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MITSUBISHI LECTURE

HIGHWALLS, STOCKPILES AND DUMPS
SAFETY AND PRODUCTIVITY

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ABSTRACT

Risk lies at the heart of all mining and nowhere more so than in slope design. Mining is principally about two areas of risk; safety and economics. This lecture addresses the main elements of slope design and presents a view of the state of the art in terms of safety, design, prediction of performance, success and 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 open cut slope design is examined for two stages, feasibility and operating.

1.0 INTRODUCTION

Risk lies at the heart of all mining. At the base level mining is fundamentally about these two elements; safety and productivity. In essence these are the two principal areas of risk and this lecture addresses risk in open cut mining from the perspective of a long term practitioner. Movement and failure of walls is one of the main factors affecting the level of risk and in many mines the operational risks from wall failures are a daily event. 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.

Many consider the geotechnical input to a safe and efficient open cut mine is contained only in a single element, the slope design. However, it is fundamental to the understanding presented in this lecture that geotechnical engineering for open cut mining has two components:

- The Slope 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 planned productivity and the overall risk objectives.

Starting out in the profession, it was the belief of the author that designing slopes was the principal task. However, with time and experience, the task has become less and less about the actual slope designs themselves and more and more about slope management. This is in part a reflection of the difficulty with achieving an optimum slope design in the early phases of project development, which also serves to highlight 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 cut mine design? These are some important questions covered in this lecture, which presents a personal view of safety and economic risk arising from slope design and slope management.

2.0 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, Figure 1. The wheel barrow is a metaphor for the sailing ship, a little like the camel as the "ship of the desert".

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 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 these two systems, both of which attempt to define levels of uncertainty and risk are essentially the same.

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

Risk = Chance of Occurrence × Consequence.

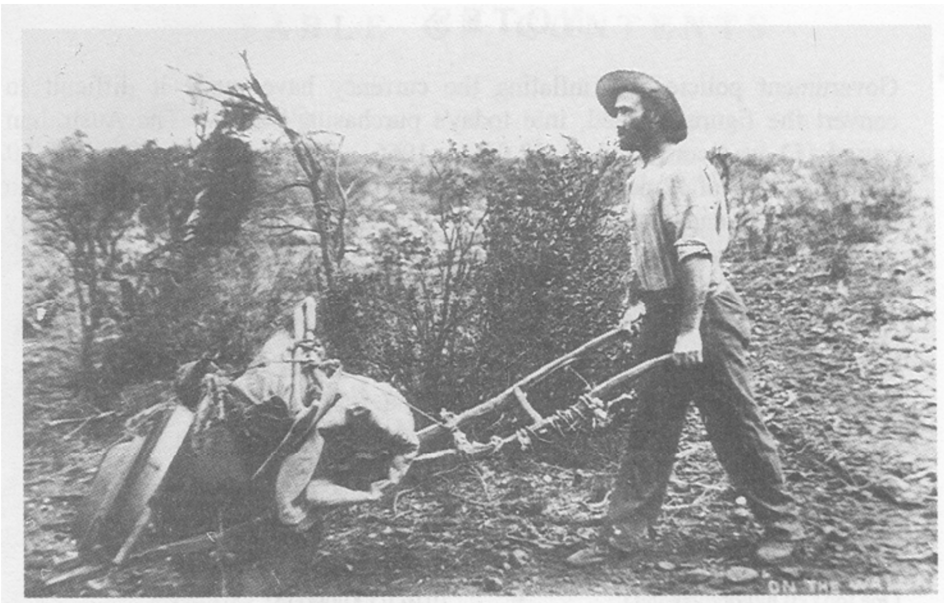

Figure 1
James Balzano, “On the Wallaby Track” in the Eastern Goldfields of W.A. 1895.

A knowledge of the risks in any given situation implies a vision of the future about the likely course of events. In mining, risk means some body of knowledge or experience that would lead to an understanding of both the chance of occurrence of a particular event and the potential consequences arising if that event comes to pass.

