A RISK CONSEQUENCE APPROACH TO OPEN PIT SLOPE DESIGN

Dr O K H Steffen, Mr P J Terbrugge, Dr J Wesseloo, Mr J Venter
SRK Consulting, South Africa

ABSTRACT

Open pit slope design has conventionally been effected as a bottom up function utilising available geotechnical information. This results in a decision criterion based on Probability of Failure and Factor of Safety with a risk assessment being carried out on the proposed design slopes. The design approach recommended reverses the process using fault event tree decision methodology. The consequences of this approach are that acceptable risk criteria have to be determined by mine owners. Slopes are then designed by the technical staff to achieve these corporate goals. Benefits that arise from the process are that the owners take a proactive decision on the risk benefit relationship allowing the technical staff to optimise the geotechnical exploration programme and design.

1 INTRODUCTION

Slope design has over the years become the domain of specialist geotechnical practitioners. While this has benefited the technology of the slope design processes, it has also alienated the responsibility of the risk versus reward relationship from the mine design engineer. Given the uncertainties that prevail within the geotechnical discipline, there always exists a probability that a slope may not perform as predicted, and in the worst case can result in a catastrophic failure. Avoidance of failure is reduced by lowering the slope angle but at a cost to the mining enterprise.

Mining is a high risk business and, due to the fact that owners have an appreciation and an appetite for risky ventures, is often successful. In contrast, technical specialist are generally risk averse and have an appetite for technical excellence. In many instances, the slope angles are the dominant parameter that define the mineral reserve, and therefore become a critical decision for the owner. Suitable communication between the owner and technocrat is required to enable the best decision to be made on design slope angles.

The design process suggested in this paper allows the owner to determine the level of risk that is acceptable to him and allows the geotechnical specialist to develop the steepest angles that can satisfy the risk criteria. Risk criteria are therefore set on the basis of consequences of potential failures, which develop a joint ownership of the selected slope angles. No longer is there abdication of responsibility from management to the technical specialist, who is not qualified to determine the acceptable risk levels. The risk/consequence process incorporates the mining business context of the slope into the design criterion. It also enables the identification of areas where geotechnical exploration would maximise the risk reduction.

2 THE RISK/CONSEQUENCE ANALYSIS IN DESIGN

Benefits of adopting the risk/consequence approach to slope design for open pit mining operations, effectively allow the owners to define their risk criteria taking account of the specific consequences of potential failures, or the benefit of steeper slopes at higher risk, and tasking the designers accordingly.

Further benefit from the process allows the designer to specifically identify the amount of drilling and testing required for input to the design process.

With this in mind the risk/consequence analysis process reverses the traditional design approach to slopes for open pit mines, viz:

- Collect all the geotechnical data that could be required for design to a confidence level appropriate for the application.
- Design the slope to a *FOS* or *POF* criterion commonly used by geotechnical engineers.
- Provide the resulting slope angles to the mine planners for their design and economic calculations.
- Apply monitoring procedures to determine the adequate performance of the slope according to the expectations of the geotechnical engineer.

In contrast, the risk/consequence analysis uses the following design process:

- Determine the risk criteria for each consequence at the outset.
- Establish best practice management tools for the slope performance required.
- Calculate the *required POF* for slope design.
- Perform the slope design to the required reliability at the required level of design.
- Collect geotechnical data appropriate for the next required level of design confidence.

This reversal of the traditional approach to slope design has the objective of delivering a design in conformance with the business requirements of the project. The corollary to this is that the business objectives have to be decided *a priori*.

A generic flow chart illustrating the design process for pit slopes which incorporate the risk/consequence philosophy is included as Figure 1.

