# GEOTECHNICAL CONSIDERATIONS IN OPEN PIT MINES

## GUIDELINE

DEPARTMENT OF MINERALS AND ENERGY WESTERN AUSTRALIA

MOSHAB
Mines Occupational Safety and Health Advisory Board

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**FOREWORD**

This Department of Minerals and Energy (DME) guideline has been issued to provide further explanation of the requirements of Regulation 13.8 of the Mines Safety and Inspection Regulations 1995 (MSIR) which pertain to the application of sound geotechnical engineering practice in open pit mines. The application of sound geotechnical engineering practice is considered to be an integral component of Part 2 of the Mines Safety and Inspection Act 1994 (MSIA).

It is emphasised that this guideline is not totally inclusive of all factors concerning the application of geotechnical engineering in open pit mining. Further, its full scope may not be applicable to the specific requirements of every mine. For example it would not be necessary to establish blasting procedures nor to conduct regular mapping of geological structure in sand pits with homogenous materials. Nonetheless, the general concept of the guideline can be applied to all mines in accordance with local conditions.

Comments on and suggestions for improvements to the guidelines are encouraged. Further revision of the document will take place at approximately two yearly intervals to reflect changes in legislation and to accommodate new information resulting from improvements in technology and operational procedures.

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## 1.0 INTRODUCTION

The potentially hazardous nature of open pit mining requires the application of sound geotechnical engineering practice to mine design and general operating procedures, to allow safe and economic mining of any commodity within any rock mass*.

The intent of this guideline is to provide examples of good geotechnical engineering practice and to assist mining operators in achieving compliance with Regulation 13.8 of the Mines Safety and Inspection Regulations 1995 (MSIR 1995). This guideline seeks to encourage the application of **current** geotechnical knowledge, methodology, instrumentation, and ground* support and reinforcement* techniques and hardware to the practical solution of geotechnical engineering issues in open pit mining. In situations where the current level of geotechnical knowledge and/or technology does not satisfy the needs of the problem at hand, further research and development work is encouraged.

Regulation 13.8 of the MSIR 1995 may be described as a non-prescriptive performance based standard. The general obligations of mine management are stated, however, Regulation 13.8 does not provide specific minimum standards to be achieved. Hence, the regulation does not limit the general duty of care in the Act, and the requirements remain current as the understanding of geotechnical issues improves.

It is recognised that open pit mining experience and professional judgement are important aspects of geotechnical engineering that are not easily quantified, but can contribute significantly to the formulation of various acceptable and equally viable solutions to a particular mining problem. Management at each mining operation should recognise, identify and address the geotechnical issues that are unique to each particular mine, using current geotechnical knowledge, methodology, software and hardware appropriate to the situation.

It is appreciated that all the geotechnical considerations discussed in this guideline **do not apply to all mines**. Conversely, this guideline may not cover all the issues that need to be addressed at all mines. However, sound management requires that the techniques appropriate to a given set of conditions be selected and applied.

A glossary of pertinent geotechnical concepts and terms and a selection of relevant geotechnical and mining engineering references are provided. The list of references is by no means exhaustive, and should not be taken as representing the DME's complete or preferred literature source.

This guideline has been compiled on the basis of wide spread auditing of industry practice, consultation and interaction between the DME and Industry.

* As described in Appendix A

## 2.0 LEGISLATIVE REQUIREMENTS (WA)

The Mines Safety and Inspection Regulations 1995 contains regulations (in Part 13), that apply to the geotechnical considerations that must be adequately considered during the design, operation and abandonment of an open pit excavation. These regulations are given below.

**Geotechnical considerations**

**13.8.** (1) The principal employer at, and the manager of, a mine must ensure that geotechnical aspects are adequately considered in relation to the design, operation and abandonment of quarry operations.

Penalty: See regulation 17.1.

(2) Each responsible person at a mine must ensure that the following measures are taken in relation to ground control in the quarry -

(a) adequate consideration is given to local geological structure and its influence on wall stability;

(b) adequate consideration is given to shear strength of the rock mass and its geological structure;

(c) a proper analysis is carried out of rain water inflow, surface drainage pattern, groundwater regime and mine de-watering procedures and their influence on wall stability over time;

(d) where necessary, appropriate designs of rock reinforcement are applied and used, and the quality of installation is verified;

(e) analysis is carried out of open pit wall stability for the projected geometry of the pit;

(f) appropriate drilling and blasting procedures are used to develop final walls; and

(g) appropriate methods of open pit wall monitoring are used over a period of time to determine wall stability conditions.

Penalty: See regulation 17.1.

(3) Each responsible person at a mine must ensure that appropriate precautions are taken and written safe working procedures are followed if open pits are excavated through abandoned underground workings, or in close proximity to current underground workings.

Penalty: See regulation 17.1.

**General penalty**

**17.1** The penalty for contravention of a provision of these regulations that refers to this regulation is-

(a) in the case of an individual. $5 000; and

(b) in the case of a corporation, $25 000.

## 3.0 GEOTECHNICAL CONSIDERATIONS

Geotechnical engineering is a comparatively new discipline that has developed rapidly during the past 30 or so years. Geotechnical engineering deals with the whole spectrum of natural geological materials/ground, ranging from low strength soils to high strength rocks. The inherent variability of naturally occurring materials is an important aspect that needs to be recognised and allowed for in geotechnical engineering.

There are also a number of significant challenges in geotechnical engineering that have not yet been fully resolved in the strict scientific sense. Furthermore, there is no single solution to the geotechnical design and operation of any given mine. These are important points to understand, particularly because of the variability in the ground conditions* and the mining methods in use in WA. **Nevertheless, the application of sound geotechnical engineering practice has enabled substantial and stable excavations to be constructed in challenging ground conditions*.**

Consequently, the regulations are couched in general terms and do not contain detailed prescriptions. The application of sound geotechnical engineering practice in the pursuit of safe, practical, and cost effective solutions to rock instability/ground control* issues is the basic aim of this guideline and of Regulation 13.8.

The regulations require that mine management is able to demonstrate that it has adopted "sound practice+" in the field of geotechnical engineering as applied to open pit mining. The use of "sound practice" means that practices and methods will evolve and improve continually. Mine management will recognise that a well managed ground control* plan is a necessary component of any successful mining project. A ground control management plan* would include pre-mining investigations of ground conditions*, development of a mine plan and design according to the assessed ground conditions* and required rates of production etc.. Once mining is underway, a system of ground performance monitoring and re-assessment of mine designs should be undertaken such that the safe operation of open pits can be maintained for the duration of mining.

Regulation 13.8 and this guideline contain a number of important terms and concepts that need to be understood to appreciate what is required to comply with the regulation. These terms and concepts are explained in the Appendices - to which the reader should refer.

* As described in Appendix A

\+ "sound practice" - practice which is recognised as being developed on the basis of generally available current knowledge of technology and systems of work.

### *3.1 Planning for total mine life*

*13.8 (1) The principal employer at, and manager of, a mine must ensure that geotechnical aspects are adequately considered in relation to the design, operation and abandonment of quarry operations.*

***Design approach***

The regulations require that geotechnical issues be systematically considered during the whole life of a mining operation, from its beginnings in the pre-feasibility study stage, through the operation of the mine, to the final closure and abandonment of the mine. The design of open pit excavations will endeavour to prevent hazardous and unexpected failures of the rock mass* during the operating life* of the open pit.

The importance of a systematic approach to mine planning and design using soundly based geotechnical engineering methods cannot be over-emphasised. Open pit mines can represent a complex engineering system with many sub-systems that need to function in an integrated manner for the mine to operate safely and economically. **Mine planning and design**[2] has, as its goal, an integrated mine systems design whereby a mineral is extracted and prepared at a desired market specification at a minimum unit cost within the accepted/applicable social and legal constraints.

The words "planning" and "design" are sometimes used interchangeably, however, they are more correctly seen as separate but complementary aspects of the engineering method. **Mine planning** deals with the correct selection and coordinated operation of all the sub-systems, eg. mine production capacity, workforce numbers, equipment selection, budgeting, scheduling and rehabilitation. **Mine design** is the appropriate engineering design of all the sub-systems in the overall mine structure, e.g. production and near-wall blasting, loading and haulage platforms, electric power, water control (eg. pumping, depressurisation), dust control, ground support and reinforcement*, and excavation geometry.

It is strongly recommended that a formal mine planning and design system be established early in the life of a mine. Such a system might involve the regular informed discussion, as often as required, of a range of planning and design issues in the current operational areas and the new areas of the mine. The **"**mine planning and design meeting**"** should be an interdisciplinary meeting requiring the involvement, as necessary, of a range of expertise including: survey, geology, mining engineering, drilling and blasting, geotechnical engineering, rehabilitation, workforce supervision and management (principal and contractor).

It is often useful, as part of this planning and design system, to adopt a formal mining approval process for the development and/or mining of currently producing or undeveloped mining blocks. This formal mining approval process would include the production of plans, cross-sections and longitudinal projections of the mining block(s), as appropriate, plus a written description of the proposed mining work to be done and the mining issues that need to be addressed. A draft mining plan and the associated notes for the ore block(s) in question should be issued, in a timely manner, for discussion at the next mine planning and design meeting. Following discussion and resolution of the issues, final approved mining plan(s) and notes can be issued.

It has been found that notes from past mine planning meetings can form a valuable summary as to why certain mining decisions have been made and thereby assist with decision making in the present and future.

* As described in Appendix A

Formal mine plan approval should include the signatures of the people responsible for each relevant component of the plan - e.g. survey, geology, drilling and blasting, geotechnical, planning and design aspects plus the Quarry Manager and the Registered Manager - as appropriate.

***Geotechnical design considerations***

It is recognised that during the geotechnical design stage there is usually limited detail of the overall rock mass* available, and that it is necessary to make a number of assumptions/simplifications to arrive at a balanced mine design.

Geotechnical data for design can be obtained from a number of sources including: published literature, natural outcrops, existing surface and underground excavations, chip and diamond drilling (for determining rock mass strength*, structure, and hydrogeological data), geophysical interpretations, seismic records, pump tests, field tests, trial pits, and experience. It would be a statement of the obvious to say that the quality and usefulness of these sources of data is widely variant. However, qualitative information is better than none and, if nothing else, such data can be used to identify the areas requiring more detailed investigation and analysis.

Once the potential for economic mining has been identified it is considered sound practice to geotechnically log some diamond cored boreholes as soon as the core becomes available. Re-logging core for geotechnical purposes, after it has been stored or split for assay determination, is necessarily inefficient (double handling) and may give unreliable data on discontinuity characteristics. The reliability of data from re-logging of core initially drilled for exploration purposes, particularly core that has not been adequately stored or oriented, is limited.

Obviously, the number of geotechnical holes required for a particular project will depend on the level of available geological/geotechnical information at the site and the size and mine life of the project. For instance, it is possible that very few, and potentially no geotechnically logged drill holes could be required for mine excavations in close proximity to existing pits (that have similar geological conditions and can be accessed to define the relevant geotechnical design parameters).

The information gained from geotechnical investigations notably provides valuable information for mine design, but also assists with the development of a mineral resource estimate, and ultimately an ore reserve estimate. Particularly in marginal deposits, the geotechnical mine design limitations may define whether the resource can be classified as a reserve and therefore whether or not it should be mined.

Once there is considered to be adequate geotechnical design information, a **ground control management plan*** should be formulated. The plan should define the most appropriate excavation geometry (and ground reinforcement and support - where required), excavation methods, monitoring strategies (eg. monitoring of ground movements, mapping of geological structure*, and recording general ground performance), and emergency action procedures. The size of the mining operation will obviously be a major factor in determining the amount of effort and resources that are required to develop and implement the ground control management plan*. It will be necessary to apply considerable mining experience and judgement when establishing the ground control management plan* at a mine for the first time. With experience, it will be possible to successively refine the plan over time to address the ground control* issues identified as being important to the continued safe operation of a mine.

* As described in Appendix A

The issues that would need to be considered include:

- depth and operating life* of mining projects;
- potential for changes in expected ground conditions* in the wall rock mass* (eg. rock strength, earthquake events, rock stress*, rock type* etc.);
- production rate;
- size, shape and orientation of the excavations;
- the location of major working benches and transportation routes;
- potential for surface water and groundwater* problems;
- the equipment to be used, excavation methods, and handling of ore and waste;
- the presence of nearby surface features (for example public roads, railways, pipelines, natural drainage channels or public buildings);
- the potential for the general public to inadvertently gain access to the mine void during and after mining; and
- time dependent characteristics of the rock mass* (particularly after abandonment).