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)

is particularly relevant to open cut mining.

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 cut mine 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 open cut mining 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.

3.0 NATURE OF SOIL AND ROCK IN MINING

Traditionally open cut mining has been divided into two areas:

- Soft Rock Mining – mainly coal and
- Hard Rock Mining – mainly metalliferous.

However in geotechnical terms this is really an artificial segregation because in engineering terms all materials behave as one (Johnston 1991):

> *"…… all geotechnical materials are part of one continuous spectrum."*

and

> *"…… one continuous science extending from soft soils to hard rocks. All geotechnical materials behave according to the same engineering principals …."*

with any

> *"obvious differences a function of degree rather than fundamental nature."*

So while the basic science is the same, there are some differences (Sullivan 1993). Open cut slope design usually incorporates four main disciplines:

- soil mechanics,
- rock mechanics
- hydrogeology and
- geology.

Every mine requires some or all of these four disciplines to a lesser or greater degree. This is highlighted in Figure 2 which shows the approximate inputs required for two contrasting mine developments:

- a strip coal mine in Tertiary soil with major aquifers; and
- a hard rock, base metal open pit mine.

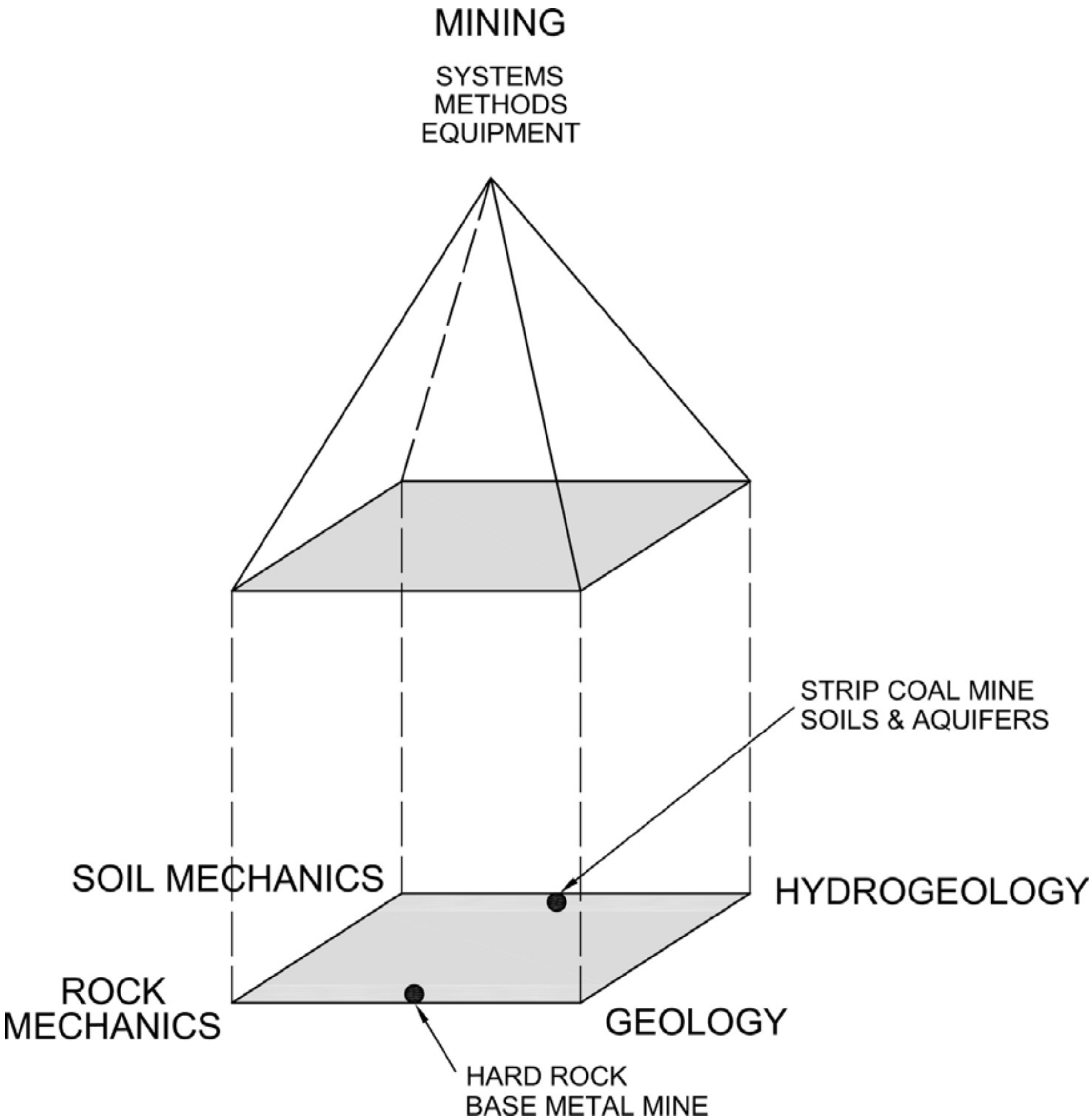

Figure 2
Engineering and Scientific disciplines required for open cut slope design

However, these scientific and engineering disciplines are not a series of narrow parallel specialisations but a continuum, a four-phase field, where the disciplines merge. A fundamental corner stone is geology; the ability to understand geology, its patterns, manifest subtleties and variations. Thus mining geotechnics is a geologically based science.