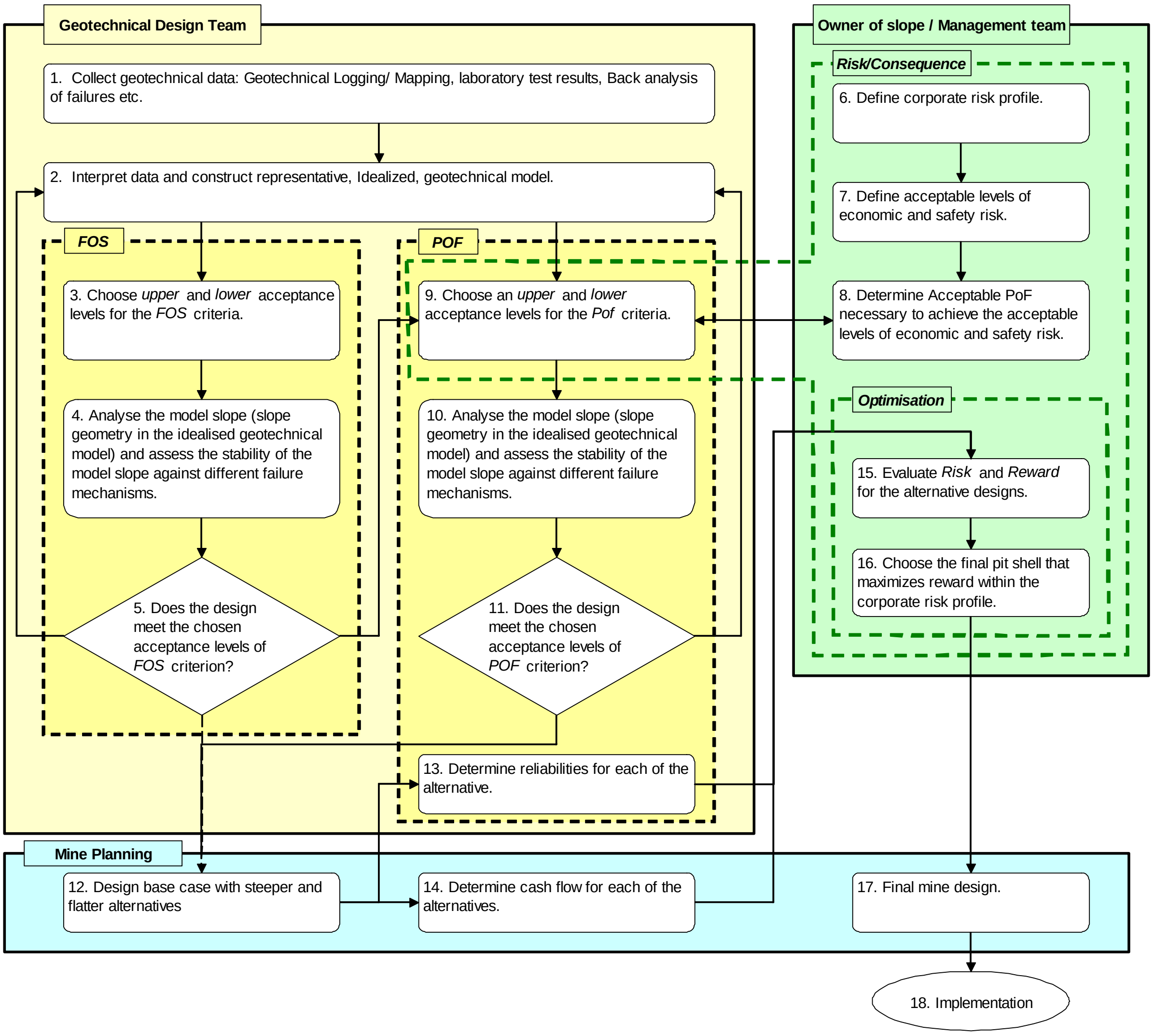


Figure 1: Generic Flow-chart of the open pit slope design process.

2.1 Risk within the Mining Context

In evaluating the geotechnical risk profile for an open pit mine, it is essential that these risks be seen in the context of the total mine planning risk. The geotechnical discipline is only one of the disciplines on the mine that function under conditions of uncertainty, and the geotechnical uncertainty is only one of several sources of uncertainty impacting on the achievement (or non achievement) of the mine plan. The major aspects impacting on the achievement of the mine plan are illustrated in Figure 2.

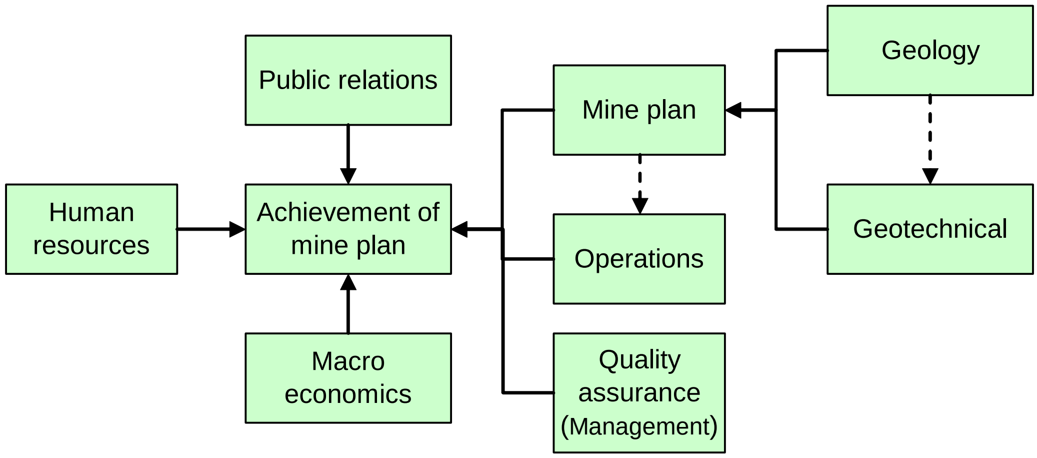


Figure 2: Sources of uncertainty impacting on the achievement of the mine plan.

