Data Uncertainty

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Abstract

There is a demonstrated need in the open pit mining industry to quantify, report and relate the effects of data uncertainty on the slope angles selected as part of the pit slope design process. In response to this need, this paper outlines a system that is directed at reporting the confidence in the geotechnical information used in the slope designs at levels that are commensurate with each stage of project development, a reporting system that is linked to (a) the levels of effort at the different stages in the life an open pit and (b) the slope angles for the pits that define the reserves. It proposes that the target levels of geotechnical effort be matched by target levels of confidence in the geotechnical data. The levels of confidence suggested are subjective, but are intended to provide guidelines to the level of certainty required at each stage of project development. The terminology used to describe the different levels of uncertainty is equivalent to the 'inferred', 'indicated' and 'measured levels of confidence used by the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC) to define the level of confidence in mineral resources and ore reserves. A definition of a "geotechnically competent person" and/or a reviewer for slope designs to complement the equivalent standards for the presentation of ore reserves is proposed and presented with a list of key items that must be checked when the level of confidence in the geotechnical domains, the design sectors, and the attributes of the geotechnical parameters within each domain and sector is determined.

INTRODUCTION

A key objective of the open pit slope design process is to establish slope angles that are as steep as possible without compromising safety, ore recovery, financial return or the environment. Determining and reporting the levels of uncertainty in each component of the geotechnical model used to establish these slope angles is a fundamental requirement of the slope design and management decision process. Both require not only an understanding of the causes and impact of data uncertainty, but also how to quantify it, how to report it, and how best to relate it to the slope angles being selected. Unfortunately, there is considerable anecdotal evidence demonstrating that these last three items have not been well understood by the mining industry, a lack that has hindered the operational and economic viability of a number of mining projects. This paper, which is based on Chapters 8 and 9 in the book Guidelines for Open Pit Slope Design (1), is directed at closing this gap in our knowledge.

CAUSES AND IMPACT OF DATA UNCERTAINTY

Uncertainty can be defined as the condition of not knowing indisputably that we are factually correct. In open pit mining, geologists, engineering geologists and geotechnical engineers rarely have the comfort of knowing indisputably that they have correctly predicted the inherently variable properties and characteristics of natural soil and rock materials. Instead, they are faced with knowing almost indisputably that their estimates of the locations of lithological boundaries and major faults and the values of many and various material properties may not be real.

The types of uncertainty faced by the geologist, engineering geologist and geotechnical engineer can be placed in three groups: geological uncertainty; parameter uncertainty; and model uncertainty.

- Geological uncertainty embraces the unpredictability associated with the identification, geometry of and relationships between the different lithologies and structures that constitute the orebody wall rocks being targeted. It encompasses, for example, uncertainties arising from features such as incorrectly delineated lithological boundaries and major faults, and unforseen geological conditions.
- Parameter uncertainty represents the unpredictability of the parameters used to account for the various attributes of the geotechnical model. Typically, it will include uncertainties associated with the values that are adopted for geotechnical parameters such as the friction angle, cohesion, dilation angle, and deformation modulus.
- Model uncertainty accounts for the unpredictability that surrounds the selection process and the different types of analyses that are used to formulise the slope design and estimate the reliability of the pit walls. Examples include the various two-dimensional methods of limit equilibrium stability analysis and the more recently developed three-dimensional numerical stress and displacement analyses that are now being used in pit slope design. Model uncertainty exists if there is a possibility of obtaining an incorrect result even if exact values are available for all of the model parameters.

Invariably, these uncertainties become embedded in the geological, structural, rock mass and hydrogeological models and are carried through the stability analyses into the bench, inter-ramp and overall slope designs. The end result can be unreliability and possible poor performance of the pit slopes. The immediate question is, how do we quantify and report these uncertainties at levels that are commensurate with each stage of project development?

