Risk lies at the heart of all mining and nowhere more so than in pit slope design. Mining is principally about two areas of risk; safety and economics. This paper addresses the main elements of pit slope design and presents a view of the state of the art in terms of safety, design, prediction of performance, success and pit slope management.

There has been a recent trend for serious injury and fatalities due to stability in open pit mines. The causes and contributing factors are analysed in relation to geotechnical knowledge, pit slope design and management.

Currently there is no standard classification system for mine slope designs and it is considered doubtful if a universal system is possible. Designs are usually formulated in accordance with many different methodologies, various engineering principals and a number of different philosophical approaches, with results often presented in terms of Factors of Safety or Probabilities of Failure. However wide experience has demonstrated that even with apparently detailed engineering investigation and analysis at Feasibility Level, at the Operating Stage mine slope angles are regularly subject to large changes. The general experience is that these changes are ± 5° and 16° overall, which is considerably outside the accepted order of accuracy. For large deep mines these are huge changes and represent significant risks to the operations.

The current state of practice in pit slope design is examined for two stages, feasibility and operating.

1.1 INTRODUCTION

Risk lies at the heart of all mining and for many operating mines the risks from pit wall failures are a daily event. At the base level mining is fundamentally about two elements; safety and economics. In essence these are the two principal areas of risk and this paper addresses risk in open pit mining from the perspective of a long term practitioner. The real level of risk, that is the level which actually occurs in practice, is illustrated with reference to many recent safety incidents and in economic terms by the performance of many of the medium to large scale mines which the author has had direct experience.
The title of this paper Pit Slope Design and Risk, implies the geotechnical input to a safe and efficient open pit mine is contained only in a single element, the pit slope design. However, it is fundamental to the understanding presented in this paper that geotechnical engineering for open pits has two components:

- The Pit Design, in essence the design of the environment in which mining will take place; and
- Pit Slope Management, the management of that environment in order to adequately achieve the overall risk objectives.

Starting out in the profession, it was the belief of the author that designing pit slopes was the principal task. However, with time and experience, the task has become less and less about the actual slope design itself and more and more about Pit Slope Management. This is primarily a reflection of the difficulty with achieving an optimum slope design in the principal phases of project development and in part highlights significant economic risks.

What does experience tell us about risk and is it changing in either of the key areas? What is the experience over the last decade? Are there underlying problems in what we are doing or can realistically achieve as geotechnical engineers? Are we fully cognisant of all the technical issues? Do we really understand risk as it relates to open pit mine design? These are some important questions covered in this paper, which presents a personal view of safety and economic risk arising from pit slope design and pit slope management.

2.1 RISK AND UNCERTAINTY

Risk is about uncertainty and the reality is that risk has always been with us:

“Ever since sailing ships put to sea in search of riches in foreign lands, risk has been at the heart of commerce.”

Mining is just one arm of commerce and the mining example that best illustrates this is the example of the lone miner and his wheel barrow. The wheel barrow is a metaphor for the sailing ship, a little like the camel as the ship of the desert, but the concept is the same. I would have to admit that when confronted by this image and a knowledge of the reality of environmental conditions in say the Great Sandy Desert in Australia I am somewhat horrified at the risks that apparently were willingly adopted.

The science of management recognises four types of uncertainty or risk:

1. Risks you can calculate.
2. Risks that are incalculable but which have a known result.
3. Risks that are incalculable but where the outcome will fall within a range of results.

4. True ambiguity, where the outcome is impossible to predict.

Let’s look at how a well known practitioner builds on a wealth of experience to address this same issue in geotechnical engineering (McMahon 1985). McMahon recognises the following classes of uncertainty or risk:

1. Known Knowns,
2. Known Unknowns and
3. Unknown Unknowns.

The true origins of this system are not clear, but I do note that Donald Rumsfeld, US Attorney General, recently used the same terms in relation to terrorists and Iraq. A simple comparison shows the two systems that attempt to define levels of uncertainty and risk are essentially the same.

In this paper the concept of risk is addressed in terms of both chance of occurrence (likelihood) and consequence, where;

\[
Risk = \text{Chance of Occurrence} \times \text{Consequence}.
\]

Risk implies a vision of the future about the likely course of events. Hence risk in mining means some knowledge or experience that would lead to an understanding of both the chance of occurrence and consequences of a particular result (or results). Geotechnical engineers are accustomed to collecting data, measuring things, producing charts, calculating Probabilities of Failure, Factors of Safety, etc. However in many instances such models can only capture what is already known or understood. The concept that;

“We only see what we know” (D.H. Stapledon personal communication)

This is particularly relevant to pit slope design and risk.