Achievement of the planned target depends on the following basic credentials:

- The ore resource model performs as predicted.
- The geotechnical model performs as predicted.
- The assumptions made with regard to productivity and costs are achievable.
- Skills in management, leadership and HR can support the plan.

For proper management of resources, it is important that the different disciplines function at the same knowledge and confidence level. In our experience, however, the situation often arises where the support for a mine plan is unbalanced. The geological, metallurgical and mining systems input to the mine plan is often at a much higher level of knowledge and confidence than the geotechnical input.
Steffen (1997) has suggested the classification of slope designs into three classes, similar to the classes specified by the *JORC* and *SAMREC* codes for resource estimation. The three classes, *inferred*, *probable* and *proven* for slope design, each represent an increased level of geotechnical knowledge and confidence.
The three suggested classes require various levels of data confidence as described below:

- Inferred Slope Angle:
  Corresponds with application of typical slope angles based on experience in similar rocks. Quantification will be on the basis of rock mass classification and a reasonable inference of the geological and groundwater conditions within the affected rock mass.

- Probable Slope Angle:
  Corresponds with a design based on information which allows a reasonable assumption to be made on the continuity of stratigraphic and lithological units. Some structural mapping will have been carried out utilising estimates of joint frequencies, lengths and conditions. All major features and joint sets should have been identified. A modicum of testing (small sample) for the physical properties of the in situ rock and joint surfaces will have been carried out. Similarly, groundwater data will be based on water intersections in

exploration holes with very few piezometer installations. Data will be such as to allow simplified design models to be developed to allow sensitivity analyses to be carried out.

- Proven Slope Angle:
  Requires that the continuity of the stratigraphic and lithological units within the affected rock mass is confirmed in space from adequate intersections. Detailed structural mapping of the rock fabric is implied, which can be extrapolated with a high confidence for the affected rock mass, and that strength characteristics of the structural features and the in situ rock determined by the appropriate testing procedures should allow reliable statistical interpretations to be made. Groundwater pressure distributions within the affected rock mass should have been measured using piezometer installations to allow a high confidence in the groundwater model. Data reliability should be at a confidence of 85% for the design to be effected.

The uncertainties that are present within each of these activities shown in Figure 2, gives rise to the probability of achieving or not achieving the stated NPV (or whatever other criterion is stipulated). The proper understanding by the planning engineer of the performance in each of these areas is essential for optimizing the mining operation. The geotechnical risk, and on the same bases the other risks, can be communicated in a quantified and transparent manner by using the risk/consequence analysis process.

For operating mines, the variance within each area can be determined from the reconciliations of actual with planned outcomes. Ore resource model performance can be reconciled on a tons, grade and metal balance. Slopes can be reconciled on the basis of failures experienced to those predicted. Productivity and costs are a straight forward comparison between predicted and actual for the last number of years, while management efficiency could be measured on the basis of how many contingencies or changes in the mine plan are effected, whether the short term planning and long term plans are in sync, and by how much.

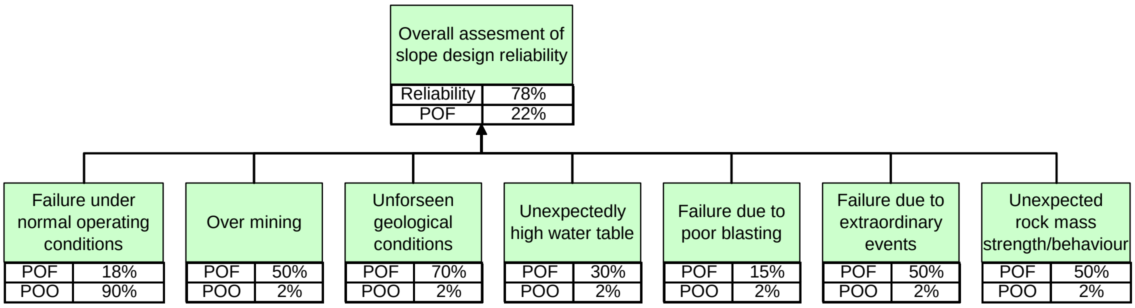
Risk models should also incorporate mitigation strategies. For the four major uncertainties mentioned above, typical mitigation measures would include the exposed ore strategy, slope management strategies, technology and management strategies, with quantification of risk allowing for these strategies to be optimised in monetary terms.
This process allows the determination of the probability of achieving the mine plan using a simplified economic model and assumed variances.