It follows that early identification of relevant geotechnical issues at a site will greatly assist with the development of a well-balanced ground control management plan*.

***Operational geotechnical considerations***

During operation of the pit, the (newly developed) ground control management plan* is used to improve the geotechnical database, and to assess the suitability of the current mine design and the general stability of the mine. This on-going assessment is required because of the relative paucity of data that is usually available when the mine design (and ground control management plan*) is first formulated. An example of the on-going review of geotechnical databases is mapping of geological/geotechnical features (e.g. the orientation, spacing and length of planes of weakness) as mine faces/walls are exposed.

Pit wall mapping data is necessary to determine the sizes, shape and orientations and modes of failure of potentially unstable blocks of rock - particularly in a hard rock* environment. Once the full scope of each relevant rock failure parameter has been derived, it is then possible to establish more appropriate mine design strategies to control the hazards that may result from rock failure.

A well-managed ground control management plan* should include regular discussions of all ground control* issues with relevant mine personnel both during mine inspections and in more formal planning meetings. In particular, changes in the geological structure* and general rock mass* appearance and the detection of incipient rock mass failures* should be noted during the development of a mine. This will allow for early recognition of instability issues so that a review and modification (if necessary) of extraction techniques, mine design, ground support and reinforcement*, and monitoring practices can be completed before any problems become difficult or expensive to control. It is not uncommon, throughout the operating life* of an open pit, that alterations will be made to the general mine plan (eg. blast design optimisation to minimise blast damage*, and wall cut-backs); therefore, when designing mines, a certain amount of flexibility is required.

* As described in Appendix A

***Abandonment***

By the time of mine closure, there should be adequate data to address all the long-term geotechnical concerns in regard to the abandonment of a mine.

Before open pits can be legally abandoned, the DME requires that all long term drainage, environmental, and public access issues are adequately considered and controlled. Environmental requirements for abandoned mines are specified by the license conditions imposed by the DEP and the lease conditions imposed by the DME during the mining project approval process. The Departmental guideline on "Safety bund walls around abandoned open pit mines" describes the requirements for limiting inadvertent public access to open pits after abandonment.

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**The application of soundly based geotechnical engineering methods to the mine planning and design process can result in significant improvements to mine safety, productivity and economic efficiency and should be included as an integral part of each mining project.**

### *3.2 Geological structure*and rock mass strength**

> *13.8 (2) Each responsible person at a mine must ensure that the following measures are taken in relation to ground control in the quarry -*
> *(a) adequate consideration is given to local geological structure and its influence on wall stability;*
> *(b) adequate consideration is given to shear strength of the rock mass and its geological structure;*

Rock mass failure* occurs when the driving forces acting on a given body of material exceed the resisting forces within that body of material. In a freshly excavated slope, the force resisting failure can be attributed to the shear strength of the rock mass* and/or geological structure*. The driving force (that precipitates failure) is primarily dependent on the unit weight of the rock mass*, the geometry of the wall/slope and the potential modes of failure (which define the geometry and size of the block of potentially unstable material). In soft rock*, failure can propagate through the intact rock, and/or along geological structure*. In hard rock* the path of minimum shear strength/resistance is predominantly along rock mass defects/geological structure*. It follows, therefore, that mine operators must identify the relevant modes of failure (the sources and magnitudes of the potential driving forces), and also determine and quantify the shear strength and other forms of resisting forces pertinent to that rock mass* and mode of failure. For example, the shear strength of geological structure* dipping downwards into pit walls is less important than structure dipping downwards into the mine void for planar and wedge modes of failure. Therefore, the relevant orientation of rock mass* defects also must be taken into account.

Determination of representative shear strength values is a critical part of slope design[2], as relatively small changes in shear strength can result in significant changes in design pit wall geometry. The main obstacles to determining reliable shear strength parameters are the availability of sufficient/suitable shear strength test data, the level of understanding about the rock mass* (particularly prior to mining), and the influence of other factors, such as variable rock weathering*, on the shear strength of the rock mass* and rock mass defects.

* As described in Appendix A

Where persistent foliation or closely spaced orthogonal jointing exists, problems can develop with the maintenance of safety/catch berms. Where catch berms cannot be maintained, a method will need to be developed to limit the risk associated with falling/sliding rocks or sub-batter scale failures (e.g. ground containment* and restricted access).

Therefore the design size, shape and orientation of open pit excavations relative to the geological structure* needs to be recognised as a major factor controlling the number, size and shape of potentially unstable blocks that may form within the pit walls. It follows that the design and selection of any ground support and reinforcement* also takes due consideration of the size, shape and orientation of the pit walls in relation to the geological structure* in the rock mass*.

It is recommended that a systematic and on-going approach be adopted to develop a site-specific geotechnical model of the orientation and other characteristics of the geological structure* within pit walls. An example of a systematic approach used to develop a site specific geotechnical model is given below:

- Use of scanline or other methods of geotechnical wall mapping and/or oriented core logging to establish baseline geotechnical data on planes of weakness within the rock mass* with a minimum of bias. This approach is particularly useful when mines are developed as a series of cutbacks. Wall mapping should attempt to quantify orientation, persistence, spacing, roughness and wavelength, wall rock strength, aperture, infill, degree of weathering and moisture content of planes of weakness.
- Take representative samples of the rock mass* and determine relevant shear strengths and groundwater* characteristics.
- Use of (preferably computer based) plotting, analysis and presentation methods of geological structure* data, for example DIPS[3], to better define orientation, persistence, spacing and other characteristics of joint sets.
- Identify the general geotechnical domains* in the rock mass* throughout the mine.
- Transfer of this data to geological plans and/or computer models for use in the design of pit walls and wall support and/or reinforcement (where required).

It must be recognised that steeper and higher batters will generate greater driving forces and thereby increase the potential for rock mass failure* and represent a higher risk to the operations. It should also be acknowledged that batters excavated within rock masses that contain persistent geological structure* have greater potential to develop large wall-scale failures than those excavated within rock masses that contain defects with shorter trace lengths. The ramifications of small-scale failures are not as important as those for large-scale failures - particularly if the small-scale failures are being contained by catch berms. One common method for control of small batter-scale failures is to install local ground support and/or reinforcement. Control of large wall-scale failures, on the other hand, is generally more important and also more difficult. Potential large scale failures are usually controlled by excavating slopes/walls to a shallower angle, depressurisation of groundwater* in the wall rock mass*, or installing more costly ground support and/or reinforcement than that used for stabilising small-scale rock mass* instability.

Geotechnical design methods, discussed in more detail in Section 3.5, can be used to assess the likely interaction between the size and shape of the excavation, geological structure* and the required levels of ground support and reinforcement*.

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* As described in Appendix A

### *3.3 Hydrogeological considerations*

> *13.8 (2) Each responsible person at a mine must ensure that the following measures are taken in relation to ground control in the quarry -*
>
> *(c) a proper analysis is carried out of rain water inflow, surface drainage pattern, groundwater regime and mine de-watering procedures and their influence on wall stability over time;*

The influence of groundwater* or incident rainfall is often not given the level of importance it warrants when designing a mine. The importance of hydrogeological considerations for pit wall design and management is well documented (e.g. Hoek and Bray 1981)[2]. Some of the more significant effects water can have on the general integrity of pit walls include:

- increase in pore pressure within the rock mass* (which reduces shear strength),
- softening of infill or rock material (particularly clays),
- slaking of soft rock* due to wetting and drying cycles,
- erosion of weaker bands of rock by water seepage or run-off,
- reduced blasting efficiency, and
- corrosion of ground support and reinforcement*.

The hydrogeological environment of an open pit needs to be understood to an appropriate level to ensure adequate provision is made for the removal of rainfall and groundwater* inflow as the mine continues to expand. Groundwater* is likely to be more of an issue in a new mine, or new area(s) of a mine, where very little of the groundwater* has been actively abstracted before mining commences.

In order to understand the hydrogeological conditions at a mine site, it is necessary to undertake adequate investigation of the range of geological conditions, and characteristics of water flow throughout the site. It is recommended that this investigation be carried out in conjunction with exploration drilling. The major characteristics of aquifers within the rock mass* should be established prior to the commencement of mining. Relevant information can be obtained by simply noting the depth of any water make or loss during drilling, however, the most useful information is gained from packer testing. If it is recognised early in the resource investigation phase that groundwater* control will be an issue, exploration drill holes can be planned for use as piezometers/monitoring bores or production bores, and dewatering/depressurisation programs can be better designed so that the required levels of depressurisation can be achieved.

Furthermore, as open pit wall failures often occur after rain, it may be necessary to develop an understanding of the time-lag and mechanisms of infiltration of surface water into the rock mass*.

The approach to groundwater* control can be divided into two general categories; water abstraction in advance of mining (eg. in-pit and out-of-pit production bores); and water abstraction during mining (eg. sumping/trenching into the pit floor and sub-horizontal drainage holes). Each method can be used individually, or in combination to produce the required result. Selection of the most appropriate depressurisation method will depend largely on the local and regional hydrogeological conditions, the relative importance of depressurisation to the mine design, and the required rate of mining.

Unsealed drill holes intersected by open pit excavations can be a potential source of high pressure and/or high flow rates of water - particularly in artesian conditions. The sudden

*As described in Appendix A

unexpected in-rush of water from a drill hole can represent a hazard to the safety of the workforce and can cripple mine production if the flow rate is sufficiently large. Every effort should be made to adequately seal drill holes before the commencement of mining. Effective sealing of exploration holes requires a good understanding of the sources of water (e.g. aquifers or shear zones) likely to be transmitted by the drill holes through the rock mass*. Ideally the down-hole path of exploration holes should be surveyed and plotted on plans and cross-sections, not just the collar and the toe positions.

Water drainage paths through and around the mine must be designed such that rainwater runoff or groundwater* seepage does not pond at the crest or toe of critical slopes within pit walls. Surface drainage should be designed taking into account the consequences of flooding, including loss of life, equipment damage, and loss of production. In the possible event of loss of life or injury to personnel, the surface drainage paths must be designed to at least take account of rainfall expected from a 1 in 100 year, 72 hour flood event. The design criteria to be used will be dependent on the level of risk that mine management is willing to accept and can justify as meeting their duty of care. The general principles for establishing the expected flows for a given design rainfall event are described by Australian Rainfall & Runoff [4].

The adequacy of the design and construction of any diversion works will need to be proven by geotechnical principles.

Any significant natural drainage paths truncated by mining will need to be re-established prior to abandonment.

The potential for corrosion or weakening of any artificial ground support or reinforcement should be established. In order to qualify the potential for this, water samples should be taken and chemically analysed. It is preferable that samples be taken during exploration drilling, as well as during mining.

### *3.4 Rock/ground support and reinforcement*

*13.8 (2) Each responsible person at a mine must ensure that the following measures are taken in relation to ground control in the quarry -*

*(d) where necessary, appropriate designs of rock reinforcement are applied and used, and the quality of installation is verified;*

The use of rock support and reinforcement in open pit mines has waned over recent years. In the 1980s to early 1990s, there was a trend to use cable bolting as a "blanket" form of support over all final walls in a mine. The intent of this mine design approach was to allow the extraction of more ore by mining steeper slopes than would normally be done without rock reinforcement. During this period, however, it became apparent that large-scale failures were difficult to control using this design approach. The result is that rock reinforcement is now almost entirely being used for stabilisation of batter-scale wedges/blocks of rock within pit walls. This case history exemplifies the importance of adequately matching the design of rock support and reinforcement to the ground conditions*. (For example there is generally less benefit of stiff reinforcement in soft rock* than in strong stiff rock, and achieving large stable slopes with "global" wall reinforcement and aggressive wall angles is difficult.)

*As described in Appendix A

Even though the volume of wall rock being reinforced at individual mines is less in recent times, when it is applied, it still involves large volumes of material. It therefore is essential that each rock reinforcement element is correctly designed and installed. Anything less could not be said to be "sound practice".

It is recommended that the design of ground support and reinforcement* be based on a thorough understanding of the following points, particularly item 1:

1. geological structure* in and around the pit walls;
2. rock mass* strength;
3. groundwater* regime (particularly in terms of corrosion potential);
4. behaviour of the rock support or reinforcement system under load;
5. rock stress* levels and the **changes** in rock stress during the life of the excavation; and
6. the potential for seismic events.