One of the fundamental questions with any mine development is;

“Is there past experience with the geology and geotechnical conditions?”

If there is limited or no past experience with similar geology or similar rocks then there must be uncertainty and hence risk.

Even a simple engineering design concept such as the Factor of Safety of a slope, which most mine managers, superintendents and mining engineers would think of as an absolute number that is universally applicable, is in reality only a factor of the experience and expertise of the engineer involved in the design process. It is purely an
index. This is because judgement decisions are made at every stage of the design process, from drilling or mapping to analysis (Sullivan 1994 and Mostyn and Li 1993). This principle applies equally well to Probability of Failure. Hence even in these relatively straightforward areas of engineering calculation the reality is once again uncertainty and risk.

What about Consequence? If the problem is simple and can be effectively conceptualised, for example a plane that undercuts the haul road, then the consequence is easily understood and the risk may be calculated. However with large open pits, problems due to inadequate design or management systems can take years to become apparent and often only manifest themselves in the medium to long term or when a couple of critical elements coincide. The reality with pit slope design is that in many instances you need a lot of past experience to correctly foresee, calculate or estimate consequence. Hence in this other component of risk, particularly when the problems are difficult, there is also significant uncertainty and risk.

3.1 THE MINE OPERATING ENVIRONMENT

The three principal elements of a pit slope design are illustrated in Figure 1:

1. Firstly the bench and berm geometry, which is the basic building block of any slope;

2. Secondly the inter-ramp slope (height and angle) and

3. Thirdly the overall slope (height and angle).

For any one slope and any one mine, one and or all of these elements could be the critical design element, requiring analysis and design. In some mines consideration of all three is essential and they may form competing design elements. The potential impact of those elements on the two main areas of risk, safety and economics, are set out in Table 1.
TABLE 1
PIT SLOPE DESIGN ELEMENTS AND RISK AREAS

<table>
<thead>
<tr>
<th>SLOPE DESIGN ELEMENT</th>
<th>COMPONENT</th>
<th>MAIN CONTROLLING OR INFLUENCING FACTOR</th>
<th>RISK AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Geotechnical Issues</td>
<td>Mining Systems</td>
</tr>
<tr>
<td>BENCH GEOMETRY</td>
<td>Angle</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td></td>
<td>Berm Width</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>INTER-RAMP</td>
<td>Angle</td>
<td>●</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>●</td>
<td>1</td>
</tr>
<tr>
<td>OVERALL</td>
<td>Angle</td>
<td>●</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>●</td>
<td></td>
</tr>
</tbody>
</table>
As illustrated in Table 1 the basic building block of any slope is the bench geometry; bench height, bench angle and berm width. This is nearly always the first element of design for an open pit. Once this design element is complete it is usual then to evaluate both inter-ramp and overall slopes.

The bench geometry is a function of both geotechnical conditions and mining systems, although in certain geotechnical conditions environmental factors will play a role. At the larger slope scales the principal control is usually the geotechnical issues, Table 1.

As discussed above, risk and successful open pit mining are fundamentally about two elements, safety and economics. Although bench geometry can impact on both areas of risk the principal concern is safety, Table 1. However at the larger slope scales the principal risk should only be economic, assuming a sound Pit Slope Management Program is in place with careful and regular review.

The following sections of this paper address risk in relation to open pit design firstly in terms of safety and secondly in economic terms. These elements are addressed for both slope scales, small and large. The state of the art and indeed the success or otherwise achieved in these areas is highlighted using actual operating experience.

4.1 SAFETY

4.1.1 Historical Perspective

Thirty years ago and even as recently as about ten years ago, the general understanding in mining geotechnics and the author’s particular experience was that people were hardly ever at risk from medium to large scale failures in open pit mines:

“...... slopes seldom fail without giving adequate warning”. (Hoek and Bray 1974).

Failures on this larger scale were almost always economic issues. However more recently there have been a significant number of fatalities and serious disabilities due to rockfall and larger failures and this trend may even be increasing.

4.1.2 Experience with Larger Scale Failures

Table 2 presents an assessment of eight serious incidents of which the author has some knowledge and or direct experience. In this example a serious incident is defined by a fatality(s) and/or serious injury. These incidents have occurred over about the last eight years. Obviously eight examples is insufficient to draw any statistically reliable conclusions, but that is not the objective of this assessment. Rather the aim is to highlight some key areas of Pit Slope Design and Management, which appear to be contributing to increased risk in the area of safety. It is stressed these conclusions are
the opinion of the author only and there may also be other elements of which the author is unaware.

The contributing factors may be summarised into four principal areas, which are presented in order of decreasing frequency:

1. Geotechnical Issues – 14 cases.
2. Access, Procedures and Controls – 3 cases.
3. Warnings Ignored – 2 cases.
4. Pit Design Issues – including implementation of design – 2 cases.