QUANTIFYING DATA UNCERTAINTY

In our daily lives we cope with uncertainty intuitively by using our own previous experience to rank and guide our choice. In open pit mining, we evaluate and update the uncertainties in the geological, structural, rock mass and hydrogeological parameters within each geotechnical domain and design sector using relative frequency concepts and probability distributions aided, if necessary, by subjective assessments of how the data was collected.

Relative frequency concepts and probability distributions are widely used in slope design. Typically, the emphasis is on direct measurement and then either organising the data in a structured manner as a way of examining variability within a range of values or distinguishing between populations within or across different domains. Using the same concepts to assess levels of confidence in the data is an accepted but less common practice and frequently requires specialist knowledge. Even so, direct measurement to determine probabilities is a standard technique and all slope design practitioners should be familiar with the statistical measures of central tendency and scatter, notably the expected value, E[x], the standard deviation, σ[x], and the coefficient of variation, V(x) (1, Appendix 2)

In open pit mining, subjective assessment is usually in the form of engineering judgement. However, many aspects of the process by which individuals making the judgement accept responsibility for their judgements raise questions of credibility and defensibility. Consequently, as more sophisticated slope design and risk assessment procedures are introduced more rigorous techniques of quantifying the measure of the confidence in the outcome will be needed by the industry.

Probably the best known methods of subjectively assessing uncertainty are Bayesian probability, calibrated assessment, Delphi panel and probability encoding.

- Bayesian probability (2) provides an organised system for using new information to update prior knowledge, indicating how opinions held before an experiment should be modified by the results of the outcome. It is a good approach when the fundamental mechanism is understood and the data comprises a representative sample of the value being assessed. Geostatistical estimation of ore reserves is one example. Evaluating concrete strengths is another. However, the method does rely on objectively derived subsidiary probabilities. Thus, a truly subjective Bayesian assessment must still be based on one of the other models of subjective assessment.

- The calibrated assessment approach adjusts individual assessments to reflect the assessor's known biases. Thus, two sets of assessment are required: assessments of the values in question; and an assessment of the assessors. The assessors can be assessed by their peers or through a set of questionnaires that quantify their biases with respect to known conditions.

- In the Delphi approach the individuals in a defined group of experts are each provided with the same set of background information and requested to perform assessments in writing. These assessments are then provided anonymously to each of the other experts, who are encouraged to adjust their assessments in light of their peer's assessments. The iterations are continued until the results stabilise. In situations where consensus cannot be achieved, the group average may be used.

- Probability encoding is similar to the calibrated assessment approach except that an encoding analyst works with each expert to obtain a more accurate assessment instead of simply correcting the expert's assessments based on pre-determined calibration factors. The method tacitly assumes that the expert is incompetent in quantitatively assessing his own uncertainty and uses the encoding analyst to bridge the gap. The limitations of the method are that it depends on the credibility of the analysts and there is no mechanism for achieving consensus.

A number of texts outlining the concepts and principles that underpin subjective assessments are available in the public domain, but for those who wish to pursue the subject in more detail the book 'Degrees of Belief - Subjective Probability and Engineering Judgement' (3) is recommended. The techniques outlined in the book have been widely used in civil engineering, especially in underground nuclear waste disposal projects, but have not yet featured in the mining industry.

REPORTING DATA UNCERTAINTY

In response to the need to report the confidence in the geotechnical information used in the slope designs at levels that are commensurate with each stage of project development, a geotechnical reporting system that is linked to (a) the levels of effort at the different stages in the life of an open pit and (b) the slope angles for the pits that define the reserves has been proposed by the Large Open Pit project studies. The system is outlined in Table 1.