However, the one element missing that can play a predominant or controlling role in any geotechnical design is the mining engineering; the methods; mine layout, planning, economics, mining systems and equipment.

4.0 GEOLOGICAL AND GEOTECHNICAL COMPLEXITY

Some mines are inherently more geologically complex than others. This geological complexity is linked together with the mine scale in establishing the overall geotechnical complexity of the project. It is the nature of geology that even with comparable levels of exposure, and comparable levels of investigation and sampling, some mines will be more difficult than others.

In broad terms that complexity also applies to geotechnical factors.

Figure 3 shows the relationship between geotechnical conditions and the homogeneity or geological complexity of the mine. This figure is based on a somewhat subjective classification of 50 open cut mines with which the author has been associated. The mines tend to fall in two broad groupings:

- coal and oil shale (Sedimentary Rocks); and
- metalliferous (igneous, volcanic and metamorphic rocks).

The coal and oil shale mines are inherently less complex geologically than the metalliferous mines; although they can have poorer geotechnical conditions. This is partially a reflection of the increased influence of groundwater. It is also a function of the fact that on the whole, sedimentary processes are about sorting and distribution according to grain size, both of which lead to uniformity and hence in the wider perspective to greater predictability.

The trend from good to poor geotechnical conditions is also a partial reflection of the age of the rocks involved, with the younger rocks representing in general, poorer geotechnical conditions.