As expected in most cases there were multiple contributing factors and this is in accord with general engineering experience; when something goes seriously wrong there is usually more than one cause.

Two important conclusions are:

1. The overriding influence of geotechnical issues in these serious larger scale failures and
2. The concern that specific warnings apparently went unheeded in two of the cases.

The fact there is a high frequency of geotechnical issues with larger pit wall failures is obvious to a certain extent, because with adequate knowledge and understanding, the disaster could have been averted in the first place. Although the fact these serious events are still occurring, raises the question as to what is the experience base that is being brought to bear on these stability situations. The most frequently occurring factor under geotechnical issues is that either the slope designs were too steep for the geotechnical conditions or that inherently “risky” geological and geotechnical settings were not recognised. This latter element also accords with the author’s general experience elsewhere with a large number of other cases, not counted in these examples.

The recognition of potentially unsafe or risky ground conditions is a difficult issue because as identified above, this element is highly dependent on the expertise and experience of the individual specialists, mainly geotechnical. It is often a judgement call based on experience, although there is also the truism that experience often only comes from bad judgement. However that should be one of the key roles of Pit Slope Management Programs, to help manage the residual risks not covered or captured by the experience or expertise of those involved. A sound comprehensive Pit Slope Management Program is the only way the “risk” environment that is open pit mining may be effectively managed. It is the author’s experience that where these programs are comprehensive and subject to regular critical review this should be sufficient to avoid disaster.
The cases where warnings were apparently not taken seriously is also a real concern and the immediate question that springs to mind in this regard is; were there economic pressures, either individual or corporate, that may have influenced decision making in these cases?

Access, Procedures and Controls should be combined with the Pit Design Issues because both examples entail elements of inadequate control of the mining operation. Although probably not strictly geotechnical there is a growing trend for geotechnical engineers to fulfil the role of “mine policeman” and be responsible for much more than simple geotechnical issues.

The role of history, although not separately listed, was also an element in two incidents. It is the author’s experience from this, and other cases of multiple deaths from landslides (Analysis of the Thredbo Landslide, Sullivan 2000) that failure to incorporate historic incidents or performance into assessment of future stability can be “fatal”. History aids judgement particularly in areas of understanding potential consequence, but also the chance or likelihood of an adverse event occurring. In two of the examples similar but infrequent failures to those which contributed to the serious incident, had occurred in the past, but somehow the significance of these was “Lost, Forgotten or Ignored”, which was also a theme from the Thredbo Landslide (NSW State Coroner 2000).

These examples where history was lost highlight the importance of using risk as the product of likelihood and consequence; infrequent events (low chance of occurrence) but with major consequence are high risk.
<table>
<thead>
<tr>
<th>INCIDENT</th>
<th>PIT DESIGN ISSUES</th>
<th>GEOTECHNICAL ISSUES</th>
<th>CONTROL OF INPIT ACCESS AND EXCAVATION</th>
<th>FAILURE TO HEED EXPLICIT WARNINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poor Pit Design Element</td>
<td>Inadequate Implementation of Design</td>
<td>Risky Geological / Geotechnical Setting Or Design Too Steep</td>
<td>Failure to Appreciate Role of Water</td>
</tr>
<tr>
<td>Failure onto pre-split drilling rig</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large pit wall failure</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Loss of equipment over pit edge</td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Failure undercuts equipment¹</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Failure leads to mudflow</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Highwall failure onto equipment</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Large pit wall failure¹</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Slope failure onto mine personnel</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Note¹ Failure to appreciate significance of previous incident (history)
- ● Principal Factor or Concern
- ● Minor Factor or Concern
4.1.3 Rockfall

Rockfall are at the other end of the scale from the larger scale failures and this group includes both individual rocks and groups of rocks.

The contributing factors may be summarised into three principal areas, which are presented in order of decreasing frequency:

1. Access, Procedures and Controls – 6 cases.
2. Excavation Practices – 5 cases.
3. Design Issues – 4 cases.

Items 1 and 2 and to a lesser extent 3 are all issues about the management of the immediate working environment. This environment is most strongly influenced by the bench geometry, the basic building block of the pit slope design. The critical aspects are firstly a good design and secondly the maintenance of the design with good blasting and wall excavation practices.

After a gap of many decades “catch fences” are once again becoming popular. This follows on from the success with catch fences in the civil environment. However it is the author’s experience that if designed properly cost is an issue and often the design is inadequate leading to fence failure and a less safe situation than if the fence was not used in the first place.