Table 8.1: Suggested levels of geotechnical effort and target levels of data confidence by project stage

	PROJECT STAGE				
Project level status	**Conceptual**	**Pre-feasibility**	**Feasibility**	**Design and Construction**	**Operations**
Geotechnical level status	Level 1	Level 2	Level 3	Level 4	Level 5
Geological model	Regional literature; advanced exploration mapping and core logging; database established; initial country rock model	Mine scale outcrop mapping and core logging, enhancement of geological database; initial 3D geological model	Infill drilling and mapping, further enhancement of geological database and 3D model	Targeted drilling and mapping; refinement of geological database and 3D model	Ongoing pit mapping and drilling; further refinement of geological database and 3D model
Structural model (major features)	Aerial photos and initial ground proofing	Mine scale outcrop mapping; targeted oriented drilling; initial structural model	Trench mapping; infill oriented drilling; 3D structural model	Refined interpretation of 3D structural model	Structural mapping on all pit benches; further refinement of 3D model
Structural model (fabric)	Regional outcrop mapping	Mine scale outcrop mapping; targeted oriented drilling; database established initial stereographic assessment of fabric data; initial structural domains established	Infill trench mapping and oriented drilling; enhancement of database; advanced stereographic assessment of fabric data; confirmation of structural domains	Refined interpretation of fabric data and structural domains	Structural mapping on all pit benches; further refinement of fabric data and structural domains
Hydrogeological model	Regional groundwater survey	Mine scale airlift, pumping and packer testing to establish initial hydrogeological parameters; initial hydrogeological database and model established	Targeted pumping and airlift testing; piezometer installation; enhancement of hydrogeological database and 3D model; initial assessment of depressurisation and dewatering requirements	Installation of piezometers and & dewatering wells; refinement of hydrogeological database, 3D model, depressurisation and dewatering requirements	Ongoing management of piezometer and dewatering well network; continued refinement of hydrogeological database and 3D model
Intact rock strength	Literature values supplemented by index tests on core from geological drilling	Index and laboratory testing on samples selected from targeted mine scale drilling; database established; initial assessment of lithological domains	Targeted drilling and detailed sampling and laboratory testing; enhancement of database; detailed assessment and establishment of geotechnical units for 3D geotechnical model	Infill drilling, sampling and laboratory testing; refinement of database and 3D geotechnical model	Ongoing maintenance of database and 3D geotechnical model
Strength of structural defects	Literature values supplemented by index tests on core from geological drilling	Laboratory direct shear tests of saw cut and defect samples selected from targeted mine scale drill holes and outcrops; database established; assessment of defect strength within initial structural domains	Targeted sampling and laboratory testing; enhancement of database; detailed assessment and establishment of defect strengths within structural domains	Selected sampling and laboratory testing and refinement of database	Ongoing maintenance of database
Geotechnical characterisation	Pertinent regional information; geotechnical assessment of advanced exploration data	Assessment and compilation of initial mine scale geotechnical data; preparation of initial geotechnical database and 3D model	Ongoing assessment and compilation of all new mine scale geotechnical data; enhancement of geotechnical database and 3D model	Refinement of geotechnical database and 3D model	Ongoing maintenance of geotechnical database and 3D model
Target levels of data confidence					
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%

Table I *- Suggested levels of geotechnical effort and target levels of data confidence by project stage. Source, Table 8.1, Guidelines for Open Pit Slope Design (1).*

The reporting system proposes that the target levels of geotechnical effort (Level 1 through Level 5, Table 1) be matched by target levels of confidence in the data as outlined in the lowermost part of Table 1. The levels of confidence suggested are subjective, but are intended to provide guidelines to the level of certainty required at each stage of project development. They also provide an indication of the level of expenditure that may be required and when and where it is most likely to be needed. For example, for the geological model, the greatest level of effort and expenditure will occur early in project development, with quite high levels of confidence being obtained by Level 2. For the geotechnical model, the greatest level of effort is likely to be at Level 2, with confirmatory work being performed in Level 3 to ensure that the level of confidence is at the required level before the detailed, Level 3 engineering studies commence.

Descriptive guidelines for estimating the level of confidence at each level of effort linked to the slope angles for the pits that define the reserves are outlined below. The terminology used to describe the different levels of uncertainty is equivalent to the 'inferred', 'indicated' and 'measured levels of confidence used by JORC, the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (4) to define the level of confidence in mineral resources and ore reserves, as illustrated in Figure 1.