The next step is to subdivide the main uncertainty drivers into more detailed components that can be measured or estimated more accurately, and a parameter distribution defined. An understanding of the risk regime in which the mine operates allows the optimization of the slope design in terms of the balancing of risk and reward. This is done by evaluating alternative mine plans, each with its associated slope design reliability, economic performances and the risk of non-achievement of the mine plan.
The final step would then be to apply this model to the proposed pit plans to closure. In this paper we consider only the contribution of the slope design to the risk/consequence relationship.

2.2 Risk/Consequence Evaluation Process

For each of the slope classes, be it *inferred*, *probable* or *proven*, the reliability of the design is quantified by the *POF*, determined by calculation using the available geotechnical information at the level appropriate to the particular level of study. An overall assessment of the slope design reliability can be obtained through a fault tree as shown in Figure 3.

Conventional stability analyses are carried out with the distribution of geotechnical parameters incorporated in the determination of the *POF*. This is represented as 'normal conditions' in the fault tree in Figure 3. Contributing factors that will affect the stability of the slope are changes in geology, groundwater and rock strengths, together with mining related issues such as over digging or blasting as indicated. This approach allows for the rational handling and weighing of the contribution of different scenarios on the overall assessment of the slope design reliability. The calculation of *POF* in rock slope design often does not take into account the other sources of uncertainty impacting on the slope design reliability.



POF: Probability of failure
POO: Probability of occurrence

Figure 3: Example of a fault free analysis for slope failure.

In general terms, having determined the reliability of the slope design, be it bench, stack or overall, at the Top Fault, the assessed *POF* value is then carried forward into the risk/consequence or event tree (logic diagrams) analyses, where the risk of a defined incident is evaluated. The risk/consequence analyses can, however, also be performed independently to determine the appropriate slope design reliability to achieve the desired level of confidence in achieving the mine plan or to ensure the desired safety level at the mine.

The risks associated with a major slope failure can be categorized by the following consequences:

- Injury to personnel or fatalities
- Damage to equipment
- Economic impact on production
- Force majeur (a major economic impact)

- Industrial action
- Public relations, such as stakeholder resistance due to social and/or environmental impact etc.

Three of the six consequences are all economically related, although on different scales. These differentiated scales equate to the acceptable risk (or the risk criterion) that would apply to each case. Each of the risks quantified must be acceptable to the mine owners, and the risks are related to the *POF* calculated in the fault tree via the slope management process determined in the event tree.

It is therefore incumbent on mine management to take a proactive decision on the acceptable risk criterion, which is independent of any technical input, so that the mine designs can be developed by the technical staff to achieve that objective.

Risk is defined as the consequence resulting from a failure multiplied by the probability of the failure occurring and can therefore be quantified (i.e. *Risk* = *POF* x *Consequence*). The risk evaluation process is illustrated in Figure 4 showing a fault tree for calculating the *POF*, the logic diagrams (event trees) for determining the risk exposure that follows from the selection of a specific slope design and the evaluation of the risks against determined risk criteria.

The risk/consequence analysis is generally performed with the use of logic diagrams. The logic diagram is developed to represent the slope management strategies and processes at the mine. Since the value of the process is dependent on site ownership, it is an essential ingredient that the subjective evaluation of system reliabilities be defined within a workshop environment with all the site knowledge available being included.

Subjective decisions are made by experienced persons on the likelihood of failures of the component of the slope management system as instituted on a mine. Estimates of component failures are presented as triangular distributions obtained from the best estimate and lowest and highest credible estimates. These are referred to as ‘knowledge based’ probabilities compared to frequency based probabilities from historical records.

The use of knowledge based probabilities has been proven effective and acceptable. Discussion on the topic of knowledge based probabilities is provided by Vick (2002) and Baecher and Christian (2004).

In addition, it should be noted that the logic diagram is generally not sensitive to small changes in assigned probabilities but rather to changes in the tree structure which represent the management strategies and processes at the mine.