The **timing** of the installation of ground support and reinforcement* should be considered as an integral part of the design to limit the potential for ravelling of the rock mass*. In those areas requiring reinforcement, the delay in the installation of the ground support should be minimised as far as is reasonably practicable. It is recognised that several days or longer may elapse from the firing of a blast, before the shot area is clear of debris and is made ready for the installation of ground support and reinforcement*. However, extended delays in the installation of ground support, in the order of weeks, may jeopardise the effectiveness of the ground control* because of reduced access, and the general loosening (and weakening) of the rock mass*.

**Corrosion** is an important factor that needs to be considered in the design and selection of the rock support and reinforcement. The influence of corrosion will mean that virtually none of the conventional forms of rock support and reinforcement can be considered to last indefinitely; they all have a finite design life. Two causes of corrosion are oxidation of the steel elements, and galvanic consumption of iron by more noble (inert) metals, for example copper.

It should be recognised that the various levels of rock support and reinforcement, together with their surface fittings, combine to form an overall **ground support and reinforcement* system** that consists of different layers. Each layer has its own unique contribution to make to the success of the system. It is essential that each element/layer of support and reinforcement is combined in such a manner that the overall support and reinforcement system is well-matched to the ground conditions* for the design life of the excavation.

It is therefore imperative that the mine management develop a quality control* procedure that ensures that the standard of installation and reinforcement elements used actually meets that required by the design criteria for all ground conditions* in the mine.

It should be noted that all engineering design procedures are based on various simplifying assumptions that may restrict the application of a particular design procedure in certain circumstances. There should be a clear understanding of the origins and the limitations of the various design procedures when applying them in geotechnical engineering.

* As described in Appendix A

### *3.5 Pit wall design*

> *13.8 (2) Each responsible person at a mine must ensure that the following measures are taken in relation to ground control in the quarry -*
> *(e) analysis is carried out of open pit wall stability for the projected geometry of the pit;*

Before mining commences, it is necessary to establish an appropriate excavation design geometry from which to base the overall mine plan. It is acknowledged that the "final" pre-mining design may be modified with time, as additional data becomes available during operation; however, it is essential that the "final" pre-mining geotechnical design be adequately attuned to the anticipated local ground conditions* before mining commences. In this way, the potential for hazardous rock mass* failures to occur unexpectedly during mining is reduced significantly.

The process of geotechnical analysis of pit wall stability and design is well documented (e.g. Hoek and Bray 1981)[2]. Relevant factors considered in the design of open pit excavations have been given earlier in this guideline. An example of one specific factor to be accounted for in pit wall design is the potentially adverse effects of "bullnose" promontories within long straight open pits.

It follows that to achieve higher levels of accuracy of pit wall design, a greater level of investigation, careful engineering, and sound judgement are required. It should also follow that when poor ground conditions* are identified in the early stages of investigation, or there are significant surface infrastructure or natural features near the pit, then the level of risk is higher, and the standard of geotechnical data required for mine design is also higher.

It is also recognised that the final design of open pit walls represents a balance between safety and the economic viability of the operations, as it is generally not feasible to design the pit walls for “permanent” stability. It is often said that the best geotechnical design is one that fails the day after mining ceases. In practice, however, a fall-as-you-leave pit wall design cannot be realistically achieved.

Call[5] recommends that the following steps should be followed with any mine design:

1) Define the geological domains and mining sectors.
2) Conduct a bench design analysis to determine the maximum inter-ramp slope.
3) Conduct inter-ramp design analysis using economic criteria for the selection of inter-ramp angles.
4) Evaluate the resulting slope for potential instability, and modify design if required.

There are a number of ground control* design methods that can be used. All these methods rely on having a good understanding of the prevailing ground conditions* before undertaking the design. The design methods that can be used include:

- empirical or experience based methods developed from extensive local information;
- deterministic/limit equilibrium methods - using geotechnical parameters derived from either laboratory testing or back analysis of existing failures;
- kinematic (stereographic and block analysis methods) - e.g. SAFEX[6], DIPS[3]; and
- numerical modelling, and
- physical modelling.

*As described in Appendix A

Design criteria for each of these methods can differ; however, each design criterion is dependent on the level of acceptable risk of any particular failure and the degree of inherent uncertainty regarding the characteristics of the rock mass* and design method.

It is recommended that a sensitivity assessment be carried out to determine the effect of critical geotechnical parameters involved with wall stability. This will assist with assessment of the quality of geotechnical data obtained and required and the appropriate mine design options. Common methods used to increase the effective stability of pit walls include reducing slope angles, controlled blasting practices, installing reinforcement, and depressurisation of groundwater*. Any deficiencies that are highlighted in the analytical methods should encourage further work to remedy these matters, extend the use of the method or develop a new method.

The most common forms of design analysis are the kinematic or deterministic methods for which there are several packages available commercially. These methods are relatively simple to follow. Numerical modelling allows the design of pit walls and interaction with underground workings to be considered in much more detail than is the case with empirical or deterministic design methods. One of the drawbacks for the use of numerical methods is that they generally require considerably more data input, which cannot always be adequately provided.

Computer-based numerical modelling packages have developed rapidly during the past 10 to 20 years and this trend is likely to continue. A wide range of design packages are currently available that can be run on most standard mine site computers. However, it must be recognised that differences exist between the solution methods used by the major numerical modelling techniques - e.g. finite element, finite difference, boundary element, and distinct element codes. These different solution procedures can give rise to some variation in computation of stresses and strains. The design engineer must acknowledge the differences and limitations between each of the numerical model codes with respect to the problem at hand.

The difficulty the simplified numerical model input data has in accurately representing the inherent variability of the complex rock mass* should also be recognised. It is therefore a prerequisite that significant mining experience and judgement is required to interpret and use the results correctly. It is also recommended that each numerical modelling technique be calibrated against observed ground response to mining at each mine.

Considerable engineering judgement and mining experience is required to determine the appropriate levels and methods of geotechnical investigation required for the development of a geotechnical model of a particular mine, and to determine the method/s of analysis best suited for pit wall design.

* As described in Appendix A

### *3.6 Blasting considerations*

*13.8 (2) Each responsible person at a mine must ensure that the following measures are taken in relation to ground control in the quarry -*
*(f). appropriate drilling and blasting procedures are used to develop final walls;*

Inappropriate drilling and blasting practices can result in substantial damage to the rock mass* within the operating and final pit walls. There is a need to have standardised drilling and blasting patterns that have been determined using well founded and recognised blast design procedures, and that are appropriate to the ground conditions* at the mine site.

The factors that control the level of wall damage caused by drilling and blasting include:

- rock mass* properties such as orientation, persistence and spacing of geological structure*, presence of groundwater*;
- the degree of "confinement" and amount of burden shifted by the proposed blast;
- inadequate removal of rock debris from earlier blasts from the toe of batter slopes;
- the degree of rock fragmentation required;
- selection of the appropriate hole diameter;
- control of individual hole collar position, hole bearing, inclination and length;
- the type and amount of stemming used;
- placement of holes in a suitable pattern to achieve the required excavation geometry;
- the use of specific perimeter holes such as stab holes, or smooth blasting techniques (e.g. pre-splitting, post-splitting, or cushion blasting.);
- selection of appropriate initiation system(s) and initiation sequence of the blast or blasts;
- specific types or combinations of explosives. Explosives must be selected according to the given ground mass conditions e.g. groundwater* or reactive shales can affect the result of a blast. Explosives must also be selected to achieve required energy levels, maintain compatibility with the initiation systems, the explosives' expected product life in blast holes;
- control of explosive energy levels in the near-wall holes and preferably using decoupled explosive charges, with a cartridge diameter less than the blast hole to minimise blast damage* at the excavation perimeter;
- the required mining bench height and the depth of subgrade drilling (subdrill); and
- availability of well maintained drilling, explosives handling and charging equipment of appropriate capacity.

The perimeter/final wall blast hole and explosives system will need to take into account all these relevant issues to arrive at the optimal final product (safe and economic pit walls). There are a number of commercially available, computer-based, drilling and blasting design packages that may be used on a mine-ownership or consulting basis. There has also been a considerable amount of work done on the development of rock fragmentation design methods by organisations such as the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Brisbane, international research groups, consultants and explosives manufacturing companies[7,8].

* As described in Appendix A

The application of recognised drilling and blasting design practices and procedures developed to suit local conditions should be an integral part of a balanced ground control management plan*. Where necessary, the advice of the explosive manufacturer(s) and supplier(s) should be sought on the appropriate use of various combinations of explosive(s) and initiation system(s).

It is considered good practice to qualitatively and quantitatively monitor the extent of blast damage* and evaluate the success of blasting methods as the open pit expands and deepens. Blast monitoring tools include: visual observations, vibration records, noise records, video footage, displacement markers, and complaint records. Blast monitoring results should then be used as part of an ongoing critical review of drilling and blasting to ensure that the blast design is performing to the standards required and is producing the required product.

While consultation of the workforce on such matters is recommended, it is not appropriate that fundamental decisions on important aspects of blast design and practice be left in the hands of individual miners on the job, without any blast engineering support. Nonetheless, mine management needs to ensure that the workforce is provided with on-going training in the safe and efficient handling and use of explosives and initiation devices.

When open pits are located in close proximity to significant surface or subsurface infrastructure or natural features, the effect of blast vibration and fly rock must be taken into account within the mine plan. Blast vibration monitoring may be required to help assess the impact of blasting on the specific infrastructure and the pit walls (and any associated ground support and reinforcement*) that may be supporting the infrastructure.

The detonation of explosives, particularly large production blasts in open pits that mine through large scale underground workings, can trigger seismic activity or audible rock noise. Any occurrence of this should be recorded, noting for example the location, time, subjective description, number of events, any rock falls, etc. If the rock noise continues for some time, or occurs at unexpected times, then further investigation of the situation may be advisable as this could be a pre-cursor of more serious seismic activity in the future.

### *3.7 Monitoring*

> *13.8 (2) Each responsible person at a mine must ensure that the following measures are taken in relation to ground control in the quarry -*
>
> *(g) appropriate methods of open pit wall monitoring are used over a period of time to determine wall stability conditions.*

During the mine design process, it is necessary to make simplified assumptions of the complex *in situ* rock mass* characteristics. In each case, these simplifications introduce sources of uncertainty and potential failure into the design. The inherent uncertainty associated with geotechnical engineering means that it is necessary to regularly monitor the performance of the pit walls to verify the stability or otherwise of relevant areas in the mine.

Sources of uncertainty include inadequate details of the rock mass* (e.g. variable time dependant behaviour of rock masses, groundwater*, variation in geology within walls), human error (e.g. observation, computation and testing errors), and operational mining variation from the design (e.g. undercutting of batter faces). Monitoring of the pit walls therefore becomes an important tool for locating any potential failures of ground before the unstable rock mass*

*As described in Appendix A

becomes hazardous. Well designed monitoring programs can help differentiate between normal elastic movements, inconsequential dilation and incipient pit wall failure. Early detection of wall failure allows mine operators to plan and implement appropriate actions with sufficient notice such that the effect of the failure on mine safety and productivity is minimal.

The specific nature of monitoring programs required for a given open pit will be dependent on the site-specific conditions of the mine. For example, stiffer rocks will tend to deflect less than softer rocks before failure, and certain rock types* or structure can be weakened by water, thus necessitating more frequent monitoring after periods of rain. Regardless of the variation in the performance of various mine slopes, if there is adequate monitoring and a good level of understanding of the ground conditions* at each site, there should be no "unexpected" failures. **Slope failures do not occur spontaneously[5]. There is scientific reasoning for each failure, and failures do not occur without warning if the failed area is being well monitored.**

Conversely, once unusual pit wall movements such as cracking have been observed, it does not necessarily follow that the wall will collapse. Investigation by Sullivan[9] found that of the pit walls displaying cracking and dislocation, 30% will fail in three months and only 60% will collapse within two years.

**It is clear, therefore, that each site must have its own monitoring strategy, matched to local ground conditions*.**

Pit slope monitoring programs should start off simple, and become more refined or complex as conditions demand. To begin with, monitoring can be kept to visual inspection only, provided safe foot access can be maintained to all berms. Where safe foot access cannot be maintained or guaranteed, monitoring equipment that can be operated remotely should be installed on the respective slope faces or crests. Visual monitoring alone is acceptable until the pit wall expresses one or more signs of potential instability.

Visual signs that allude to incipient failure of pit walls include:

- formation and widening of tensile cracks,
- displacements along rock defects in the batter face,
- bulging of the slope face or toe,
- ravelling of rock within the slope,
- increased water seepage,
- bending of reinforcement or rock support elements, and
- rock noise and ejection.