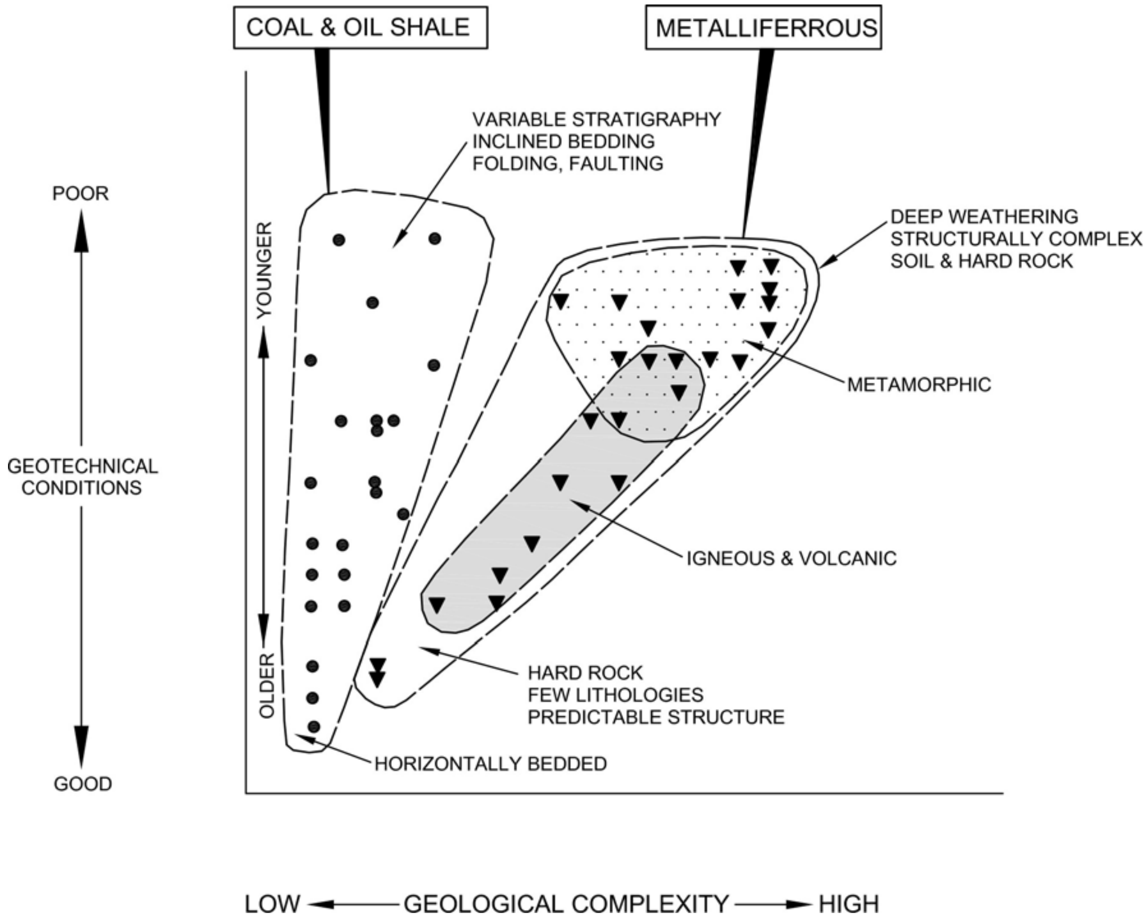

Figure 3
Relationship between geotechnical conditions and geological complexity based on the authors experience with 50 projects.

As the geological and geotechnical complexity increases the overall risk also increases. The impacts as they relate to mine development, design and slope management include:

- increased reliance on a good geological model,
- increased levels of specific geotechnical investigations required,
- increased difficulty in achieving representative sampling and
- increased reliance on a good slope management program.

5.0 THE MINING ENVIRONMENT

The principle elements of two open cut mines are illustrated in Figures 4a) and b). In a deep open cut mine, Figure 4a) the three design elements are:

