability.

Hydrogeological model

The hydrogeological model consists of hydrogeological units, hydraulic conductivities, flow regimes, phreatic surfaces and the pore pressure distribution and water quality distribution.

Rock mass model

The rock mass model consists of the intact rock strength, defect shear strength, rock mass strength and rock mass classification. These are used to determine the input parameters for geotechnical analyses thus having an understanding of their variability and reliability is a key issue.

Geotechnical domains

The geotechnical model is used to define geotechnical or geomechanical domains that exhibit similar rock mass and structural characteristics. Geotechnical domains form the basis of geotechnical design sectors or areas.

Geotechnical model and design

Many design approaches imply a requirement for a geotechnical model and some level of confidence. Terzaghi's observational design approach (Peck, 1969) requires the following:

- assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role
- establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.

Bieniawski's (1992) design principles require 'minimum uncertainty of geological conditions'; whilst Stacey (2004, 2009) states the following:

- minimisation of uncertainty (collection of information, e.g. site characterisation, rock properties, groundwater, in situ stresses)
- concept formulation (geotechnical model).

These requirements are described in broad terms with a focus on accounting for possible conditions and reducing uncertainty.

Geotechnical Model confidence

The geotechnical model needs to be at a level of confidence that is commensurate with the level of design that is being applied or study that is being undertaken. Basing complicated and high level analyses for an implementation design on a very crude and simple geotechnical model does not make sense and ultimately design reliability could be governed by the confidence of the geotechnical model and its various components.

A number of authors have provided guidance on the required confidence of geotechnical models. Steffen (1997) linked slope angles and the degree of design confidence based on the uncertainty of the underlying geotechnical data to the resource-reserve process and proposed the classification shown in Table 1. Whilst the Steffen (1997) paper focused on open pit mines, the concepts covered in the paper are also applicable to underground mines.

Table 1: Geotechnical confidence classifications proposed by Steffen (1997).

Category 1 – proven slope angles	Geotechnical investigations carried out to a feasibility study standard. In essence designs should have a minimum confidence level of 85 per cent requiring: • continuity of stratigraphy and lithological units confirmed in space through adequate intersections • detailed structural mapping of rock fabric is implied • strength characteristics of structural features and the rock mass through appropriate testing • groundwater pressures have been measured.
Category 2 – probable slope angles	Equates to a design based on information that allows the following: • reasonable assumptions on continuity of stratigraphy and lithological units • some structural mapping has been carried out and all major features and joint sets should be identified • limited rock testing for physical properties of the in situ rock and defects has been carried out • preliminary groundwater analysis • enough information gained to conduct simplified design models with sensitivities.
Category 3 – possible slope angles	Equates to an inferred design using limited geotechnical investigations. Typical slope angles will be based on experience verified with rock mass ratings and some inference to geological conditions within the affected rock mass.

Haile (2004) proposed a framework for classifying geotechnical models based on the structure of resource-reserve reporting codes. To avoid confusion with resource and reserve classifications, Haile introduced the terms 'implied', 'qualified', 'justified' and 'verified' described as follows:

- implied: i.e. with a low level of reliability, with only global estimates of geotechnical characteristics being available
- qualified: i.e. geotechnical model has a reasonable level of confidence
- justified: i.e. with a high level of confidence in the intrinsic spatial variability of geotechnical characteristics
- verified: i.e. based on in situ knowledge of the rock mass, which provides a reliable model of the intrinsic variability of geotechnical characteristics.

Table 2 outlines the general requirements for a geotechnical model. Haile (2004) also provided qualitative guidance relating the geotechnical data requirements for different study stages through to operation to the mining method and orebody geometry. This approach factors in the geotechnical risk associated with different mining methods and orebodies (e.g. a wide shallow pit versus a deep narrow pit).

Table 2: Geotechnical classification of mining projects (Haile, 2004).