Records of visual observations made during regular inspections of pit walls, play a very important part in building up a history of ground behaviour for assessment of pit wall conditions.

If any signs alluding to incipient pit wall failure exist, visual monitoring will need to be supplemented with more frequent, accurate, and/or wide spread monitoring, using one or more of a variety of instrumentation methods. Considerable judgement, experience and technical support are required for the selection, location, operation and maintenance of some of the more advanced monitoring equipment.

*As described in Appendix A

***Monitoring techniques***

In open pit mining, the most common monitoring instrumentation used is one of several forms of displacement monitoring techniques. A wide range of displacement monitoring equipment and techniques has been used by the mining industry to assess the condition of pit slopes. Some of the more commonly used include:

- survey techniques (e.g. EDM and GPS levelling or photogrammetric surveys.)
- displacement monitoring pins and tape extensometers fixed across cracks or major rock defects;
- borehole inclinometers; and
- extensometers anchored within the rock mass* via boreholes drilled into pit slopes.

In some conditions, e.g. in deep open pits that mine through underground workings, seismic monitoring can be used to detect changes in the performance/condition of the pit walls.

It should be noted, when monitoring dilation of tension cracks, that tension cracks may propagate in series from the slope crest outwards and that the selection of both the pit wall area to be monitored and the appropriate displacement monitoring method should take this into account. It should also be noted that survey monitoring has some inherent error, which can vary due to a number parameters such as diurnal effects, dust, vibration and installation problems. Pit walls will also invariably move elastically, once the overlying material is removed. The amount of elastic movement that will occur will largely depend on the elastic modulus of the material, and the magnitude of confining pressure removed by mining (a function of density and depth). Every effort must be made to minimise or quantify the effects of these variables so that wall monitoring will provide meaningful results. Pit slope survey monitoring procedures have been described in several publications[10,11]. It is expected that a mine will employ a recognised method of monitoring that provides a suitable degree of accuracy.

In critical areas, it is recommended that monitoring systems be installed with warning devices attached (e.g. a horn, or flashing light). The preferred method for setting off alarms is to use a monitoring system that is compatible with a data logger with computational capability so that solenoid switches can be activated electronically once a specified rate of movement has been recorded.

**It is strongly recommended that mines adopt a systematic approach to the collection, analysis and interpretation of geotechnical monitoring data as it applies to mine design.** It is also recommended that the mine operator implement more than one of these techniques in every monitoring program. This will help identify sources of error, and provide more information on the mode of failure from which the best course of remedial action can be established.

An important aspect of any monitoring program is the development of a monitoring strategy, which is implemented rigorously within the mine's ground control management plan*. The strategy should define the monitoring schedule, the time allowed and methods used for data recording, interpretation, and reporting, and provide basic courses of action to be taken in the advent of signs of impending pit wall failure. It is essential that the monitoring data collected is correctly assessed and the results and recommendations passed on to the relevant operations personnel at regular intervals for assessment of the performance of pit walls.

*As described in Appendix A

The task of predicting the exact timing of failure is difficult, as the point of ultimate failure is dependent on a number of factors including rock type*, slope height, the presence of water, and the mode of failure. The best documented sign of impending failure (using displacement monitoring results) is an increase of the **rate** of movement of any given pit wall slope.

For example, it has been illustrated by Broadbent & Zavodni[12] that the onset of collapse can be predicted once movements reach 3 mm/day and imminent failure can be expected when the rate of movement reaches 200 mm/day. By comparison Sullivan[9] suggests that imminent failure is signified by a movement of 1000 mm/day. As explained in Appendix A, the amount of movement expected before wall collapse in soft rock* is greater than that expected for hard rock*. **It is therefore essential, to be able to use rates of ground movement as a tool for the prediction of imminent wall failure, that the frequency and accuracy of monitoring is appropriately matched to the local ground conditions*.**

The common approach used to predict imminent collapse is to graph the rate of movement of a pit wall. Imminent failure is expected when this plot becomes exponential. Again, the judgement of the onset of asymptotic movement will be based on well-founded geotechnical engineering assessment. It is useful practice in this case to increase the frequency of measurement proportionally to the increase in movement rate. The course of action to be taken by the mine operator once asymptotic rates of movement are noted will depend on the circumstances prevailing at a given mine site.

***Selection of monitoring method***

In most cases, the monitoring methods used at a site will be those determined as being the most cost effective. Cost effectiveness is a measure of:

- The **cost per unit** of monitoring equipment - e.g. the cost of using a surveyor, already employed at the site for general volumetric definition can be argued to be nil, and the only real cost is survey prisms.
- **Time taken to get the raw data** - e.g. if simple crack monitoring methods take too much time to access and measure, it could be necessary to employ additional personnel, or other important work may be delayed.
- **Required accuracy levels** - e.g. if it is required that the exact source/extent/depth of the movement in the slope be known for stabilisation, it could be necessary to install expensive borehole extensometers/inclinometers. If, due to inexplicable or inherent errors, there is excessive deviation of results, other methods must be used.
- **Robustness** - mine dust, or vibration, excessive heat, or fly rock may create problems for the instrumentation.
- **Time taken to process the raw data**. If the format of the required information, e.g. movement rates, cannot be provided to the appropriate personnel with enough warning, other methods should be used.
- **Site access**. If berms have been "lost", or the site is remote from the minesite office, automatic monitoring systems become more viable.
- **Vision**. If there is a requirement that monitoring continues through the night, EDM survey or visual monitoring is not always practicable.
- **Training or specialist personnel** requirements and associated costs - e.g. contract labour used to either install equipment or treat data.
- **Susceptibility to vandalism or theft**. The monitoring system needs to be easily securable.

*As described in Appendix A

### 3.8 Mining through underground workings

| |
|---|
| 13.8 (3) Each responsible person at a mine must ensure that appropriate precautions are taken and written safe working procedures are followed if open pits are excavated through abandoned underground workings, or in close proximity to current underground workings. |

Mining through underground workings presents a number of potential hazards that must be accounted for in the mine design. A range of mine planning related geotechnical issues must be investigated, including:

- Definition of the extent and status of the underground excavations (e.g. use of probe drilling and/or remote sensing applications to locate the mine voids, determine whether underground mine voids are filled or partially collapsed, and/or whether the underground voids encountered in the base of the open pit equate to those shown in the mine plans of the underground workings). Accurate survey plans should be kept that record the location, spacing, depth, direction, angle, and number of drill holes, along with records of interpreted ground conditions* during drilling. It is also important to denote locations where voids have been removed or filled during the mining process.
- Establishing a suite of operating procedures for mining near and through underground voids that match with production requirements. Issues to be covered include personnel and equipment access, blasting strategies, infill/backfill and barricading procedures, and general reporting procedures (particularly in the case of new unstable ground being detected).
- Definition of the minimum pit floor pillar thickness such that mining equipment and personnel can safely traverse during normal mining operations.
- Determination of the likely stability of ground at the edges of underground voids and derive the positioning of safety barricades to minimise the risk to personnel or equipment working near mine voids - particularly near unfilled stopes.
- Determination of the safe thickness of "rib" pillars left between open pit walls and underground workings to ensure continued stability of the pit walls.

It is the responsibility of mine management to ensure that safe working procedures, that address each of these issues, are appropriate for the risks at each mine site, and are implemented rigorously. The implementation of these procedures should be incorporated as part of the overall ground control management plan*.

Refer to the DME Guideline “Open Pit Mining Through Underground Workings” for more discussion of the issues associated with this regulation.

* As described in Appendix A

## 4.0 HAZARD RECOGNITION

It is obvious that the level of exposure of the workforce to potentially hazardous conditions will govern the occurrence of injuries and fatalities at a mine site. It is also obvious that in order to reduce the level of exposure to hazards, a system must exist whereby hazards can be systematically recognised/identified and managed. This system of hazard recognition and management (in this case ground control* hazards) should be incorporated within the overall mine plan. The implementation of an all-encompassing mine plan presents a major challenge for mine management. A sound understanding of the ground conditions* is vital for the selection of the most appropriate mine design, mining method(s) and risk management for a new or existing mining operation. The level of risk, both in human and economic terms, will be substantially increased if the ground conditions* are not sufficiently well understood. A general grounding in hazard analysis and risk management can be found in the Australian/New Zealand Standard on Risk Management[13].

The potential exposure to risk increases from low investment, low safety-related risk at the pre-feasibility stage, to high investment risk, low safety risk at the pre-mining stage, to high investment and high safety risk at the final stages of mine design. (When the period of exposure and the height of pit walls is greatest, the area available for maneuvering at the base of the pit is at its least, and there is greatest potential for a wall failure to bury the entire area of exposed ore.) Sullivan[14] suggests that, to limit financial risk during each pre-mining stage of mining project development, the allowable deviations from optimal wall design are:

- Preliminary ± 10° to 15°
- Pre-feasibility ± 5° to 10°
- Final pre-mining design ± 1° to 3°

It is acknowledged that these design tolerances will vary between sites; depending on the resource being mined, the method of mining and site geotechnical conditions. Nonetheless, it follows that when the pit is in its final stages of mining, all the relevant geotechnical parameters in the deposit should be well understood, and the angles of the deepest walls should ideally be mined at the optimal design.

To achieve these progressively higher levels of accuracy, progressively greater levels of investigation, thorough engineering, and sound judgement are required. It should also follow that when particularly poor ground conditions* are identified in early stages of investigation, or there are significant surface infrastructures/features near the pit, then the level of geotechnical data required for safe mine design is also greater.

It is acknowledged that the "final" pre-mining design may be modified with time, as additional data becomes available during operation; however, it is essential that the "final" pre-mining geotechnical design be adequately attuned to the anticipated local ground conditions* before mining commences. In this way, the potential for hazardous rock mass failures* to occur during mining is reduced significantly.

Recognition and correct assessment of hazards[15] forms a critical part of a ground control management plan*. Considerable mining experience and professional judgement are required for hazard recognition and the selection of appropriate mine design strategies.

### *4.1 Mine Design Criteria*

It could be said that all excavated pit walls have potential for failure. The acceptability of any given failure will depend on its consequence and perceived risk. If the failure of a particular slope is deemed to have no bearing on the surrounds, or the safety and production of a mine, there is likely to be minimal concern. However, as pit wall failures usually do have an impact on their surrounds, mine slopes need to be designed to an acceptable standard, taking into account the consequence of failure and the inherent uncertainty in the geotechnical model used as the basis for the pit wall design. Therefore, pit wall design is essentially governed by two factors:

- The consequence of failure, and
- The degree of inherent uncertainty[16].

To accommodate these two design factors, it is usual practice to apply an appropriate factor of safety (FOS) and/or probability of failure (POF) to the design geometry of the pit wall. These design criteria provide a margin of conservatism to the pit wall design that is in proportion to the consequence/apparent risk of failure. When the consequence of failure and/or the level of uncertainty is high, the design criteria should be altered accordingly (resulting in a more conservative pit wall design). This approach is the most common design method used in Western Australia. An example of the FOS & POF design criteria approach is provided in Table 1. These design criteria have been developed from a combination of DME assessment of open pits in Western Australia and a selection of published literature[17,18,19]. The design criteria for class 3 and 4 pit walls in the table below represent DME's expectation for wall designs derived from a lower-bound standard of (acceptable) geotechnical data.

**Table 1 Examples of design criteria for open pit walls.**

| Wall Class | Consequence of failure | Design FOS | Design POF | Pit wall examples |
|---|---|---|---|---|
| 1 | Not Serious | Not applicable | | Walls (not carrying major infrastructure) where all **potential**[+] failures can be contained within containment structures. |
| 2 | Moderately Serious | 1.2 | 10% | Walls not carrying major infrastructure. |
| 3 | Serious | 1.5 | 1% | Walls carrying major mine infrastructure (e.g. treatment plant, ROM pad, tailings structures). |
| 4 | Serious [++] | 2.0 | 0.3% | Permanent pit walls near public infrastructure and adjoining leases. |

[+] Potential failures have been defined as those modes of pit wall failure that have either a FOS of less than 1.2 or a POF of greater than 10%.

[++] Where a mutually acceptable agreement to allow mining cannot be made between the mining company and the "owner" of the adjoining structure or plot of land. Note that a higher standard of geotechnical data is required for the design of category 3 and 4 slopes compared to category 1 and 2 slopes.

It should be noted that this table does not imply any form of direct relationship between FOS and POF. The use of one design approach over another will largely depend on the local ground conditions*, the potential modes of failure, and the amount of information available/attainable.