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

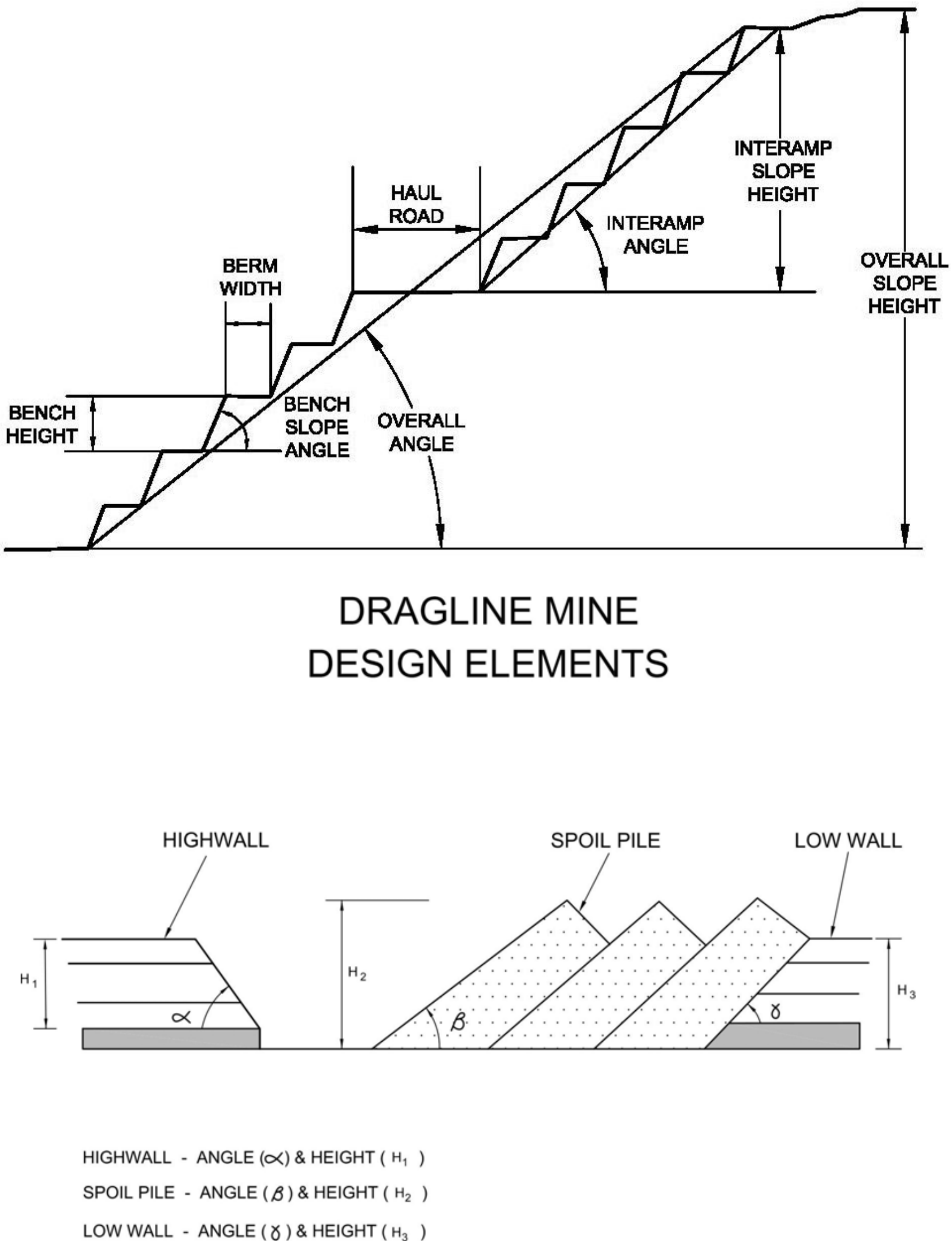

Figure 4 Slope design elements for
a) Deep open cut mine and
b) Shallow surface mine

In a shallow dragline mine, Figure 4b) the three design elements are:

1. Highwall, which is equivalent to the bench in an open cut mine;

2. Low wall, which is a "one off" design element and

3. Spoil pile.

The potential impact of those elements on the two main areas of risk, safety and economics, are set out in Tables 1 and 2.

TABLE 1
DEEP OPEN CUT MINE
SLOPE DESIGN ELEMENTS
AND
RISK AREAS

SLOPE DESIGN ELEMENT	COMPONENT	MAIN CONTROLLING OR INFLUENCING FACTOR			RISK AREA	
		Geotechnical Issues	Mining Systems	Environmental Factors	Safety	Economics
BENCH GEOMETRY	Angle	●	●	•	●	●
	Height	●	●	•	●	•
	Berm Width	●	●	•	●	•
INTER-RAMP	Angle	●	•		[1]	●
	Height	●			[1]	●
OVERALL	Angle	●	•		[1]	●
	Height	●			[1]	●

● Principal factor or main concern
• Minor factor or concern
Notes: 1 Assumes a sound Pit Slope Management Procedure is in place.

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.