The main lessons from the rockfall examples are:

1. Identification of rockfall areas and their potential is an essential first step.
2. It is essential there is education and awareness throughout the workforce about rockfall issues.
3. A protocol is required for what to do in the event of rockfall.
4. Control of access by personnel and smaller ancillary equipment into risk areas is essential.
5. The placement of ancillary items of infrastructure such as sumps, pumps, etc. requires careful consideration. These are areas frequented by those most at risk from rockfall, not large shovels, but mine personnel, light vehicles and smaller ancillary equipment.
6. Adequate separation between areas actively generating potential instability, such as cutbacks, and areas of general access is mandatory. This may be achieved with either increased distance or exclusion protection measures, such as bunding.
<table>
<thead>
<tr>
<th>INCIDENT</th>
<th>DESIGN ISSUES</th>
<th>EXCAVATION PRACTICES</th>
<th>ACCESS PROCEDURES AND CONTROLS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inadequate Catch Fence Design</td>
<td>Poor Blasting Practices</td>
<td>Inadequate Support of Poor Rock Mass Zone</td>
</tr>
<tr>
<td>Rockfall below Cutback</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockfall below Cutback</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockfall below Cutback</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bench failure and rockfall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockfall through Windscreen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ravelling rockfall on light vehicle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockfall hits light vehicle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockfall onto truck and excavator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockfall onto drill</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.1.4 Overall Summary

Overall it is considered that the trend for serious safety issues is increasing. Some contributing factors of which the author is aware include:

1. Lack of sufficient experienced personnel at all levels from management down. This situation has been exacerbated by the large expansion of the resources industry following a long period when “mining” was a relatively unattractive and relatively underpaid profession.

2. The drive to maximise economic return from resources leading to design and production pressures.

3. As the number of mines increases and the scale and depth of mining continue to grow there is a wider range of geotechnical factors and conditions to be managed. From the collations above and personal experience it is considered some of these are probably outside the individual experience of many professionals.

The lessons from incidents associated with the larger scale failures include:

- Role of history as an indicator of future risk.
- Importance of understanding the overall geological setting.
- What is the experience with moving slopes; is the behaviour always going to be the same?
- Pore water pressure responses in different materials can be critical.
- An understanding of the fundamental geotechnical character of the materials is important, particularly post failure behaviour and deformations.
- What is the experience base used to predict future performance, is it adequate or appropriate?
- If the environment is different will the performance be the same; what are the potential impacts from climate, stress, blasting?
- Monitoring must be right.

The lessons from incidents associated with the smaller scale failures (rockfall) include:

- It is not practically feasible to completely remove the risk of all rockfall in open pits.
The South African Institute of Mining and Metallurgy
International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering
Mr T D Sullivan

- All scales of rockfall have the potential to be a safety risk.
- Those most at risk are people on foot, ancillary equipment and light vehicles.
- It is essential there is awareness at all levels in the workforce and that adequate procedures and controls are in place.

5.1 MINE DEVELOPMENT, COSTS AND SLOPE DESIGN ACCURACY

5.1.1 Mine Development Stages

As noted in Sullivan (1994) and Ballard (1983) mining projects may go through a number of stages:

1. Evaluation,
2. Planning,
3. Design,
4. Construction,
5. Commissioning and
6. Operating.

Within this broad development framework, technical and financial assessments are undertaken at a number of stages. Mining studies tend to occur in Stages 1 to 3. Pit Slope Design studies tend to occur in Stages 1 to 3 and 6. Although once the mine is operational, revision of mine plans and financial reassessments usually continue throughout the mine life. In practice most mining projects usually undergo a two or three stage study program.

5.1.2 Mine Stages, Study Accuracy and Pit Slope Angles

Table 4 sets out the various project stages, together with the approximate levels of accuracy usually accepted in the industry.

However, what do the mining costs presented in Table 4 mean in geotechnical and hydrogeological terms? On the groundwater side a very major dewatering program for a large scale mine may comprise some 13% of the total mining cost. Consequently, at the Design stage a large error in this aspect, of say 30%, would only result in a 4% change in the total cost. This alone would be within the normal range of accuracy for this level of study. However with inadequate groundwater control, the real impact on costs may be on the overall viability of the mining system or equipment. This would ultimately be reflected in reduced productivity, delays and increased costs.
On the geotechnical side the impact of inaccuracies in the geotechnical design parameters is easier to quantify because it is usually understood in terms of a change in slope angle which can be related directly to waste tonnages and stripping ratios. For example, a 5° decrease in overall slope angle for an intermediate size open pit truck and shovel mine would result in about a 20% increase in costs.

The order of accuracy required in slope angles at each stage of a mining study is presented in Table 4. These numbers are approximate and individual project specific constraints such as style of mine development, orebody and pit geometry, depth and scale, will modify these numbers; nevertheless they provide a good approximate guide.