**It should also be noted that use of the design criteria given above, or any other design criteria, must be justified by mine management.** Firstly, the pit wall design must take into account the consequences of pit wall failure at the specific mine site. Secondly the geotechnical data and modelling\design methods used to design pit walls must be of an adequate standard to suitably represent the rock mass* (to attain an acceptable level of geotechnical uncertainty) for the perceived consequences of failure.

It is therefore a prerequisite that significant mining experience and judgement is required to design the geometry of open pit walls.

An example of justification of the use of a particular wall design is the use of good quality site-specific case history data of wall performance in identical geological conditions to verify the proposed design. In conjunction, mine management should implement a well-matched pit wall monitoring and ground assessment program to verify the as-mined performance of the pit walls during the life of the mining operations.

It is important to recognise that ground conditions* **can change** during mining and that the level of geotechnical uncertainty is dependent on a number of factors that are not directly attributable to "standard" rock mass* properties; including:

- loosening of the rock mass* due to blast or seismic vibrations;
- alteration of properties of some rocks on exposure to air or water over time, e.g. slaking, pore water pressure variations;
- variable time-dependent behaviour of rock mass* under static loading;
- quality of excavation and sudden changes in wall geometry, e.g. poor blasting or the formation of a “bull-nose” promontory along the wall;
- localised variation in stress, e.g. stress reduction or elevation in pit wall rock mass* near the side-walls and pillars associated with large underground stopes; and
- surcharge loading - e.g. waste dumps close to pit crests.

Should any variation from the "assumed" geotechnical design parameters be detected during mining, a reassessment of the pit wall design is required. Therefore, the mine plan must be sufficiently flexible such that changes in wall design, where required, can be readily accommodated.

In summary, the final pit wall design will need to be verified by appropriate geotechnical methods, taking into consideration a risk assessment, that includes all the parameters relevant to the stability of that particular pit wall and the safety and profitability of the operations. The scale and scope of geotechnical investigation required for pit wall design would be greater when the mine site geology is complex (when the level of geotechnical uncertainty is high), the pit is deep and has a long operating life*, and/or the consequences of failure are high.

**Mine management must ensure that the standard of geotechnical data and design criteria used to design open pit walls are suitably matched to the scope of the project**.

*As described in Appendix A

### *4.2 Open pit rock failure report form*

In order to gather relevant information on rock failure events in open pit mines a single-page rock mass failure report form has been developed, see Appendix C. The information gained from these reports will be used by the DME to statistically analyse falls of ground in WA open pit mines. Factors including failure location, failure dimensions, typical effects of failures on mines, failure mode, geotechnical features, rock mass* quality, excavation details, ground support and reinforcement* details, and monitoring information will be assessed from this data. The results from these analyses will be reported to the mining industry on a regular basis.

This rock failure report form is essentially an extension of the DME **incident** reporting process. The form does not replace the accident/incident report form - it should be filled in conjunction with the accident/incident form.

The details to be completed in the rock failure report form represent the minimum information required to achieve DME objectives. It is recommended that each mine site should maintain a record of rock failure incidents and, where relevant, develop a report form that is more directly relevant to the mine site. The general use of this mine site data will assist with improving the general understanding of **hazard recognition**, rock mass failure* and mine design at each mine site. This will, in turn, assist mine management with the derivation of appropriate and timely remedial measures, particularly at mine sites with a number of (nearby) satellite pits in similar geological environs.

*As described in Appendix A

## 5.0 CONCLUSIONS

Regulation 13.8 of the Mines Safety and Inspection Regulations 1995 succinctly lists a number of important geotechnical issues that should be addressed by mine management at the planning stages and during all mining stages. This guideline discusses these Regulations in more detail within the bounds of the principal employer's and mine management's duty of care.

The duty of care requires a well informed mine management to be aware of the recent developments in geotechnical engineering and make appropriate use of soundly based geotechnical methods. Anything less could not be said to be reasonable risk management practice. Geotechnical engineering has developed to the stage where it is now clearly an essential and integral part of the total mining process. The recent development and refinement of geotechnical analysis software can aid the application of geotechnical engineering to major mining challenges. The application of current geotechnical knowledge, methodology and hardware is a vital part of the ground control* process. A considerable corpus of current geotechnical information now exists in the public domain. A small sample of this is provided in Section 6 of this guideline.

The obligations contained in the duty of care provisions given in the MSI Act 1994 also warrant the development of a suitable ground control management plan*. This ground control management plan should identify the risks, determine the relevant rock mass* characteristics, and apply current accepted geotechnical engineering practice to a range of issues at both the batter-scale and the wall-scale of open pit mining.

Considerable judgement and mining experience are necessary to determine the appropriate level of detail at which the ground conditions* need to be investigated and for the selection of appropriate mine planning and design for each mine site. The combination of sound mining experience and professional judgement, with current geotechnical analysis and design methods, is therefore considered to be a powerful engineering tool with which a well managed mine should equip itself.

*As described in Appendix A

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# APPENDIX A

## GEOTECHNICAL CONCEPTS

This Appendix provides the relevant “terms of reference” of the more important geotechnical concepts referred to in this guideline. Each concept is provided in alphabetical order and, as with other lists of information in this document, does not represent order of importance.

### *Blast damage*

Blast damage may be described as the weakening of the rock mass by blasting practices in the open pit. Damage may be in the form of fracturing of intact rock, or simply the loosening of geological structure. The aim of any well designed rock drilling and blasting process should be to achieve the required degree of rock fragmentation with the minimum of damage to the remaining rock. Blast damage to the rock mass is an unavoidable consequence of conventional drill and blast mining methods. However, much can be done to minimise excessive damage to the rock by the use of controlled drilling and blasting practices[7,8] (e.g. pre-splitting, and modified production blasting).

The technique of drilling and blasting is a very large field that is constantly evolving and hence cannot be summarised in a few lines. Those interested in pursuing this matter further are encouraged to research the published literature and contact their suppliers of drilling equipment and explosives.

### *Geological structure*

In geotechnical engineering the term geological structure refers to all the natural planes of weakness in the rock mass that pre-date any mining activity and includes: joints, faults, shears, bedding planes, foliation and schistosity. Across these natural planes of weakness (or discontinuities), the rock mass has very little or no tensile strength - in comparison to the strength of intact rock. The number, shape and dimension of these blocks of intact rock (which strongly influence the stability of walls in open pit mines) depend on the number, persistence, shape and orientation of discontinuities present. This assemblage of discontinuities is therefore an important characteristic of any given rock mass.

Geological structure can have a range of characteristics including:

- orientation - usually specified by dip angle and dip direction;
- spacing;
- persistence or continuity;
- roughness
- waviness;
- defect wall strength;
- aperture;
- filling; and
- seepage/moisture;

The important role that geological structure has in open pit ground control* cannot be over-emphasised.

### *Geotechnical domain*

A geotechnical domain is a volume of rock with generally similar geotechnical rock mass properties. The geotechnical properties that need to be considered when defining the geotechnical domains include:

- similar geotechnical characteristics of the planes of weakness - particularly orientation, spacing, persistence and shear strength properties;
- degree of weathering and/or alteration;
- rock type*;
- pit wall orientation;
- rock mass or intact rock strength;
- deformation/elastic modulus of the rock mass;
- induced rock stress field; and
- permeability of the rock mass.

Rock mass classification methods[20] may be useful in determining the number and extent of geotechnical domains in a mine. The main rock mass classification systems that have been used in geotechnical engineering in mines include:

1. Rock Mass Rating system or RMR system[21];
2. Rock quality system or Q-system[22]; and
3. Mining Rock Mass Rating system or MRMR system[23].

Although these methods have been developed predominantly for underground tunnelling and mining, this does not preclude their use for open pits (eg Haines & Terbrugge, 1991)[24]. It is more common for geological domains in open pits to be divided into more simplistic categories - e.g. pit walls consisting of various categories of weathered rock, foliation or other major structure dipping into, out of, or across the pit.

### *Ground*

Ground refers to rock in all the possible forms that it may take from a fresh, high strength material to an extremely weathered, very low strength, essentially soil-like material. This term can also refer to most fill/buttressing materials.

The open pit mining environment in WA is characterised by a wide variety of orebody geometries, ground types, mining systems and sizes of mining operations. This diversity, combined with the high level of uncertainty that exists in our knowledge of the rock mass geotechnical conditions, must be recognised as a major challenge facing mine management. There needs to be clear recognition that there are a number of fundamental uncertainties in our knowledge of the rock mass geotechnical conditions and characteristics. Examples of these uncertainties include:

- The rock mass is not a continuum but is comprised of a large number of discontinuity bound blocks. The size, shape, orientation, location and number of these blocks throughout the rock mass is usually not well known.

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* As described in Appendix A

- Forces or stresses acting within large volumes of rock mass are also not well known and are subject to variation (e.g. variable block interaction) as the mine develops. Point measurements of the rock stress field are possible; however, the results from these measurements need to be carefully scrutinised before application.
- The strength of the rock mass is not well known and is difficult to measure in large volumes of rock. Whilst strength testing of core-sized samples of rock is relatively straightforward, large scale rock testing is difficult and expensive to conduct.
- The time dependent behaviour of the rock mass is not well known.
- Blast damage to the rock mass, particularly from large scale blasting operations, is an additional factor that has generally not been well quantified.

In view of the above uncertainties it is not surprising that even the most carefully planned and designed mines have unexpected ground instability. Consequently, it is unlikely that a particular rule of thumb or specific guideline is universally applicable in every situation, at any mine, in perpetuity.

***Ground conditions***

Ground conditions may be thought of as those fundamental geotechnical properties of the rock mass, plus the influence of mining activity in the rock, that can combine together to produce a potentially unstable situation at or near the perimeter of an open pit excavation. The main factors that may combine together to produce a given set of ground conditions include:

- geological structure;
- rock mass characteristics (e.g. rock type*, rock mass strength*, unit weight and weathering);
- local and regional rock stress;
- nearby underground workings;
- groundwater* and surface water;
- size, shape and orientation of open pit excavations with respect to geological structure and rock stress field; and
- blast damage.

Discussion on the meaning of geological structure has been provided earlier. Each of the remaining factors is discussed later in the guideline.

It is imperative that the diverse range of ground conditions, that may be encountered in Western Australian open pit mines, is recognised and understood as a challenge to achieving cost effective and safe ground control*.

***Ground containment***

Ground containment pertains to the method by which fallen ground that has not come to complete rest, or unstable ground that is yet to fall is isolated from any given area of the mine. Common methods of containment include wall catch berms, bunding, catch fences and trenches. The effectiveness of each method of containment will depend on the volume, height and nature of the potentially moving ground, the angle of the pit wall, the stiffness and

*As described in Appendix A

dimensions of moving rock, the consequence of moving ground reaching the working area, and the area available to establish the containment structure/barrier.

Each of these parameters must be adequately considered before the barrier is constructed to ensure that the selected method of containment will be adequate for the local ground conditions. For example if the catchment/containment volume is less than the volume of moving ground, the effectiveness of the ground containment* method will be greatly reduced. Where containment barriers are not adequate, the mine operator will either need to develop a system of work to allow safe access beneath the area of concern (eg clear contained rock debris from behind/within the containment barrier; mine a cut-back; restrict personnel and equipment access beneath the area), or modify the containment barrier.

***Ground control***

Ground control deals with both ground stability and instability issues that result from mine development and the economic extraction of ore. Ground control is an integral part of any well managed mining operation. The aim of an open pit ground control program is to design and manage the excavation of pit walls so that the required levels of workforce safety, serviceability, grade control, productivity and design life of a mine are achieved. A successful ground control program is not necessarily one that has had no rock mass failures*. Success is measured by the level of awareness developed before any wall/batter failure and the level of consequence of the wall/batter failure on the operations.

The ability to influence and manage ground responses to mining may vary greatly depending on the accessibility to the site and the volume of potentially unstable rock. (For example pit walls with high batter slopes (typically >20 m) can be more difficult to access for safe remedial scaling, and small volumes of rock can be removed with small-scale equipment without impacting greatly on production or personnel safety.)

It is therefore useful to consider two types of ground control:

1. **Batter scale ground control**: involving failed rock debris which is normally contained within catch/safety berms or scaled from slopes and removed during the mining process; and
2. **Wall scale ground control**: involving those factors that affect the stability of large sections of the pit wall; typically more than one complete batter slope. These large-scale issues are usually beyond the control of the general workforce to deal with (although poor blasting or excavation practice can initiate large-scale failures), and are the responsibility of the principal employer and mine management.