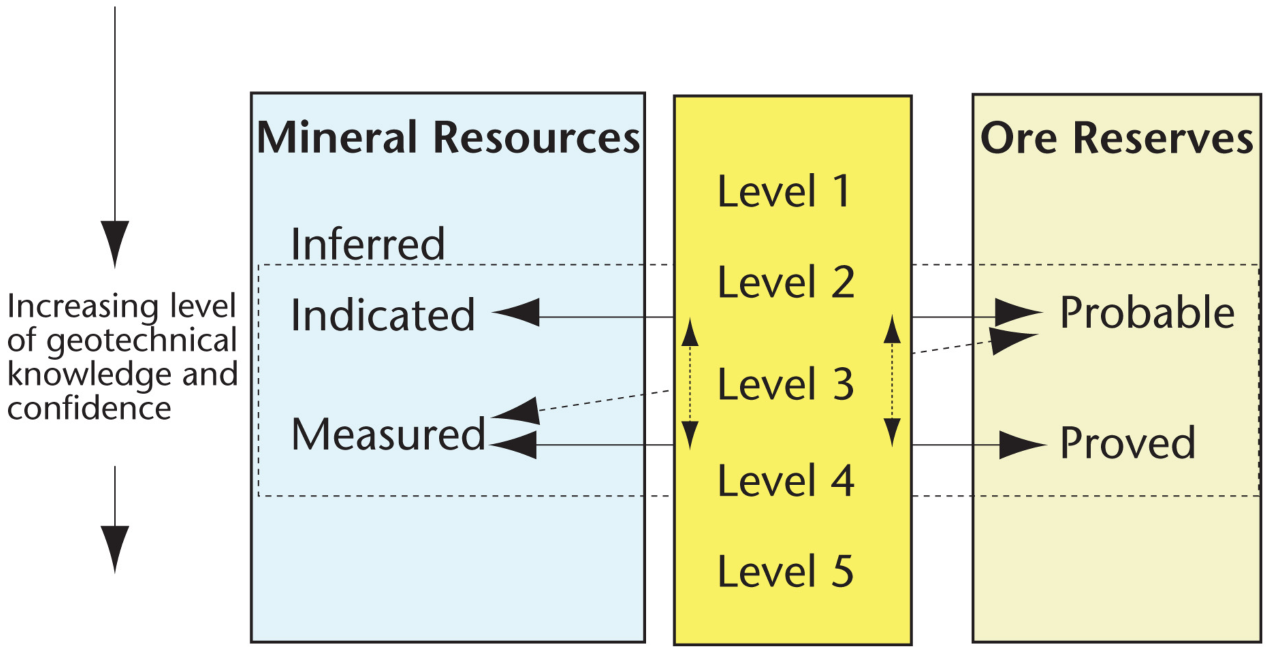

Figure 1 *- Geotechnical levels of confidence relative to the JORC code. Source, Figure 8.2, Guidelines for Open Pit Slope Design (1).*

The boundary levels of low, reasonable and high confidence are not explicitly stated by the JORC code. There is, however, anecdotal evidence that confidence levels of ±25% for Indicated Mineral Resources and ±10% to ±15% for Measured Mineral Resources are used by the industry. These boundaries are also consistent with the target levels of data confidence suggested for Levels 2, 3 and 4 in Table 1. Recent communications from the Chairman of the JORC committee (pers. com., P. Stoker) indicate that planned revisions to the JORC code will include material from the LOP project geotechnical guidelines.

LEVELS OF CONFIDENCE AND SLOPE ANGLES

To obtain a balanced design, it is essential that the measures outlined above to report the level of confidence in the geotechnical information used in the slope designs are carried through into the slope angles for the pits that define the reserves. The suggested relationships are outlined below.

Level 1, Conceptual Slope Angle

A Level 1 conceptual slope angle corresponds to the application of typical slope angles based on experienced in similar rocks, with the reliability of the geotechnical model estimated at a low level of confidence. The design basis will have been entirely inferred from reports and interpretations based on available regional data gathered from mines in similar geological environments. These preliminary data may be supplemented by aerial photographic interpretations of the regional lithology and structure and any outcrop mapping that may have been performed during exploratory project surveys. Overall, the information will be sufficient only for providing indicative slope designs and the planning of pre-feasibility stage investigations.