### TABLE 4

**APPROXIMATE LEVELS OF ACCURACY IN MINING STUDIES**


<table>
<thead>
<tr>
<th>TYPES OF STUDIES</th>
<th>GENERALLY ACCEPTED ACCURACY OF COST ESTIMATES (+ or - %)</th>
<th>APPROXIMATE ORDER OF ACCURACY REQUIRED IN OVERALL SLOPE ANGLE (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine Study</td>
<td>Equivalently Terms or Secondary Stages</td>
<td></td>
</tr>
<tr>
<td>Preliminary</td>
<td>Exploration Review Order of Magnitude</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Pre-feasibility</td>
<td>Conceptual</td>
<td>25</td>
</tr>
<tr>
<td>Feasibility</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Design</td>
<td>Detailed Mine Planning</td>
<td>5 to 10</td>
</tr>
</tbody>
</table>

5.1.3 **Summary**

In geotechnical engineering the overall slope design targets required in order for pit slope designs to match the overall mine study accuracies are:

- Bankable Feasibility Level - ±1° to 5° and
- Full Design Level - ±1° to 3°.

These are very tight tolerances and based on the author’s experience considerably less than the accuracies achieved in practice; see Section 7.1 for further discussion.
6.1 PIT SLOPE DESIGN

6.1.1 The Engineering Design Process

As highlighted by Bieniawski (1984):

“The design process (in engineering) is concerned with the methodology of problem-solving”.

Because it is largely empirically based, it must be iterative in character. The three main components of any problem solving logic flow are:

1. Situation Appraisal; the geotechnical investigations and development of the geotechnical model.

2. Problem Analysis; identification of potential failure mechanisms and analysis.

3. Decision Analysis; essentially the formulation of the pit slope design.

6.1.2 Pit Slope Design - Discussion

What is Pit Slope Design? Like most fields of engineering the design methodology centres around heuristics or “rules of thumb” (The Institution of Engineers Australia, 1990). Because pit slope design is based largely on geology, the concept of pit slope design as a heuristic is even more applicable. It is worthwhile pursuing this a little further because it provides a great insight into the nature of the process. A heuristic may be defined as:

“a method of solving matters not relying wholly on algorithms but which depends on inductive reasoning from past experience of similar problems”.

(Macquarie Dictionary, 1995).

An algorithm is a procedure for solving a particular problem in a finite number of steps. Algorithms are used for some elements of the design process, however there cannot ever be an algorithm for pit slope design.

The other key words in the definition of a heuristic are “inductive reasoning”. Inductive reasoning is:

“The process of discovering explanations for a set of particular facts, by estimating the weight of observational evidence in favour of a proposition which asserts something about the entire class of facts”.

(Macquarie Dictionary, 1995).

The Pit Slope Design is not generally a wholly deductive process where conclusions are based on completely known facts. Pit slope design is based on quantitative observations from a very small percentage sampling; there are always uncertainties and gaps in knowledge. Hence in this environment judgement is the key:
“It is the only skill which can appropriately manage a heuristic environment”. (The Institution of Engineers Australia, 1990).

In the practice of applying geotechnical engineering to mine slope design it should be recognised that in most cases there are not exact answers, merely a range of options.

6.1.3 Rational Pit Slope Design Process

Figure 2 presents a model pit slope design chart. The chart illustrates the various components of geotechnical investigation and study required at two key stages of project development; Feasibility and Operating. Also illustrated is the parallel stream of mine design and economic evaluation. This chart emphasises the interaction between mining, economics and pit slope design. The chart provides a very useful guide to the studies required and shows the streams of information gathering and interactions. A key point shown on the chart and which cannot be emphasised enough because it forms one of the basic tenets of this paper is the essential role of feedback loops.

This chart implicitly recognises a current fundamental problem with pit slope design, namely the difficulty with achieving the required design accuracy. Interaction, feedback loops and redesign continue throughout the mine life primarily because it is so difficult to get the answer right in the early part of the design process and secondly because often economic parameters are constantly changing.

Although this chart appears to indicate a logical design process leading to the answer, there is implicit in the chart the understanding that continual re-evaluation and feedback is required, because the initial answer is an answer not necessarily the answer.
6.1.4 Nature of the Investigation Process

The first step in the process is the formation of engineering models of the soil and rock mass. This is probably the most important step in the whole pit slope design process.

Geology plays a fundamental part in Pit Slope Design. In the ideal world, there would be 100% exposure of fresh rock covering all mine sites and geology would be much simpler. However, in practice good outcrops are rare, deep weathering is commonplace and surficial coverings, including transported materials or more recent geological layers are frequent. In tropical environments, vegetation is ubiquitous and in steep mountainous terrain access is difficult.