Data type	Requirements
Implied (inferred)	• Geotechnical model has a low level of reliability. • Based on global estimates of geotechnical characteristics. • Will enable only a limited scope of analysis, and development of only conceptual level, mine-wide design parameters. • Variability or uncertainty in the geotechnical model could have a significant impact on the economic viability of the project.
Qualified (indicated)	• Geotechnical model has a reasonable level of confidence. • Provides a broad indication of the intrinsic spatial variability of the geotechnical characteristics. • A reasonable scope of analysis could be applied, which broadly defines geotechnical domains, enabling the development of reasonably reliable, domain-specific design parameters. • Variability or uncertainty in the geotechnical model could have a moderate impact on the economic viability of the project.
Justified (measured)	• Geotechnical model has a high level of confidence. • Provides a good indication in the intrinsic spatial variability of the geotechnical characteristics. • A comprehensive scope of analysis could be applied to well-defined geotechnical domains enabling the development of domain-specific mine design parameters. • Variability or uncertainty in the geotechnical model would not significantly affect the economic viability of the project.
Verified	• Geotechnical model is based on in situ knowledge of the rock mass. • Provides a reliable model of the intrinsic variability of geotechnical characteristics. Performance of the recommended design parameters have been verified through historical experience from neighbouring excavations and/or interim staged pit slopes. • The design has been demonstrated to be practical and achievable. Variability or uncertainty in the geotechnical model would not adversely affect either the operational or economic viability of the project.

Read and Stacey (2009) provide guidance of target confidence levels geotechnical model requirements for large open pit slope design for different project stages. They consider: conceptual (level 1); prefeasibility (level 2); feasibility (level 3); design and construction (level 4) and operations (level 5) as shown in Table 3.

Table 3: Suggested target levels of data confidence by project stage (after Read and Stacey, 2009).

Project stage					
Project level status	**Conceptual**	**Prefeasibility**	**Feasibility**	**Design and construction**	**Operations**
Geotechnical level status	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Geotechnical characterisation	Pertinent regional information	Assessment and compilation of initial mine scale geotechnical data	Ongoing assessment and compilation of all new mine scale geotechnical data	Refinement of geotechnical database and 3D model	Ongoing maintenance of geotechnical database and 3D model
Target levels of data confidence for each model					
Geology	>50%	50–70%	65–85%	80–90%	>90%
Structural	>20%	40–50%	45–70%	60–75%	>75%
Hydrogeological	>20%	30–50%	40–65%	60–75%	>75%
Rock mass	>30%	40–65%	60–75%	70–80%	>80%
Geotechnical	>30%	40–60%	50–75%	65–85%	>80%

Descriptive guidelines for estimating the level of confidence in the data for each model component at each level of development are also provided. For consistency with the reporting of exploration results, mineral resources and reserves, the guidelines were purposely matched with the descriptive framework used by the 2004 Australian JORC Code (JORC, 2004). The JORC Code has been recently updated.

Geotechnical data and design fall under the modifying factors for JORC (2012) which requires that the confidence of the modifying factors be considered in the conversion of Mineral Resources to Ore Reserves. It is required that a least a prefeasibility study should be undertaken to support the conversion of Mineral Resources to Ore Reserves. Typically a feasibility study would have a higher level of confidence than a prefeasibility and hence confidence of the modifying factors would be higher.

The guidelines provided by Steffen (1997), Haile (2004) and Read and Stacey (2009) are all extremely useful but are essentially qualitative in nature and are subjective, often requiring considerable engineering judgment in their application. Read and Stacey (2009) have attempted to allocate numerical values to the required confidence levels yet no guidance is provided on how these numbers should be calculated or estimated.

Data reliability

The geotechnical model and it various underlying components are based on different types of data at different confidence levels, thus quantifying the reliability of a geotechnical model is fraught with difficulties. A number of key factors that influence the data reliability are briefly discussed in this paper.

Data uncertainty

McMahon (1985) outlined six types of uncertainty encountered in geotechnical engineering. 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).

When developing a geotechnical model various uncertainties need to be considered. These uncertainties also need to be considered in the context of the project life cycle and the required level of confidence. The following questions need to be asked:

- Is there sufficient data to capture natural variations in the rock mass?
- Is the spread of the data sufficient to adequately define boundaries between different rock units?
- Is the data collection consistent using industry accepted practices?
- How good is quality of data collection and what quality assurance and quality control processes are used?
- Is there a bias in the data such as direction of drilling or sampling of stronger materials?
- How good is the laboratory testing program both in quantity and quality of testing?

- How is the data managed?
- How good is the data interpretation?
- How much data?

The question of how much data is needed regularly arises during geotechnical design studies. For the geological model, this would generally be determined by resource geology and reporting requirements. Often a major structural model would also be developed although this is unlikely to include much data on the rock mass fabric.

The hydrogeological model development is often driven by mining considerations of how much dewatering is required or how much process water is required, rather than those aspects that are of interest to the geotechnical engineer. Generally this leads to the development of large scale hydrogeological models that do not adequately cater for near mine impacts, e.g. the groundwater level behind a slope.