TABLE 2
SHALLOW OPEN CUT DRAGLINE MINE
SLOPE DESIGN ELEMENTS
AND
RISK AREAS

SLOPE DESIGN ELEMENT	COMPONENT	CONTROLLING OR INFLUENCING FACTOR		RISK AREA	
		Geotechnical Issues	Mining Equipmental Systems	Safety	Economics
HIGHWALL	Angle	•	•	●	•
	Height	•	●	●	•
LOW WALL	Angle [1]	●		•	●
SPOIL DUMP	Height	●		•	●
	Angle (mid light berm)	●		•	●

[1] It is assumed the location and hence height are defined by the LOX line and hence this element is fixed

As discussed above risk and successful open cut mining are fundamentally about two elements, safety and productivity. Although bench and highwall geometry can impact on both areas of risk the principal concern is safety, Tables 1 and 2. In deep open cut mines for the larger scale of the slopes the principal risk should only be economic, assuming a sound pit slope management program is in place with careful and regular review.

Similarly in a shallow dragline mine the deformation characteristics of the spoil are usually such that movements are generally slow and hence manageable. This means instability mainly impacts on economics.

6.0 SAFETY

6.1 Introduction

The following sections of this lecture address risk in relation to open cut mining firstly in terms of safety and secondly in economic (productivity) 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.

6.2 Historical Perspective

Thirty years ago and even as recently as about ten ago, the general understanding in mining geotechnics and the authors particular experience was that people were hardly ever at risk from medium to large scale failures in open cut 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.

6.3 Experience with Larger Scale Failures

Table 3 presents an assessment of eight serious incidents of which the author has some knowledge and or direct experience (Sullivan 2006). 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. Open Cut 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: "experience often only comes from bad judgement".

Nevertheless, 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 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 Open Cut 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 responsible for ground control and much more than 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 3
LARGER SCALE WALL FAILURES
CONTRIBUTING FACTORS
FATALITIES AND SERIOUS INJURY INCIDENTS

INCIDENT	PIT DESIGN ISSUES		GEOTECHNICAL ISSUES				CONTROL OF INPIT ACCESS AND EXCAVATION		FAILURE TO HEED EXPLICIT WARNINGS
	Poor Pit Design Element	**Inadequate Implementation of Design**	**Risky Geological / Geotechnical Setting Or Design Too Steep**	**Failure to Appreciate Role of Water**	**Failure to Appreciate Post Failure Deformation**	**Poor Understanding of Significance of Monitoring**	**Inadequate Control of Excavation**	**Inadequate Control of Access**	
Failure onto pre-split drilling rig		●							●
Large pit wall failure			●	●	●	●			
Loss of equipment over pit edge	●						●		
Failure undercuts equipment [1]	•		●			•		•	●
Failure leads to mudflow	•		●	●	●		●		
Highwall failure onto equipment	•		●			?			
Large pit wall failure [1]			●	●	●	?			
Slope failure onto mine personnel			●	●				●	

Note [1] Failure to appreciate significance of previous incident (history)

● Principal Factor or Concern
• Minor Factor or Concern

6.4 Rockfall

Rockfalls 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 highwall and bench geometry. The critical aspects are firstly a good design and secondly the maintenance of the design with good blasting and wall excavation practices.

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 4
ROCKFALL
CONTRIBUTING FACTORS TO FATALITIES AND SERIOUS NEAR MISSES

INCIDENT	DESIGN ISSUES			EXCAVATION PRACTICES			ACCESS PROCEDURES AND CONTROLS		
	Inadequate Catch Fence Design	**Slope too Steep for Geotechnical Conditions**	**Inadequate Support of Poor Rock Mass Zone**	**Poor Blasting Practices**	**Berm Loss**	**Poor Control of Cutback Excavation**	**Inadequate Awareness and Access Controls**	**Location of Sumps, Pumps and Ancillary Services**	**Inadequate Separation between Unstable Area and Access**
Rockfall below Cutback	●								
Rockfall below Cutback	●								
Rockfall below Cutback					•	●	●	●	•
Bench failure and rockfall		●							
Rockfall through Windscreen				●	●				
Ravelling rockfall on light vehicle		•	●				●		
Rockfall hits light vehicle									●
Rockfall onto truck and excavator							●		●
Rockfall onto drill					●	●			

6.5 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 increase 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 cuts.