A variety of terms can be used equally well to describe the scale or size of the issues to be addressed; however, for simplicity, these two (batter and wall scale) have been used in this guideline. The distinction between batter scale and wall-scale ground control issues is less clear where the vertical distances between catch berms is greater than 20 m. Consequently some of the comments given for one particular area of ground control may also apply to the other, depending on the mining method, depth of mining and/or scale of mining operations.
Ground control involves two main aspects of mining - the local ground conditions (eg. rock strength and groundwater*), and mine planning and design issues (eg. blasting techniques, groundwater* depressurisation, wall design angles, ground containment* and ground support and reinforcement*).

It cannot be over-emphasised that a well managed and systematic approach to ground control necessarily requires a good understanding of the ground conditions.

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*As described in Appendix A

Ground control in open pit mines is largely brought about by excavating the geometry of the pit walls in accordance with the prevailing ground conditions such that there is no hazardous or commercially unacceptable rock mass failure* during the operating life* of the excavation. Ground control strategies must take into account the potential for both batter scale and wall scale rock mass failure*.

Control of the geometry of the pit walls is typically accomplished by varying the individual batter slope heights and angles, and the widths of intermediate catch berms. Where these geometrical controls do not produce a commercially viable mine, rock support and reinforcement can be used to artificially strengthen the rock mass. The use of rock reinforcement is usually limited (in more recent times) to stabilising localised areas of the pit walls deemed to be susceptible to detachments of blocks of rock, which may otherwise be mined-out inefficiently or represent a safety hazard. The decision to use rock reinforcement will be based on the cost differential between mining to a shallower overall wall angle, and the cost of the rock reinforcement.

There are a number of ground support and reinforcement* design methods that can be used. Design criteria for each of these methods can be determined from empirical, probabilistic or deterministic methods. All of these methods rely on having a good understanding of the prevailing ground conditions before undertaking the design.

It is recommended a sensitivity analysis be made for the critical geotechnical parameters involved in ground control to arrive at the optimal pit wall design. Any deficiencies that are highlighted in the analyses should encourage further work to remedy these matters, extend the use of the methods of analysis or develop a new method.

Ground control design methods will continue to evolve and develop in the future. These methods, in keeping with the engineering method, do not present an exact closed form solution with one unique answer. Rather, they are based on underlying scientific principles, strength of materials concepts, engineering computational modelling, static and dynamic loading plus considerable observations of field performance to present a range of solutions. The important issue about any ground control design method is that it must be based on sound geotechnical engineering practice.

The inherent challenges in geotechnical engineering do not excuse the application of sound geotechnical design strategies in any mining project.

### *Ground control management plan*

It is suggested that a ground control management plan be produced for a mine using a combination of relevant professional expertise; for example geotechnical engineers, surveyors, geologists, miners, and mining engineers. The ground control management plan should be critically reviewed at least annually, or more frequently if necessary, to highlight and correct any areas of deficiency noted by geotechnical monitoring and variations noted in general mine performance.

An effective ground control management plan should be applied to the whole-of-mine life. Development of the ground control management plan may be facilitated by the use of **qualitative risk assessment techniques**[25]. These techniques can assist in identifying the risks within a mining operation and develop a range of appropriate controls to effectively manage the risks. A range of geotechnical and risk assessment expertise is available in a variety of organisations such as mining companies, geotechnical consulting companies, risk assessment companies, research organisations and universities.

*As described in Appendix A

The successful implementation, review and, where necessary, modification of the ground control management plan is the responsibility of the principal employer and the mine management team.

A balanced ground control management plan should recognise and address the benefits as well as the detriments of possible courses of action. Open, informed discussion of the potential risks associated with alternative courses of action, practices, methods, equipment, technology, limitations of knowledge or data, and any other deficiencies, is considered sound geotechnical engineering practice. Those with knowledge and experience in geotechnical engineering have a duty of care to inform their colleagues or client(s) of the inherent strengths and weaknesses of any preferred course of action in an objective and unbiased manner. Responsible risk management practice requires those having sound knowledge of geotechnical engineering to communicate that knowledge. Similarly, those in management should take timely, balanced and documented decisions regarding the application of that knowledge and ensure that these decisions are promptly communicated to the relevant people.

The ground control management plan should recognise the importance of developing a mining culture in the workforce that understands the vital importance of the rock mass, as well as the people and equipment, to a viable mine. This is best achieved by establishing a team approach to ground control management, possibly involving the whole workforce. Failure to recognise the important role of the rock mass, at all scales in mining, can result in unsafe and unproductive mining.

The ground control management plan should address each of the geotechnical considerations raised in Regulation 13.8 and relevant issues in Regulation 13.9 of the Mines Safety and Inspection Regulations 1995.

***Ground/rock support and reinforcement***

The terms ground support and ground reinforcement are often used interchangeably, however they refer to two different approaches to stabilising rock[26]. **Ground support** is applied to the exterior of the excavation to limit movement of the rock mass, e.g. buttressing, meshing, strapping, concrete lining, and shotcrete. These methods typically require the rock mass to move on to the support to generate loads in the support. **Ground reinforcement** is applied to the interior of the rock mass to limit movement of the rock mass, e.g. rock bolts, grouted dowels, cable bolts and friction rock stabilisers. These methods can typically provide active restraining forces to the rock mass soon after installation with little or no movement of the rock.

Ground support and reinforcement includes all the various methods and techniques that may be used to improve the stability of the ground. Obviously, depth, shape and orientation of the excavations and the ground conditions would need to be considered when selecting the most appropriate ground support and reinforcement system.

**If ground support and reinforcement are required to stabilise a pit wall, each component must be matched to the ground conditions and expected displacements**.

***Groundwater***

Groundwater is the term used to describe the water held within the rock mass. Depending on the water bearing characteristics of the rock mass, the groundwater interacting with a mine can be sourced from within close proximity to the excavation, or up to several hundreds of metres away.

Similarly, the quantity of water that is necessary to have a deleterious impact on the ground conditions within a mine can vary by orders of magnitude.

The characteristics of the groundwater regime in and around the mine and its potential influence on the rock mass should be well defined before producing the final mine design. It is also important to systematically fine-tune the level of knowledge of the hydrogeology of a site in an on-going manner throughout the life of the mine at a level appropriate for the hazard potential to the mine. For instance, the potential for corrosion of ground support and reinforcement, erosion or softening of the rock mass, water-related blasting problems, and the likely impact of elevated pore water pressure needs to be recognised, investigated and if necessary remedied.

Furthermore, it is not uncommon for open pit wall failures to occur after rain. In these circumstances, it may be necessary to develop an understanding of the time-lag and mechanisms of infiltration of surface water into the rock mass.

***Hard rock conditions***

In hard rock mining conditions the strength of the intact rock is usually considerably greater than 25 MPa. Wall failures in hard rock are primarily controlled by the presence of geological structure, and the geometry of the pit walls. The size, shape and orientation of the potentially unstable blocks of rock depends primarily on the orientation, spacing and length of the planes of weakness in the rock mass plus the geometry and orientation of the mining excavations. Structurally controlled failures in hard rock are commonly divided into one or a combination of two principal types:

- sliding (eg wedge or planar failure), and
- toppling.

Each of these modes of failure has been well documented (e.g. Hoek & Bray)[2]. There are numerous variations of these failure modes (e.g. ravelling, step path, complex wedge formation, flexural toppling etc); however, each variation has been included as one of the two principal groups given above. Although these modes of failure are generally more relevant to hard rock mines, pit wall instability in soft rock* can also result from one or a combination of the structurally initiated modes of failure. The design of all open pit walls will therefore need to take these modes of failure into account.

It is usually the case that failure through intact hard rock only occurs in well foliated rock masses where rock stresses are acting on long thin subvertical columns of rock. This general rule may change in very deep mines, where rock stresses at depth are much higher. In deep open pits, particularly those mining through old underground workings, potential exists for seismic conditions to be generated. Under these conditions, violent fracturing of the rock mass rock could result.

***Operating life***

The term **operating life** pertains to the length of time an open pit wall is required to remain stable to protect the safety of mining personnel, equipment and surface infrastructure. For example, once the mining schedule allows for mining personnel to completely avoid any section of a pit wall for the remainder of the mining project, the wall has completed its operating life. For the purposes of this discussion open pit excavations have been divided into two terms of operation:

- short term, and

- long term.

The definition of **long term** is arbitrary; in this case it has been taken to mean a pit wall with an operating life of at least two years; **short term** walls have an operating life of less than two years. Long term walls, being exposed for greater lengths of time, represent a greater risk to the operations - due to factors such as the time dependent characteristics of rock masses and corrosion of rock reinforcement. Pit slope designs should therefore take into account the effective operating life of walls.

An example of the relevance of design operating life in ground control is the regular use of long-term haulage ramps by the workforce. The potential risk of injury is higher because more personnel use haulage ramps, and because main haulage ramps are exposed and utilised for longer periods. Hence longer-term excavations/walls should demand a greater level of geotechnical investigation both before developing the mine plan and during mining operations to reduce the level of inherent uncertainty about the rock mass and thereby better manage/control the increased risk.

***Quality control*** (for ground/rock support and reinforcement)

Suppliers of rock support and reinforcement elements should provide an appropriately detailed set of instructions for the correct installation and testing techniques for each element type. Training courses and materials should be readily available to ensure that the workforce is fully conversant with the type(s) of ground support and reinforcement in use. There needs to be a thorough understanding by all those concerned with their use of the strengths and limitations of all the rock support and reinforcement elements, which are employed.

The end users of the rock support and reinforcement should be able to demonstrate that they are following the manufacturer’s instructions for the correct installation of the equipment.

The importance of quality control to the successful design and installation of adequate ground support and reinforcement needs to be clearly recognised and proper quality control procedures should be put in place. The supplier of the ground support and reinforcement system elements should provide information on the factors that determine the quality of the installation. It is recommended that the following issues be taken into consideration when designing ground support and reinforcement programs:

- storage and handling of the rock support and reinforcement should be such as to minimise damage and deterioration to the elements;
- rock mass strength* should be adequate to allow the full capacity of expansion shell rock bolts;
- that recommended hole diameter ranges for the particular type of support or reinforcement can be achieved consistently in **all** the rock conditions likely to be encountered;
- that correct hole length can be drilled, the correct reinforcement length installed, and holes flushed clean of all drilling sludge;
- orientation of the hole is appropriate for the excavation geometry and expected mode of failure;
- corrosion issues should be recognised and remedied;
- blast vibrations may loosen threaded rock bolt and barrel and wedge systems:
- cement grout is mixed at the recommended water:cement ratio, at the recommended angular speed in the specified equipment for the time specified;

- water used for cement grout mixing is of the required quality or the cement used should be able to develop the required uniaxial compressive strength with the run of mine water supply;
- any additives (e.g. retarders, accelerators, fluidisers, etc) to the cement grout mix should be added in the recommended amounts and at the specified time in the mixing and pumping process;
- all steel components designed to be encapsulated in resin or cement grout are to be **clean** of all oil, grease, fill, loose or flaking rust and any other materials deleterious to the grout;
- where full grout encapsulation of the steel element(s) are required, the method of grouting should show a grout return at the collar of the hole; other methods that can demonstrate complete hole filling may also be appropriate;
- correct tensioning procedures (when required) should be used for the various types of rock support and reinforcement. The purpose of tensioning of cables in the ground support system must be determined to establish whether post tensioning or pre-tensioning is required.
- plates and/or straps against the rock surface should have the required thickness to prevent nuts or barrel and wedge anchors being pulled through the plate and/or strap at the ultimate tensile strength of the tendon when loaded against the rock surrounding the bore hole;
- all grout mixing and pumping equipment should be cleaned and maintained on a regular basis;
- shotcrete mix specification should state the slump of the mix, the uniaxial compressive strength and a measure of the toughness of the product at specified time intervals prior to or following field application as appropriate;
- samples of the shotcrete mix should be collected at specified intervals, under normal operating conditions, and tested in a suitably recognised concrete testing laboratory for compliance with the shotcrete design specifications; and
- shotcrete thickness should be tested regularly during placement to ensure that the specified thickness has been applied - a means of permanently marking the shotcrete surface with a depth gauge probe may be appropriate.

The cost associated with the different types of cable bolt strand is minor in comparison to the fixed costs associated with the hole drilling and grouting (e.g. equipment depreciation, drilling consumables, transportation, grouting and labour). Hence, it is **vital to ensure the correct cable bolt strand type is selected for the ground conditions and expected ground behaviour**.