The rock mass and structural fabric models are often developed as part of the geotechnical data collection program. In many cases, the geotechnical program can be leveraged off geological drilling programs, more so for underground projects.

The Western Australian (WA) Department of Industry and Resources, now known as the Department of Mines and Petroleum (DMP), published a geotechnical considerations guideline for underground mines in 1997. This document suggests that the appropriate geotechnical data are collected from a representative number of cored boreholes, preferably oriented and the suggested percentages are shown in Table 4. The same organisation also published geotechnical guidelines for open pit mines in 1999. This document outlines the need to collect geotechnical data that is consistent with type, size and life of the open pit.

Table 4: Suggested percentage of cored boreholes to be geotechnically logged (after Anon, 1997).

Stage of mine development	Suggested percentage of geotechnically logged holes
Prefeasibility study	25–50%
Feasibility study	50–100%
Operating mine	25–75%

Haines, Swart and Kruger (2006) considered geotechnical data in terms of geotechnical risks and the need to reduce risk by having a better understanding of the geotechnical environment. They provide a summary of their experience of geotechnical drilling and logging conducted for various studies, from Scoping through to Feasibility level, expressed as a proportion of resource holes drilled (Table 5). Generally there is a doubling in the percentage of geotechnical holes as the study progresses. However the values reported are significantly lower than suggested in the WA Underground Guideline (Anon, 1997).

Table 5: Percentage of geotechnical drilling to resource drilling showing range and mean values (after Haines et al, 2006).

Stage of study	Geotechnical holes to total resource drilling
Conceptual engineering (scoping)	1.6–4.9% (2.8%)
Prefeasibility (advanced scoping)	4.0–10.6% (6.6%)
Feasibility	5.0–24.0% (11.9%)

Dunn, Basson and Parrott (2011) suggested an approach based on progressively gathering data in line with the resource-reserve reporting process. By linking the geotechnical data collection program to the resource drilling program and ensuring that a representative proportion of cored holes are geotechnically logged to an appropriate level, it is possible to increase the level of geotechnical data available in the early stages of a mining project.

The early stages of a new project (scoping or conceptual) are focused on gathering the basic geotechnical data such as RQD, fracture frequency, intact rock strength estimates weathering and alteration. As the project advances (prefeasibility, feasibility and implementation), the level of geotechnical data collection increases similarly as it would for a resource geology program (see Table 6). Generally, the level of detail is expanded to also include geotechnical domain or rock mass characterisation (RMC) logging and detailed structural logging of discontinuities utilising oriented core. Appropriate testing programs are developed during prefeasibility and may be expanded in subsequent stages, depending on the degree of variability shown in the initial testing program. If there is a large scatter in results additional testing will be conducted.

Table 6: Geotechnical data requirements per study stage (after Dunn et al, 2011).

Classification				Geotechnical guidelines	
Newmont	**JORC Resource**	**JORC Reserve**	**Stage**	**Logging requirements**	**Laboratory testing (per major lithology)**
Potential economic mineralisation	-	-	1	Basic: 75–100%	-
Non-reserve mineralisation	Inferred	-	2	Basic: 75–100% RMC: 30–50% Structural: 20% (min)	5*UCS, UTS and elastic properties Defect strength per major sets
Reserve conversion	Indicated	Probable	3/4	Basic: 75–100% RMC: 30–50% Structural: 20% (min) Dedicated: as required	Additional testing depending on variability Triaxial if required
Grade control	Measured	Proven	5 and operations	As required	As required

Notes: hydrogeology and specific testing (stress measurements, raise bore index, soil Atterberg limits, etc.) to be conducted as required. Dedicated geotechnical holes required to address data gaps and for infrastructure.

Basic – RQD, fracture frequency, field strength estimates, weathering and alteration.

RMC – detailed descriptions of discontinuities and the collection of parameters for rock mass characterisation systems (Q and RMR).

Structural – orientated core and the collection of detailed data on individual discontinuities.

The percentages shown in Table 5 refer to the geotechnical logging requirements for the resource cored drill holes drilled for that stage. Additional specific geotechnical drill holes may be required to address data gaps and ground conditions in the area of proposed infrastructure away from the orebody.

Data quality

Hadjigoergiou and Harrison (2011) outline sources of error associated with data collection and testing programs, which ultimately result in uncertainty. Data collection is a critical step in the minimisation of uncertainty and includes field data collection and laboratory testing programs. A comprehensive and well-designed field data collection program is critical in reducing uncertainty. Unfortunately, these programs are often limited by the resources available or by access. 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 sometimes be addressed by using remote methods such photogrammetry for the collection of structural data or geophysical methods.