- 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.

7.0 MINE DEVELOPMENT, COSTS AND SLOPE DESIGN ACCURACY

7.1 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. Open cut 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.

7.2 Mine Stages, Study Accuracy and Pit Slope Angles

Table 5 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 5 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 cut 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 5
APPROXIMATE LEVELS OF ACCURACY IN MINING STUDIES
(after Sullivan 1994 and 2006, Ballard, 1983
Coleman and Wescott, 1983)

TYPES OF STUDIES		GENERALLY ACCEPTED ACCURACY OF COST ESTIMATES (+ or - %)	APPROXIMATE ORDER OF ACCURACY REQUIRED IN OVERALL SLOPE ANGLE (degrees)
Mine Study	**Equivalent Terms or Secondary Stages**		
Preliminary	Exploration Review Order of Magnitude	50 40	± 10 to 15
Pre-feasibility	Conceptual	25	± 5 to 10
Feasibility		15	± 3 to 5
Design	Detailed Mine Planning	5 to 10	± 1 to 3

7.3 Summary

In geotechnical engineering the overall slope design targets required in order for open cut 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.

8.0 OPEN CUT SLOPE DESIGN

8.1 The Slope Design Process

Like most fields of engineering the design methodology centres around heuristic's or "rules of thumb" (The Institution of Engineers Australia, 1990). Because open cut slope design is based largely on geology, the concept of a 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 open cut mine 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 open cut slope design process is not generally a wholly deductive process where conclusions are based on completely known facts. 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.

Geology also plays a fundamental part in open cut mine 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% (Blythe 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 open cut slope designs is probably smaller than for any other major facet of the mine design.

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).

8.2 General 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.

8.3 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 6.

TABLE 6
DESIGN FACTORS OF SAFETY FOR OPEN CUT SLOPE DESIGN
(after Sullivan 1994 and 2006, Hoek and Bray 1981; and
C.O. Brawner Personal Communication)

DESIGN SITUATION		FACTORS OF SAFETY COMONLY USED OR ACCEPTED IN PRACTICE	
Applicability	**Geotechnical Conditions**	**Range**	**Preferred Value**
General slope design	simple geological and geotechnical conditions	1.2 to 1.3+	1.2
	complex geology, soil and or soft rock; groundwater		1.3
	to stabilize a large moving slope	1.0 to 1.3	1.1
	rigorous back analysis of large failure available		1.1
Slope below haul road or important infrastructure		1.2 to 1.5*	1.3

* 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 7 presents the probabilities of failure commonly used and accepted in practice.

TABLE 7
DESIGN PROBABILITIES OF FAILURE FOR MINE SLOPE DESIGN
(after Sullivan 1994 and 2006, Kirsten 1983, McCracken and Jones 1990; Priest and Brown 1983; Pine 1992)

DESIGN SITUATION			**FACTORS OF SAFETY COMONLY USED OR ACCEPTED IN PRACTICE**	
Design Element	**Applicability**	**Geotechnical Condition**	**Range %**	**Preferred Value %**
Bench Slope	General		10 to 50	
		Continuous defects	0 to 10	10
		Discontinuous defects	10 to 50	20 to 30
Overall or inter-ramp slope	General		1 to 3[+]	
Overall or inter-ramp including haul road or key infrastructure			<1[*]	

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

9.0 PIT SLOPE DESIGN – STATE OF THE ART

Using the slope design targets in Table 5 it is possible to gain a view of the state of the art in open cut mine slope design as it relates to economic risk. Based on the author's experience with medium to large scale open cut 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 ± 3° 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 6 and 7.

10.0 CONCLUSIONS

Large scale operating experience has shown that major changes in slope angles are the norm. 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.

The fundamental problems with open cut slope designs 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.

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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