At this stage of the project that data assessments have been almost entirely performed subjectively.

Level 2, Pre-feasibility Slope Angle

A Level 2 pre-feasibility slope angle will correspond to the application of typical slope angles based on experience in similar rocks, but with quantification based on a preliminary rock mass classification and a reasonable inference of the geological and groundwater conditions within the affected rock mass; the estimated reliability of the geotechnical model remains, however, at a low level of confidence. The data used are inferred from interpretations based on the information provided during the conceptual stage of development, augmented by data obtained from outcrops, exposures in road cuttings and river banks, trenches, pits, workings and drill holes at the proposed mine site. All these data may be limited or variably distributed and/or of uncertain quality. Any sampling, field testing and laboratory testing procedures must be sufficient to satisfy designated international standards for site investigation and laboratory testing (e.g. ISRM, ASTM). The information will be sufficient to form working plans and Level 2 pre-feasibility slope design studies.

At this stage of the project the data assessments have still largely been performed subjectively, but they have been supplemented by quantitative assessments as measurable data became increasingly available.

Level 3, Feasibility Slope Angle

A Level 3 feasibility slope angle corresponds to a design based on a geological model that allows reasonable assumptions to be made on the continuity of stratigraphic and lithological units; the level of reliability of the geotechnical model is now upgraded to a reasonable level of confidence. The data have been based on the results of mine site feasibility investigations. Sampling locations have been spaced closely enough to sustain 3D dimensional interpretations of the domain boundaries to the limits of mining, based on boundary intersections and the continuity of the structural fabric, rock mass properties and hydrogeological parameters within each domain. Some structural analyses have been performed, utilising estimates of joint frequencies, lengths and conditions. All major features and joint sets should have been identified. Testing (small sample) for the physical properties of the in situ rock and joint surfaces will have been carried out. Similarly, groundwater data will be based on targeted pumping and airlift testing, and piezometer installations. All sampling, field testing and laboratory testing procedures must be sufficient to satisfy designated international standards for site investigation and laboratory testing (e.g. ISRM, ASTM).

At Level 3, project features such as structural and lithological domain boundaries, especially those at depth, have mostly been assessed subjectively. However, there will have been a significant increase in the availability of measurable data, enabling the uncertainty in the values assigned to the structural, rock mass and hydrogeological parameters within each domain to be assessed. At the completion of the investigations variations may occur and alternative interpretations may be possible, but in the view of a geotechnically competent person these would be unlikely to affect the potential economic viability of the project.

Level 4, Design and Construction Slope Angle

A Level 4 design and construction slope angle requires that the reliability of the geotechnical model has been estimated at a high level of confidence. The work will be performance-based to confirm and update the results obtained during the feasibility investigations. It will include detailed mapping, observation of slope behaviour, the possible installation of trial slopes, observation of groundwater behaviour and confirmation of pumping parameters, field testing and laboratory testing All sampling, field testing and laboratory testing procedures must be sufficient to satisfy designated international standards for site investigation and laboratory testing (e.g. ISRM, ASTM). The data will be sufficient to confirm the results of the Level 3 feasibility slope design.

At Level 4, the uncertainty in the values assigned to the structural, rock mass and hydrogeological parameters within each domain have mostly been assessed quantitatively. With the increased amount of outcrop and subsurface information, it will have become possible to apply quantitative assessments to geological boundaries that were previously assessed subjectively

Level 5, Operations Stage Slope Angle

The Level 5 operations stage commences with mining. It is marked by the ongoing maintenance and refinement of the geotechnical database and comparisons of the selected slope angles and expected mining conditions with reality. At this advanced stage of the project the majority of the data assessments have been performed quantitatively.