Hadjigoergiou (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 rigourously implementing the following principles (Dunn, 2013):

- understand what data is needed and the goals of the program
- 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.

Data interpretation

Data interpretation is a critical component in the development of the various components that make up the geotechnical model and is often subjective. The delineation of lithology, mineralisation, alteration and weathering boundaries is reliant on the number of intersections (drill hole or mapping) and the quality of interpretation by the geologist. A number of visualisation, modelling and interpolation tools are available to assist in this process however these is still a significant reliance on the competent professional . These limitations are also applicable to the major structural model.

For the hydrogeological model, data needs to be interpreted in the context of the geological and structural and if either of these has a low confidence, then it is likely that the confidence of the hydrogeological model will be negatively influenced.

For the development of the rock mass model, data from a number of sources needs to be collated and interpreted. Laboratory test results need to be scrutinised to ensure that they are valid tests and that they have been correctly interpreted. Geotechnical logs need to be reviewed and collated for both rock mass and rock fabric data. The use of histograms, cumulative distributions and descriptive statics are useful tools for interpreting laboratory and logging data. Statistical tests to evaluate differences in data and whether data subsets can be combined should be undertaken. The visualisation and interrogation of geotechnical data in three dimensions is extremely useful in the interpretation of rock mass and laboratory testing data.

Assessing reliability

Read (2013) discussed methods that can be used to assess parameter uncertainty and model uncertainty. Similarly a number of other authors (Fillion and Hadjigeorgiou, 2013; Thomas, 2013) have recently evaluated the application various statistical methods in assessing geotechnical laboratory testing data and for comparing data sets.

Parameter uncertainty

Read (2013) concluded that for parameter uncertainty, the coefficient of variation is a valuable screening mechanism when making decisions about the level of confidence in a selected design parameter. However, it is subjective and does not provide a numerical measure of the reliability of the data. To overcome this difficulty it was suggested that a modified Bayesian approach (Harr, 1996) could be applied to estimate the expected value of the reliability of a data set. The method uses a simple spreadsheet format and can be applied to any set of geotechnical data such as rock mass and hydrogeological parameters. It is particularly useful for evaluating laboratory testing data sets.

This method can also be applied to logging and rock mass classification data provided the data is arranged into equal length intervals. This approach has been applied by the author to both testing and logging data for various projects and was found to be useful in determining properties for geotechnical domains and choosing design analyses input properties. This method supplements the more common approach of using the mean, standard deviation and median for assigning values. There would also be value in applying this approach to data sets for different study stages to assess whether the data reliability does in fact improve as the project progresses.

Fillion and Hadjigeorgiou (2013) explored how small-sampling theory could be applied to assessing the results of laboratory testing from an operating mine. They showed that even if the number of specimens tested is higher than the minimum proposed by the International Society for Rock Mechanics (ISRM) suggested methods, the sample size was too small to obtain a reliable strength value for most of the rock domains. It was also discovered that the minimum sample size obtained using the confidence interval approach is significantly influenced by the test results sequence used for the analyses. This can arise when samples from a relatively small limited zone are tested resulting in misleading statistics. This highlights the need to have a reasonable spatial distribution of testing data so that the material variation is captured.

Thomas (2013) provided an overview of various statistical tests that could be used to assess the similarities in properties between data sets from different areas. These methods can be applied to assess whether data can be combined or to assess if there are real differences between data sets or areas and is potentially a useful tool to assist in defining geotechnical domains.

Model uncertainty

Read (2013) concluded that assessing model uncertainty in relation to the locations of through-going fault traces and the boundaries between lithologies and alteration units is significantly more complex and reviewed the following two solutions:

1. subjective assessments prepared by competent geologists, engineering geologists and geotechnical engineers, acting individually or as members of a review panel, as a means of quantifying the uncertainty associated with model geometries and boundaries
2. generalised plurigaussian simulation to simulate lithologies and structures as a means of quantify the uncertainty associated with model geometries and boundaries.

It was concluded that that generalised plurigaussian simulations can be used to quantify the uncertainty associated with single structures or single sets of structures within a model but that they are too complex a process to apply to a complete or large scale model. Due to these limitations, the use of subjective assessments based on the judgment and opinion of experienced practitioners to qualitatively assess the uncertainty associated with model geometries and boundaries is likely to remain as the standard industry approach for the foreseeable future.