By way of example it was estimated that for a civil engineering dam investigation natural rock exposures often represented about 3% of the foundation. Cored boreholes and trenches increased the visible evidence by less than 1% (Blyth and de Freitas 1984). From this 4% a geological model of the foundations was required. In mining, the areas to be investigated are much larger and the exposures are often limited to boreholes alone. Furthermore it is seldom economically feasible to investigate the geotechnical conditions for a mine to the same extent as for civil structures. In effect the percentage sampling for pit slope designs is probably smaller than for any other major facet of the mine design.

It is no wonder than that McMahon (1985) who pioneered the application of probability theory to pit slope design considers:

“It has always seemed to me that uncertainty is the very essence of geotechnical engineering. Our materials are natural in origin, often irregular in form and highly variable in their properties. They are usually obscured from sight and can be investigated only to a small extent at great expense”.

So how then is it possible to carry out the first part of the process in slope design, that is to adequately understand and categorise the nature of the materials, the model?

Woodall (1985) reflected on this problem of a good geological model in his paper titled “Limited Vision: a personal experience of mining geology and scientific mineral exploration”. His term was vision:

“Vision is concerned with making observations: quantitative observations such as measurement, and observations of form and pattern. Vision is perception: an awareness of the significance of observations and insight or intuition. We live and work with limited vision”.

In summary the problems faced at this first step in the process include:
• Lack of sufficient large scale exposures,
• Very small percentage sampling,
• Major gaps and uncertainties; and
• Inaccurate investigation tools (Sullivan, Duran and Eggers 1992).

6.1.5 General Pit Slope Design Objectives

What are the general pit slope design rules? One definition of the ultimate aim of a pit slope design is to:

“achieve an optimum design – a compromise between a slope which is steep enough to be economically acceptable and one which is flat enough to be safe” (Hoek and Bray, 1981).”

Of course this is a fine definition and one with which it is very hard to argue on any matter of principle. However, what is the practical reality to statements such as:

“steep enough to be economically acceptable”

or

“flat enough to be safe”.

The other general definition of the optimum pit slope design is the following, which anyone who has ever worked extensively in open pits has probably encountered:

“The best design is the one which falls down the day that the last truck leaves the pit”.

This is a nice, clear, simple statement that has immediate appeal and which you often hear repeated. But the reality is that the current state of the art is such that only rarely can this ever be achieved and then probably more by luck than good engineering design.

6.1.6 Conventional Design Rules

As noted above Factors of Safety are only an index (Mostyn and Li, 1993) which is of most value when used on a comparative basis (Hoek and Bray, 1981). In many ways it is an index of the education, experience and judgement of the slope designer, because judgement decisions have played a role at all stages in the data collection, collation and processing. Hence consideration of Factor of Safety probably only has meaning, when the investigation techniques, choice of shear strength parameters, groundwater conditions, etc. are also considered.
Notwithstanding the preceding discussions some guidelines are required in order to educate judgement and typical design Factors of Safety commonly used and accepted in practice are presented in Table 5.

### TABLE 5
DESIGN FACTORS OF SAFETY FOR PIT SLOPE DESIGN

<table>
<thead>
<tr>
<th>DESIGN SITUATION</th>
<th>FACTORS OF SAFETY COMMONLY USED OR ACCEPTED IN PRACTICE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Applicability</td>
</tr>
<tr>
<td>General slope design</td>
<td>simple geological and geotechnical conditions</td>
</tr>
<tr>
<td></td>
<td>complex geology, soil and or soft rock; groundwater</td>
</tr>
<tr>
<td></td>
<td>to stabilize a large moving slope</td>
</tr>
<tr>
<td></td>
<td>rigorous back analysis of large failure available</td>
</tr>
<tr>
<td>Slope below haul road or important infrastructure</td>
<td>1.2 to 1.5*</td>
</tr>
</tbody>
</table>

* Hoek and Bray (1981) recommend 1.5 in this instance
* Hoek and Bray (1981) recommend 1.3 and a conservative choice of strength parameters

Probabilistic analyses offer an alternative to Deterministic methods of design. Where applicable, they can be linked directly to risk and economic cost benefit analyses. They are in general a preferred method of design. In many instances the Factor of Safety can be replaced directly by the probability of failure. Perhaps more usefully the two can be linked to provide a probability of failure for the design Factor of Safety which can be chosen not arbitrarily as say 1.2 or 1.3 but based on a certain probability of failure. Table 6 presents the probabilities of failure commonly used and accepted in practice.
TABLE 6
DESIGN PROBABILITIES OF FAILURE FOR MINE SLOPE DESIGN
(AFTER SULLIVAN 1994, KIRSTEN 1983, McCracken and Jones 1990; Priest and Brown 1983; and Pine 1992)