***Rock mass / Intact rock***

A rock mass is the *in situ* rock which has been rendered discontinuous by systems of geological structural features such as joints, faults and bedding planes[2]. A discontinuous rock may not necessarily be detached from the rock mass. The term intact rock pertains to the rock material between the structural features within a rock mass.

***Rock mass failure***

A failure of the rock mass in open pit walls and/or floor involves the relocation of a body of material from its original position within the wall. This will occur when the driving forces acting on a defined body of material are greater than the forces resisting movement of the body of material. Examples of driving forces include water pressure and gravity, examples of resisting forces are joint friction and compressive forces applied by ground support such as cable bolts.

***Rock mass strength***

The strength of the rock mass[27] is controlled by the complex interaction of a number of factors including:

- intact rock substance strength;
- geological structure (planes of weakness) - particularly orientation, persistence, in-fill materials, spacing and shear strength parameters;
- groundwater;
- alteration of minerals on exposure to stress, air and/or water with time; and
- mining effects (e.g. blast damage).

It should be recognised that the estimated strength of the rock mass, in general, is dependent on the volume of the rock being loaded/tested. Strengths measured from small core-sized tests on intact rock are therefore generally not representative of the overall rock mass. This volume or scale dependence of rock strength is not found in other engineering materials, e.g. concrete or steel. Furthermore, the extent of knowledge of the inherent variability of rock properties throughout a large-scale mine is usually limited compared to engineered materials. Consequently, the design of structures using engineered materials can be undertaken with more confidence, than the design of structures in rock - due to a larger margin for unknown error in rock mass properties.

Rock mass strength is one of the least well-defined parameters in the field of geotechnical engineering. There is a need to have a much better understanding of rock mass strength, ranging from small pieces of intact rock with a volume measured in cubic centimetres to very large volumes of rock measured in thousands of cubic metres. There are some obvious practical difficulties in conducting tests on large volumes of rock. The limitations that exist in this area of geotechnical engineering need to be recognised, particularly with regard to the use of numerical modelling techniques.

One of the better recognised methods of determining rock mass strength is to back-calculate strength parameters from existing wall failures[2]. This presupposes that a reasonably significant failure has occurred before a mine owner can better design a mine. Whilst mining pit walls to failure is not advocated by the DME, should a large failure occur inadvertently, the DME encourages the use of back-analysis of rock mass properties and modes of failure to derive more accurate pit wall design criteria and thereby reduce the risk of similar failures recurring.

The range of ground behaviour expected around an open pit excavation is, in simplistic terms, dependent on whether the rock mass is classified as "soft rock*" or "hard rock".

***Rock stress***

A rock stress field has both magnitude and orientation and can be considered to consist of two components:

1. pre-mining (*in situ*) stress field; and
2. mining induced (disturbance) effects.

The pre-mining stress field is dependent on essentially two components:

1. forces exerted by the weight of overlying rock mass; and
2. lateral tectonic forces in the earth's crust.

Some variation in pre-mining stress may develop as a result of changes in groundwater pressure (particularly in saturated sediments) or as a result of tectonic movements.

The removal of rock by mining causes the *in situ* pre-mining stress originally carried by that rock to be redistributed to the remaining surrounding rock. The resultant rock stress field around an open pit provides the environment that can result in one of the following things happening:

- sudden movement or slip occurs on pre-existing planes of weakness in the rock mass; and/or
- failure through the intact rock mass creating a new plane or planes of weakness on which movement can occur.

The level of stress required to initiate either of these events is largely dependent on the mechanical strength of the rock mass. As the vast majority of open pits in WA are relatively shallow, stress related instability is generally not of concern. Nonetheless, as mines deepen, stresses will increase and the potential for stress related instability would increase.

Once failure of the rock mass occurs, the elevated stresses are redistributed throughout the remaining rock mass and a modified/induced stress equilibrium established. The duration of the modified equilibrium conditions will depend on the extent of initial ground movement or rock damage and the susceptibility of the remaining rock to further changes in ground stress. In some cases, subsequent smaller changes in stress can induce greater damage than that caused by the initial change in stress.

The subject of rock stress and its potential influence on mining activity needs to be recognised. There are two types of stress measurements that can be undertaken:

1. absolute rock stress measurements; and
2. stress change measurements.

Several methods can be used to estimate the magnitude and orientation of the rock stress field[27,28], in terms of absolute stress levels or stress changes - see the DME guidelines on "Geotechnical considerations in underground mines". Should stress monitoring be required, mine management will need to establish the most relevant method.

It is not suggested that every mine undertake a comprehensive program of rock stress measurement. However, mine management should recognise that rock stress is an issue that requires attention when planning a mine. When deciding whether or not to undertake a rock stress measurement program it is necessary to consider a number of things including: - the size and operating life of the mine, mining depth, the overall rock mass strength, presence of major geological structure, production rates, and the presence of existing underground mining within the immediate proximity of the open pit. Issues of concern for interaction with underground workings include; dimensions of underground openings and pillars in relation to the pit walls and the presence or absence of fill or water, and the potential for natural seismic activity.

It will be appreciated that all of these rock stress "measurement" methods require that strain, or some other parameters, are measured and then converted into a stress magnitude by means of elastic or seismic theory. The determination of reliable rock mass stress magnitudes and orientations is not something to be undertaken lightly or in haste. Considerable experience, technical skill and use of appropriate equipment plus technical backup are required for success in obtaining reliable results.

***Rock type***

It should be recognised that different rock types (eg. ultramafic, sedimentary etc) react differently to mining excavations. This is due to the individual characteristics of each rock type (e.g. fabric grain size, texture and alignment) which form the basis of engineering properties of rock (e.g. tensile strength, shear strength or elastic modulus). In many cases, even rock classified as being similar type will react differently to mining - eg. the presence of certain minerals can weaken the rock. In some cases, the cause of diverging behaviour within "like-rocks" is only evident after thin section assessment under a microscope.

***Rock weathering***

Weathering is the process by which rocks are broken down and decomposed by the action of external agencies such as air, water, and changes in temperature. The weathering process is limited to the decomposition of rock *in situ* - there is no transportation of material (e.g. by erosion). The two main types of weathering are **mechanical** (e.g. shrinkage and expansion due to temperature changes, and **chemical** (e.g. certain minerals being leached from the rock or other compound elements being formed by interaction with water).

It follows that, the engineering properties of rock will be significantly affected by the degree and nature of weathering. Weathering is the main agency by which soft rock* conditions are developed in metalliferous mines in WA.

***Soft rock conditions***

The recognition of soft rock ground conditions is a very important geotechnical issue when considering the stability of open pit walls. The mechanics of soft rocks falls partly within soil mechanics and partly within rock mechanics, and the exact interplay between the two sciences is not well known. There is, therefore, a need for the combined application of both soil mechanics and rock mechanics principles to soft rock materials. The definition of the boundary of soft rock between soil and hard rock is not precise, however, for the purposes of this guideline, the boundary has been arbitrarily defined as rock with an intact rock uniaxial compressive strength between 0.5 to 25 MPa[2,29,30].

One of the peculiar characteristics with soft rock is the destabilising effects that high pore water pressures can have on slopes excavated in this material. It is common that the dissipation of pore water pressures in soft rock and soils may result in these materials gaining strength as they "dry out" or reconsolidate. Conversely, rapid water depressurisation may lead to a reduction in rock mass strength (Nikraz *et al* [31]). The dissipation or build-up of pore water pressures is largely controlled by the permeability of the rock mass and the rate of water depressurisation.

Ground subsidence due to fluid withdrawal is well documented (up to 8 m has been recorded in other parts of the world) and may need to be addressed in some regions.

This apparent time dependent behaviour of soft rock can have a significant effect on the strength of materials and also the stability of pit walls. It is obvious, therefore, that soft rock issues are complex; this needs to be recognised and addressed in the mine planning and design process.

In some conditions, foundation failure (failure through rupture of the pit floor) is possible. The failure path through intact soft rock can assume a hemispherical/circular form through intact rock, however, failure can also occur along rock mass discontinuities (discussed in more detail in the hard rock section below). The rate of failure is generally slower and signs of impending failure are usually more obvious and more easily monitored in soft rock.

# APPENDIX B

## GLOSSARY OF TERMS

The following represent brief explanations of some geotechnical and mining terms. They are not intended to be dictionary definitions or detailed technical explanations.

**Abutment.** The areas of unmined rock at the edges of mining excavations that may carry elevated loads resulting from redistributions of stress.

**Batter slope.** The sections of rock mass between catch berms within pit walls - usually excavated to a specific inclination/angle from the horizontal.

**Bedding planes.** Planes of weakness in the rock that usually occur at the interface of parallel beds or laminae of material within the rockmass.

**Buttress.** A body of material either left unmined or placed against a section of the pit wall to prevent continued movement or propagation of wall failure.

**Cable bolts.** One or more steel reinforcing strands placed in a hole drilled in rock, with cement or other grout pumped into the hole over the full length of the cable. A steel face plate, in contact with the excavation perimeter, would usually be attached to the cable by a barrel and wedge anchor. The cable(s) may be tensioned or untensioned. The steel rope may be plain strand or modified in a way to achieve the appropriate load transfer from the grout and the steel strand to the rock mass.

**Catch berm**. The width of lateral ground (bench) separating successive batter slopes. The purpose of the catch berm is to both reduce the overall angle of the pit walls, and to catch any loose material or local scale rock mass failures, thus reducing the risk of injury to the workforce at the base of the pit.

**Catch fence**. A fence constructed either vertically or at an angle to the vertical at the required off-set distance from the toe of a slope. The purpose of the catch fence is to catch any loose material falling from overlying blocky ground, thus reducing the risk to the workforce at the base of the pit walls.

**Controlled drilling and blasting.** The art of minimising rock damage during blasting. It requires the accurate drilling and placement and initiation of appropriate explosive charges in the perimeter holes to achieve efficient rock breakage with least damage to the remaining rock around an excavation.

**Dip.** The angle a plane or stratum is inclined from the horizontal.

**Discontinuity.** A plane of weakness in the rock mass (of comparitively low tensile strength) that separates blocks of rock from the general rock mass.

**Dowel.** An untensioned rock bolt, anchored by full column or point anchor grouting, generally with a face plate in contact with the rock surface.

**Earthquake.** Groups of elastic waves propagating within the earth that cause local shaking/trembling of ground. The seismic energy radiated during eathquakes is caused most commonly by sudden fault slip, volcanic activity or other sudden stress changes in the Earth's crust.

**Elastic.** The early stage of rock movement (strain) resulting from an applied stress which does not give permanent deformation of the rock - where the rock mass returns to its original shape or state when the applied stress is removed.

**Fault.** A naturally occurring plane or zone of weakness in the rock along which there has been movement. The amount of movement can vary widely.

**Fill.** Waste sand or rock, uncemented or cemented in any way, used either for support, to fill stope voids underground, or to provide a working platform or floor.

**Foliation.** Alignment of minerals into parallel layers; can form planes of weakness/discontinuities in rocks.

**Friction rock stabilisers.** Steel reinforcing elements, typically C shaped, that are forced into holes in the rock and rely on friction between the side of the hole and the element to generate a force to limit rock movement. The anchorage capacity of the device depends on the anchorage length and the frictional resistance achievable against the wall of the hole.

**Geology.** The scientific study of the Earth, the rock of which it is composed and the changes which it has undergone or is undergoing.

**Geological structure.** A general term that describes the arrangement of rock formations. Also refers to the folds, joints, faults, foliation, schistosity, bedding planes and other planes of weakness in rock.

**Geotechnical engineering.** The application of engineering geology, structural geology, hydrogeology, soil mechanics, rock mechanics and mining seismology to the practical solution of ground control challenges.

**Ground control.** The ability to predict and influence the behaviour of rock in a mining environment, having due regard for the safety of the workforce and the required serviceability and design life of the mine.

**Hazard.** A set of circumstances which may cause harmful consequences. The likelihood of its doing so is the risk associated with it.

**Induced stress.** The stress that is due to the presence of an excavation. The level induced stress developed depends on the level of the in-situ stress and the shape and size of the excavation.

**In-situ stress.** The stress or pressure that exists within the rock mass before any mining has altered the stress field.

**Instability.** Condition resulting from failure of the intact rock material or geological structure in the rock mass.

**Joint.** A naturally occurring plane of weakness or break in the rock (generally aligned subvertical or transverse to bedding), along which there has been no visible movement parallel to the plane.