Parameter uncertainty is routinely catered for in design analyses by sensitivity or probabilistic analyses that consider a range of possible values. Possibly this approach can be applied to the geological and structural models and fault positions and boundaries can be varied to assess the impact on the geotechnical design. Tapia, Contreras and Steffen (2007) and Hewson, Butcher and Dunn (2011) outlines how this approach was used to in slope design work undertaken at Chuquicamata Mine and the KCGM Super Pit respectively.

Conclusions

The geotechnical model forms the basis of geotechnical design. The complexity and confidence level of the geotechnical model needs to be matched to the project life cycle and by implication the reporting of resources and reserves. This paper provides an overview of geotechnical models and how their confidence level and reliability are influenced by the uncertainty of the underlying data.

Currently, there are a number of useful qualitative guidelines that relate the required level of geotechnical effort and data to the project life cycle. In some cases confidence levels have been specified but there are difficulties in assessing confidence levels. A number of methods that can be used to assess the uncertainty and reliability of laboratory testing and rock mass classification data have been briefly explored. These methods can be used to determine the confidence level and reliability of some components of the geotechnical model such as intact and defect strength properties and the rock mass quality. These are being evaluated on various projects by the author.

For assessing the confidence and reliability of the positions of major geological boundaries and fault traces we are reliant on the use of subjective assessments based on the judgment and opinion of experienced practitioners and this is likely to continue for some time.

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References

Anon, 1997. Geotechnical considerations in underground mines – guideline, Department of Industry and Resources.

Anon, 1999. Geotechnical considerations in open pit mines – guideline, Department of Industry and Resources.

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

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

Dunn, M J, Basson, F R and Parrott, T T, 2011. Geotechnical data – a strategic or tactical issue?, in Proceedings Fourth International Seminar on Strategic versus Tactical Approaches in Mining, (Australian Centre for Geomechanics: Perth).

Dunn, M J, 2013. Uncertainty in ground support design and implementation in underground mining, in Proceedings Seventh International Symposium on Ground Support in Mining and Underground Construction, pp 345–358, (Australian Centre for Geomechanics: Perth).

Fillion, M H and Hadjigeorgiou, J, 2013. Reliability of strength estimates based on limited laboratory data, in Proceedings Slope Stability 2013 (ed: P M Dight), pp 163–176 (Australian Centre for Geomechanics: Perth).

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 (eds: Q Qian and X Zhou), pp 2063–2067 (CRC Press: Leiden).

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

Haile, A, 2004. A reporting framework for geotechnical classification of mining projects, AusIMM Bulletin, September/October:30–37.

Haines, A, Swart, A and Kruger, A, 2006. Proactively mitigating geotechnical risks in open pit and underground mining, in Proceedings Strategic versus Tactical Approaches in Mining 2006 (Australian Centre for Geomechanics: Perth).

Harr, M E, 1987. Reliability Based Design in Civil Engineering, 290 p (McGraw-Hill: New York).

Hewson, S, Butcher, R and Dunn, M, 2011. Optimisation of the Eastern Pit Wall of the superpit: an example of a staged capital-delivered geotechnical design to increase project value, in Proceedings Slope Stability 2011.

JORC, 2004. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code) [online]. Available from: <http://www.jorc.org> (The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia).

JORC, 2012. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code) [online]. Available from: <http://www.jorc.org> (The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia).

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

McMahon, B K, 1985. Geotechnical design in the face of uncertainty, Australian 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(2):171–187.

Read, J, 2013. Data gathering, interpretation, reliability and geotechnical models, in Proceedings Slope Stability 2013 (ed: P M Dight), pp 81–89 (Australian Centre for Geomechanics: Perth).

Read, J and Stacey, P, 2009. Guidelines for Open Pit Slope Design, 496 p (CSIRO Publishing: Collingwood).

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, 104:29–34.

Stacey, T R, 2009. Design – a strategic issue, The Journal of The South African Institute of Mining and Metallurgy, 109:57–162.

Steffen, O K H, 1997. Planning of open pit mines on a risk basis, Journal of The South African Institute of Mining and Metallurgy, March/April: 47–56.

Tapia, A, Contreras, L F and Steffen, O, 2007. Risk evaluation of slope failure at the Chuquicamata Mine, in Proceedings 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering (ed: Y Potvin), (Australian Centre for Geomechanics: Perth).

Thomas, R D H, 2013. A statistical approach to account for elevated levels of uncertainty during geotechnical design, in Proceedings Slope Stability 2013 (ed: P M Dight), pp 325–335 (Australian Centre for Geomechanics: Perth).