<table>
<thead>
<tr>
<th>Design Element</th>
<th>Applicability</th>
<th>Geotechnical Condition</th>
<th>Range %</th>
<th>Preferred Value %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench Slope</td>
<td>General</td>
<td>Continuous defects</td>
<td>10 to 50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Discontinuous defects</td>
<td>0 to 10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 to 50</td>
<td>20 to 30</td>
</tr>
<tr>
<td>Overall or inter-ramp slope</td>
<td>General</td>
<td></td>
<td>1 to 3°</td>
<td></td>
</tr>
<tr>
<td>Overall or inter-ramp including haul road or key infrastructure</td>
<td></td>
<td></td>
<td>&lt;1°</td>
<td></td>
</tr>
</tbody>
</table>

* Pine (1992) - 2%
* McCracken and Jones (1990) - 0.5%
* Priest and Brown (1983) - 0.3%

7.1 PIT SLOPE DESIGN – STATE OF THE ART

7.1.1 Economic Risk

Using the slope design targets in Table 4 it is possible to gain a view of the state of the art in pit slope design as it relates to economic risk. Based on the author’s experience with medium to large scale open pit mines over the past two to three decades more than 90% have undergone major slope design changes. These changes have occurred either in the transition from Feasibility to Operating Stage or during the Operating Stage itself. The changes in overall slope angle have ranged from ± 5° to 16° overall for slope heights up to 1000m. The major portion of the changes lies within ± 6° to 9°. This actual operating experience with slope angles is a long way outside the orders of accuracy expected. All these mines have clearly carried significant economic risk for at least some phase of their development.
The majority of these mines had engineering studies and supporting design documents with quoted factors of safety and or probabilities of failure which were in general accord with the design rules in Tables 5 and 6. The question then is; in what part of the investigation and pit slope design process does the inherent problems and risks lie?

7.1.2 Investigation and Design – State of Practice

It is outside the scope of this paper to provide a detailed appraisal of every element of what can be a very detailed process for slope design. The aim is to use the actual operating experience to highlight the general state of practice in a number of principal areas. It should be understood the state of practice the ranking can be a combination of firstly poor or inaccurate tools or techniques, secondly limitations imposed by the nature of the site, access, inadequate sampling, etc.; and thirdly inadequacies in engineering practice.

The assessments are presented separately in Tables 7 and 8 for Feasibility Studies and Operating mines because clearly there is potential for substantial improvement when large exposures and actual mining experience are available at the Operating stage.

At the Feasibility Stage the conclusions from the author’s experience are:

1. It is very difficult from oriented core alone to formulate an optimum slope design, one that does not carry significant risk.

2. Limitations governed by available exposures means that it is almost impossible to adequately define the architecture of the 2nd and 3rd order major structures. Since these are often the structures involved in inter-ramp and overall slope instability there is uncertainty and risk.

3. Delineation of Structural Domains is a key part of the slope design chart, Figure 2, but clearly it is data dependent and hence suffers in the same way as models.

4. The geotechnical (and structural) model is the fundamental basis for any analyses and hence if the design is reliant on correct structural data, items 1 and 2, then the design must carry significant risk.

5. It is possible to very accurately calculate a rock mass strength from borehole data. However the experience has been that unless the strength is so high that it probably has little impact on stability, these rock mass strengths are approximate only, subject to significant uncertainty and hence there is risk.

6. Numerical modelling (Flac, UDEC, Phases, etc) will have extreme difficulty matching reality. The benefit of such modelling at this stage may lie with parametric modelling of special conditions or areas.
### TABLE 7
FEASIBILITY LEVEL

PRESENT STATE OF PRACTICE IN QUANTIFICATION OF ELEMENTS OF A PIT SLOPE DESIGN

<table>
<thead>
<tr>
<th>DESIGN ELEMENT</th>
<th>STATE OF PRACTICE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excellent</td>
</tr>
<tr>
<td>Oriented Core</td>
<td></td>
</tr>
<tr>
<td>Geological Mapping – Major Structures</td>
<td></td>
</tr>
<tr>
<td>Rock Mechanics Mapping</td>
<td></td>
</tr>
<tr>
<td>Hydrogeological Testing</td>
<td></td>
</tr>
<tr>
<td>Laboratory Testing</td>
<td></td>
</tr>
<tr>
<td>Geotechnical Model</td>
<td></td>
</tr>
<tr>
<td>Rock Mass Strength Models</td>
<td></td>
</tr>
<tr>
<td>Structural Domains</td>
<td></td>
</tr>
<tr>
<td>Mine Design Sectors</td>
<td></td>
</tr>
<tr>
<td>Limit Equilibrium Analyses</td>
<td></td>
</tr>
<tr>
<td>Probabilistic Analyses</td>
<td></td>
</tr>
<tr>
<td>Numerical Modelling</td>
<td></td>
</tr>
</tbody>
</table>