**Kinematic analysis.** Considers the ability or freedom of objects to move under the forces of gravity alone, without reference to the forces involved.

**Loose (rock).** Rock that visually has potential to become detached and fall. In critical areas, loose rocks must be scaled to make the workplace safe.

**Mining induced seismicity.** The occurrence of seismic events in close proximity to mining operations. During and following blast times there is a significant increase in the amount of seismic activity in a mine. Mining induced seismicity is commonly associated with volumes of highly stressed rock, sudden movement on faults or intact failure of the rock mass.

**Ore.** A mineral deposit that can be mined at a profit under current economic conditions, taking into consideration **all** costs associated with mine design and operation.

**Ore reserve.** A volume of known ore zones that a mine has identified as being suitable for mining at some time in the future.

**Pillar.** An area of ground (usually ore) left within an underground mine to support the overlying rock mass or hanging wall.

**Plane of weakness.** A naturally occurring crack or break in the rock mass along which movement can occur.

**Plastic.** The deformation of rock under applied stress once the elastic limit is exceeded. Plastic deformation results in a permanent change in the shape of the rock mass.

**Ravelling.** The gradual failure of the rock mass by rock blocks falling/sliding from pit walls - usually under the action of gravity, blast vibrations or deterioration of rock mass strength. A gradual failure process that may go un-noticed. The term unravelling is also used to mean the same thing.

**Reinforcement.** The use of tensioned rock bolts and cable bolts, placed inside the rock, to apply large stabilising forces to the rock surface or across a joint tending to open. The aim of reinforcement is to develop the inherent strength of the rock and make it self-supporting. Reinforcement is primarily applied internally to the rock mass.

**Release of load.** Excavation of rock during mining removes or releases the load that the rock was carrying. This allows the rock remaining to expand slightly due to the elastic properties of the rock.

**Risk.** An expression of the probability - the likelihood - that a hazard will cause an undesired result.

**Rock bolt.** A tensioned bar or hollow cylinder, usually steel, that is inserted into the rock mass, usually via a drill hole, and anchored by an expansion shell anchor at one end and a steel face plate and a nut at the other end. The steel face plate is in contact with the rock surface.

**Rock mass.** The sum total of the rock as it exists in place, taking into account the intact rock material, groundwater, as well as joints, faults and other natural planes of weakness that can divide the rock into interlocking blocks of varying sizes and shapes.

**Rock mass strength.** Refers to the overall physical and mechanical properties of a large volume of rock which is controlled by the intact rock material properties, groundwater and any joints or other planes of weakness present. One of the least well understood aspects of geotechnical engineering.

**Rock mechanics.** The scientific study of the mechanical behaviour of rock and rock masses under the influence of stress.

**Rock noise.** Sounds emitted by the rock during failure, may be described as cracking, popping, tearing and banging.

**Seismic event.** Earthquakes or vibrations caused by sudden failure of rock. Not all seismic events produce damage to the mine.

**Seismicity.** The geographic and historical distribution of earthquakes.

**Seismology.** The scientific study of earthquakes by the analysis of vibrations transmitted through rock and soil materials. The study includes the dynamic analysis of forces, energy, stress, duration, location, orientation, periodicity and other characteristics.

**Shear.** A mode of failure where two pieces of rock tend to slide past each other. The interface of the two surfaces of failed rock may represent a plane of weakness, or a line of fracture through intact rock.

**Shotcrete.** Pneumatically applied cement, water, sand and fine aggregate mix that is sprayed at high velocity on the rock surface and is thus compacted dynamically. Tends to inhibit blocks ravelling from the exposed faces of an excavation.

**Slope.** Any continuous face of rock mass within the overall pit wall (without stepping/berms)**.**

**Smooth blasting.** The use of specialised drill and blast strategies (eg low strength explosives, modified production blasting, cushion blasting, pre- and post-splitting) to reduce blast damage and improve wall stability.

**Strain.** The change in length per unit length of a body resulting from an applied force. Within the elastic limit strain is proportional to stress.

**Strength.** The largest stress that an object can carry without yielding. Common usage is the stress at failure.

**Stress.** The internal resistance of an object to an applied load. When an external load is applied to an object, a force inside the object resists the external load. The terms stress and pressure refer to the same thing. Stress is calculated by dividing the force acting by the original area over which it acts. Stress has both magnitude and orientation.

**Stress field.** A descriptive term to indicate the pattern of the rock stress (magnitude and orientation) in a particular area.

**Stress shadow.** An area of low stress level due to the flow of stress around a nearby excavation, eg a large stope. May result in joints opening up causing rock falls.

**Strike.** The bearing of a horizontal line in a plane or a joint.

**Stope.** An excavation where ore is extracted on a large scale.

**Subdrill**. The length of blast hole which extends beyond the next bench floor level. Subdrill is included in the blast design to provide adequate broken rock subgrade for developing working benches.

**Support.** The use of steel or timber sets, concrete lining, steel liners, etc that are placed in contact with the rock surface to limit rock movement. The rock mass must move on to the support before large stabilizing forces are generated. Support is applied externally to the rock mass (although untensioned cables can be classified as ground support).

**Tectonic forces.** Forces acting in the Earth's crust over very large areas to produce high horizontal stresses which cause can earthquakes. Tectonic forces are associated with the rock deforming processes in the Earth's crust.

**Tensile.** The act of stretching of material. tensile forces can cause joints to open and may release blocks causing rock falls.

**Wall.** A wall can pertain to a section of, or the complete profile of the perimeter of an open pit excavation.

**Wedge.** A block of rock bounded by joints on three or more sides that can fall or slide out under the action of gravity, unless supported.

**Windrow.** A continuous mound of loose material, of appropriate height, placed at the toe or crest of a slope as a barricade to falling objects or to prevent personnel/mine equipment from falling inadvertently down pit walls. (Can also be referred to as a bund.)

# APPENDIX C

## OPEN PIT ROCK FAILURE REPORT FORM

| | |
|---|---|
| SITE DATA | Name of mine site:......................................Name of Pit:......................................<br>Name of person completing report:..........................................Position....................... |
| FAILURE DATA<br>(tick one, or more if combinations involved)<br><br>(eg sequence of events, block shape etc) | Date, Time of Failure:.......................................................................................<br>Date toe of slope failure was excavated >....................RL of toe of failure...................<br>Failure position in pit: ☐East wall ☐West wall ☐South wall ☐North wall<br>☐Hanging wall ☐Footwall ☐End wall ☐Other > describe > ...................................<br>Failure dimensions:....................[LxWxH (m)]; Estimated weight of Failure:............(t)<br>Failed batter heights:...........................(m) Failed batter angles.................................<br>Overall slope angle in failure area >..............(deg.)<br>Number of berms in failure >.................Berm width/s >.........................(m)<br>Mode of failure: ☐Planar sliding ☐Toppling ☐Wedge ☐Unravelling<br>☐Circular ☐Active-passive wedge ☐Floor heave ☐Complex ☐Unknown<br>Describe failure >.............................................................................................<br>.............................................................................................................<br>.............................................................................................................<br>.............................................................................................................<br>If Haulroad or operations were affected, describe how.......................................<br>............................................................................................................. |
| MINE/MINING PRACTICE DETAILS<br><br>FAILURE SITE GROUND REINFORCEMENT<br>(eg mesh, straps, rock bolts)<br><br>MONITORING<br>(eg visual, EDM, extensometer, crack monitoring, frequency of monitoring) | Current pit depth >................(m) Planned pit depth >................(m)<br>Surface RL ............(m).. Pit Dimensions............................... [LxWxD (m)]<br>Near-wall blasting practice: standard production☐;modified prod'n☐;smooth wall☐<br>Describe >.......................................................................................<br>...............................................Explosives used >...........................<br>Wall design; experience☐;geotechnical methods☐; None ☐<br>Was ground reinforcement used ? ( Y / N ) Installation date>..................<br>Type and capacity (each) ..........................................Length >...............(m)<br>Diameter >..................(mm) Pattern/Spacing >....................................<br>Corrosion >........................... Other surface fittings used>...............................<br>Signs of failure observed or monitored prior to failure?: Yes / No<br>Monitoring methods used >...........................................................................<br>Summarise observations or monitoring results >...............................................<br>.............................................................................................................<br>.............................................................................................................<br>............................................................................................................. |
| GEOLOGY<br>(eg rock types, major faults, folds, alteration, etc)<br><br>ROCK MASS STRUCTURES/ DEFECTS<br>(eg joints, faults, shears, foliation, schistosity, contacts, etc)<br><br>ROCK WEATHERING | Describe geology of immediate failure area .........................................................<br>.............................................................................................................<br>.............................................................................................................<br>.............................................................................................................<br>Estimate of rock material compressive strength >....................................... (MPa)<br>Was geological structure involved with failure? Yes / No<br>Defect Type / Dip/Dip direction (deg./deg.) / Length (m) / Spacing (m) / Infill (describe) / Roughness (describe)<br>1.............................................................................................................<br>2.............................................................................................................<br>3.............................................................................................................<br>4.............................................................................................................<br>Failure occurred through: (1.Soil ☐) (2. Extremely Weathered rock ☐)<br>(3. Distinctly weathered rock ☐) (4. Slightly Weathered rock ☐) (5. Fresh rock ☐)<br>(6. Combinations of 1☐, 2☐, 3☐, 4☐, 5☐) |
| WATER IN SLOPE<br><br>WEATHER CONDITIONS | ☐Dry ☐Moist/damp ☐Wet ☐ Water flowing/seeping If water flowing is it flowing through: ☐Structures ☐Intact material ☐Drain holes ☐Other >- .........................<br>Estimated water make..(litres/sec or tonnes perday)..................................................<br>Groundwater control methods:☐Production bores ☐Sumps ☐Drainage holes<br>☐None ☐Other >Describe>...........................................................................<br>Was there >2mm rain 72hrs prior..(Y/N) Water ponding near failed area (Y/N)<br>If yes describe ponding location and source >....................................................... |
| INSPECTORATE | ☐ COLLIE ☐ KARRATHA ☐ KALGOORLIE ☐ PERTH |
| INPUT | RECEIPT DATE RME signature |

Version 2 Jan 1999

# NOTES FOR COMPLETION OF OPEN PIT ROCK FAILURE REPORT FORM

1. The following form does **not** replace the accident/incident report form - it should be filled in conjunction with the accident/incident form.

2. The following form is to be completed by a person on the mine site familiar with the geotechnical issues associated with rock failure and who **has inspected** the failure area soon after the event. The completed form is to be sent to the relevant District Inspector.

# APPENDIX D

## LEGISLATIVE FRAMEWORK

The *Mines Safety and Inspection Act 1994* sets objectives to promote and improve occupational safety and health standards. The Act sets out broad duties and is supported by more detailed requirements in the *Mines Safety and Inspection Regulations 1995*. A range of guidance material, including guidelines, further supports the legislation. The legislative framework is set out in Fig 1.

Guidance material includes explanatory documents that provide more detailed information on the requirements of the legislation and include codes of practice and guidelines.

Guidelines contain practical information on how to comply with legislative requirements. They describe safe work practices that can be used to reduce the risk or work related injury and disease and may also contain explanatory information.

### FIG 1: LEGISLATIVE FRAMEWORK

| | | |
|---|---|---|
| MINES SAFETY AND INSPECTION ACT | ⇦ | Major provisions:<br>• The General Duties<br>• Management of Mines<br>• Enforcement of Act and Regulations<br>• Resolution of Issues<br>• Safety and Health Representatives<br>• Safety and Health Committees |
| **Supported By** | | |
| MINES SAFETY AND INSPECTION REGULATIONS | ⇦ | The Mines Safety and Inspection Regulations set minimum requirements for specific hazards and work practices, including reference to National Standards, developed by the National Occupational Safety and Health Commission, and Australian Standards developed by Standards Australia. |
| And | | |
| GUIDANCE MATERIAL | ⇦ | • Codes of Practice approved for Western Australian mines in accordance with Section 93 of the Act.<br>• Guidelines produced by the Mines Occupational Safety and Health Advisory Board.<br>• National Codes of Practice and National Standards developed by the National Occupational Health and Safety Commission.<br>• Australian Standards developed by Standards Australia. |

The information included in a Guideline may not represent the only acceptable means of achieving the standard referred to. There may be other ways of setting up a safe system of work, and providing the risk of injury or disease is reduced as far as practicable, the alternatives should be acceptable.