GEOTECHNICALLY COMPETENT PERSON

At the completion of the Level 3 feasibility stage of the investigation it is noted that variations may occur and alternative interpretations may be possible, but in the view of a geotechnically competent person these would be unlikely to affect the potential economic viability of the project. This requires the definition of a "geotechnically competent person". At the moment, there is no standard definition of geotechnical competence to assess and sign off slope designs for use in reserve estimate pits. However, it is considered that a definition of a "geotechnically competent person" and/or a reviewer for slope designs should be established to complement the equivalent standards for the presentation of ore reserves. Until such a definition becomes available, as suggested Chapter 1 of the Guidelines for Open Pit Slope Design book (1) the basic criteria could include:

- an appropriate graduate degree in engineering or a related earth science;
- a minimum of 10 years post-graduate experience in pit slope geotechnical design and implementation;
- an appropriate professional registration.

ASSESSMENT CRITERIA CHECKLIST

When assessing the levels of confidences in the boundaries of the geotechnical domains and design sectors, key items that must be checked include the following.

- The nature of the information used to set the domain boundaries. Was the geological and other information qualitative or quantitative? What was the spacing and distribution of the data relative to the complexity of the deposit, especially at depth below surface to the limits of mining? Were core and other field samples logged to a level of detail sufficient to support the interpretation? And what assumptions were made when preparing the interpretation?
- The effect, if any, of alternative interpretations of the data.
- The results of any audits or reviews of the data and interpretations.
- The nature and scale of planned further work.

When assessing the levels of confidence in the structural, hydrogeological and rock mass parameters within each geotechnical domain and design sector particular attention must be paid to the following items.

- The integrity of the data base. What quality control procedures were adopted?
- The nature and quality of sampling (e.g. disturbed, undisturbed).
- Field sampling techniques (e.g. chip, diatube, hand-trimmed cube, moisture loss protection).
- Drilling techniques (e.g. auger, core, core diameter, triple tube, orientation of core).
- Drilling bias, especially with respect to the orientation of the borehole relative to any major structures.
- Drill sample recovery.
- Core logging techniques (e.g. qualitative, quantitative, level of detail).
- Sample bias, especially with respect to the possibility of only the stronger materials remaining intact following core recovery and handling.
- Sample preparation (e.g. hand-trimmed, cut, sawn).
- Laboratory testing (e.g. nature, quality and appropriateness of test procedures used).
- The location of data points (e.g. nature and accuracy of surveys used to locate field sample points and borehole collars).
- The nature and scale of planned further sampling and laboratory testing work.

CONCLUSIONS

The principal objective of the geotechnical reporting system developed in Chapter 8 of the Guidelines for Open Pit Slope Design book (1) and outlined in this paper was to:

- provide an understanding of the causes of data uncertainty and its potential impact on the reliability of the pit slopes;
- highlight the need for uniform industry standards to report the uncertainties in the geotechnical data used in slope design;
- present a geotechnical reporting code that defines levels of confidence in the data that are commensurate with each stage of project development.

The key driver behind development of the system has been that all too often operating level investment decisions have been made using geotechnical data that is more appropriate to a conceptual or pre-feasibility level of investigation. For example, the project may have advanced to the design and construct stage (Level 4), but the level of confidence as judged by items such as the number of drill holes and laboratory tests may still be at Level 2.

The key benefit of using the system is considered to be that it provides a quantitative measure that can be used by corporate mine management and the investment community to assess the level of their exposure to risk. The costs of moving from Level 1 to Levels 2, 3, 4 and 5 can be estimated and incorporated in a project risk assessment. For example, the risk of moving from design into construction when the confidence in the data is at Level 2 is likely to be unacceptable. On the other hand, if the confidence is at Level 3, corporate management may consider the risk to be acceptable for development purposes. Either way, the code provides a yardstick that can be understood by everyone.

The next major initiative is to introduce the code into the industry and the investment community at all levels of management. This will require two steps. The first will be for executive mine management and geotechnical practitioners to agree on the definitions and requirements of each level of confidence. The second will be for those parties to agree on the definition of a “geotechnically competent person” that is proposed above.

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