At Operating Stage the conclusions from the author’s experience are:

1. Large scale exposures allow significant improvement in many key data areas; oriented core and mapping.

2. However the use of this improved data to refine the geotechnical models and rock mass strength is still inadequate.

3. The difficulty in the mapping area in developing geotechnical models relates to two aspects; firstly the scale and the data gaps when designing very large open pits and secondly in complex structural regions the difficulty in defining the critical design defects.
4. Rock mass strength models are still very difficult to determine without back analysis of large failures.

5. Numerical modelling is still only an approximate design tool.

**TABLE 8**

OPERATING STAGE

PRESENT STATE OF PRACTICES IN QUANTIFICATION OF ELEMENTS OF A PIT SLOPE DESIGN

<table>
<thead>
<tr>
<th>DESIGN ELEMENT</th>
<th>STATE OF PRACTICE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excellent</td>
</tr>
<tr>
<td>Oriented Core</td>
<td>•</td>
</tr>
<tr>
<td>Geological Mapping – Major Structures</td>
<td>•</td>
</tr>
<tr>
<td>Rock Mechanics Mapping</td>
<td>•</td>
</tr>
<tr>
<td>Hydrogeological Testing</td>
<td>•</td>
</tr>
<tr>
<td>Laboratory Testing</td>
<td>•</td>
</tr>
<tr>
<td>Geotechnical Model</td>
<td>•</td>
</tr>
<tr>
<td>Rock Mass Strength Models</td>
<td>•</td>
</tr>
<tr>
<td>Structural Domains</td>
<td>•</td>
</tr>
<tr>
<td>Mine Design Sectors</td>
<td>•</td>
</tr>
<tr>
<td>Limit Equilibrium Analyses</td>
<td>•</td>
</tr>
<tr>
<td>Probabilistic Analyses</td>
<td>•</td>
</tr>
<tr>
<td>Numerical Modelling</td>
<td>•</td>
</tr>
</tbody>
</table>
8.1 CONCLUSIONS

Large scale operating experience with open pits has shown that major changes in overall slope angles are the norm, ± 3° to 16°. These changes are outside the expected orders of accuracy for mine developments and indicate that many of these mines have carried significant economic risk. The majority of these mines had engineering studies and supporting design documents with quoted factors of safety and or probabilities of failure which were in general accord with the general design rules.

Mines are designed on the basis of variables that are subject to large uncertainty. In the absence of large exposures and actual operating experience with similar geology or similar rocks then there must be uncertainty and hence risk. Recent development and use of tools such as the acoustic and optical televiewer are allowing the accuracy problems with conventional oriented core to be overcome. However the problems with accurate geotechnical models still remain and are in part a function of the low percentage sampling and the gaps and uncertainties associated with adequately investigating large scale mines.

The fundamental problems with investigations for pit slope design are; the designs are based on quantitative observations from a very small percentage sampling, there are always gaps in knowledge and always uncertainties. This is compounded by lack of sufficient large scale exposures, particularly during early pit development stages, and investigation tools that are subject to large and unknown error.

The major gap in the pit slope design process at both feasibility and operating stages of mine development is how the data is manipulated and processed to allow development of geotechnical models, whether geological structure or rock mass strength based, which accurately define the ground conditions. Effective engineering analytical tools are generally available to analyse most conditions but without accurate models the engineering solutions will not match reality. The actual operating experience highlights this.

Overall it is considered that the trend for serious safety issues with pit wall stability may be increasing. Some contributing factors include:

1. Lack of sufficient experienced personnel at all levels from management down.

2. As the number of mines increase and the scale and depth of mining continue to grow there is a wider range of geotechnical factors and conditions to be understood and managed, some of these are probably outside the individual experience of many professionals.

3. Failure to appreciate when the overall geological setting carries risk.

4. The drive to maximise economic return from resources leading to design and production pressures.
5. It is not practically feasible to completely remove the risk of all rockfall in open pits. Hence it is essential that the operating environment is effectively managed. This includes adequate education of the workforce to ensure awareness, together with good procedures and controls.

6. Failure to appreciate the potential for rockfall issues at all scales.

7. Recognition that those most at risk are people on foot, in light vehicles and in ancillary equipment. Hence the particular need to be aware of access controls and positioning of sumps, etc.

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