The numerical test of the system application accuracy viz, that the sum of incidents and non-incidents should be equal to one applies only to the process steps. Since this is always determined on a YES/NO answer, the outcomes at each step equal unity, and therefore the cumulative result of the process always equals unity. However, the sum of the final consequences should add to the probability of the event occurring at all, i.e. the probability of slope failure, and cannot equal one in real terms.

This also answers the frequently expressed concern as to whether the number of decision points (i.e. questions raised within the event tree) does not affect the end result. The more independent questions that can be raised, the more reliable and repeatable the end result will be, but it always adds up to the calculated probability of failure. One should, however, guard against making the tree structure too complicated as this often leads to overlap and misunderstanding.

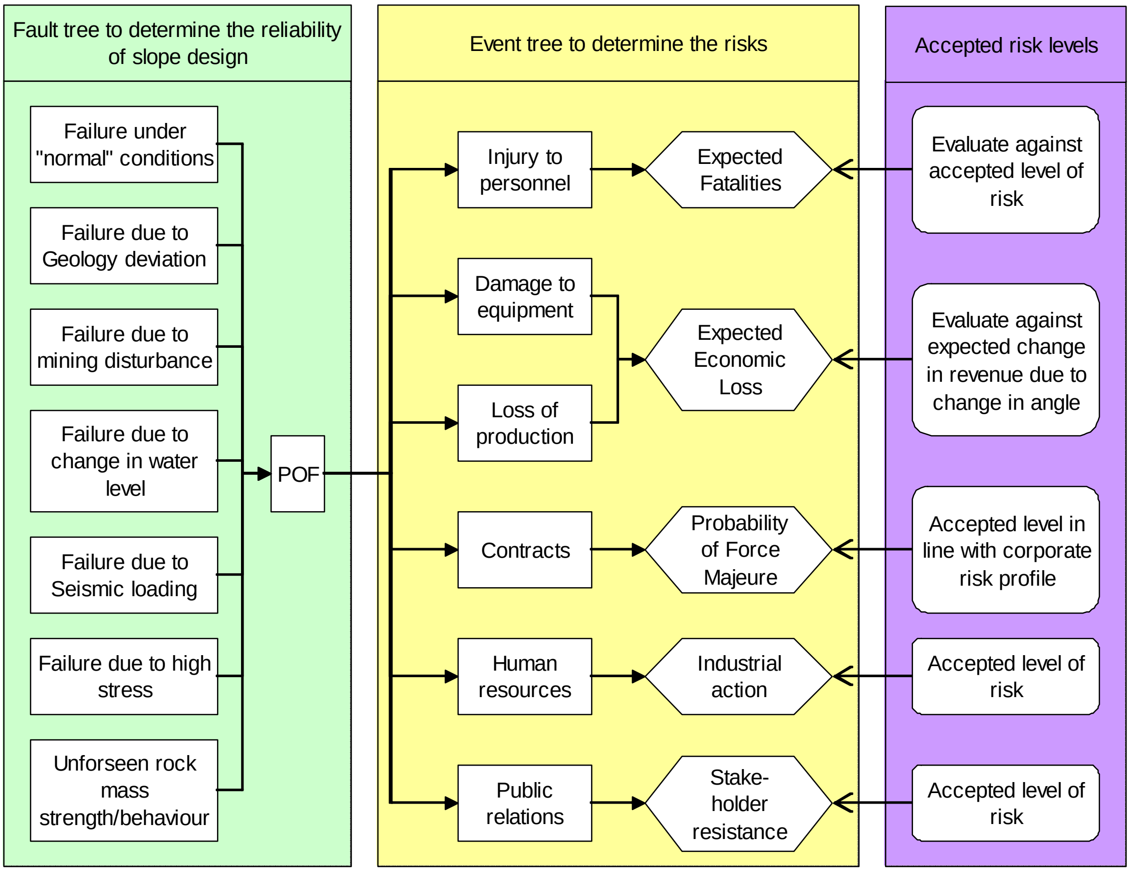


Figure 4: Risk evaluation process.

3 THE EVALUATION OF RISK TO PERSONNEL AND EQUIPMENT

Exposure to risk is determined using the event tree model as shown in Figure 5, with injuries and fatalities being managed by instituting strict slope management procedures and by changing the *POF* of the slope as required. It should be noted that the *POF* can be reduced by changing the design to a more conservative one or by reducing some of the uncertainties contributing to the high *POF*. The implementation of the slope management procedures, as indicated in Figure 5, clearly involves the low cost options which are generally exploited to the full before the slope angle is lowered to reduce the *POF*.

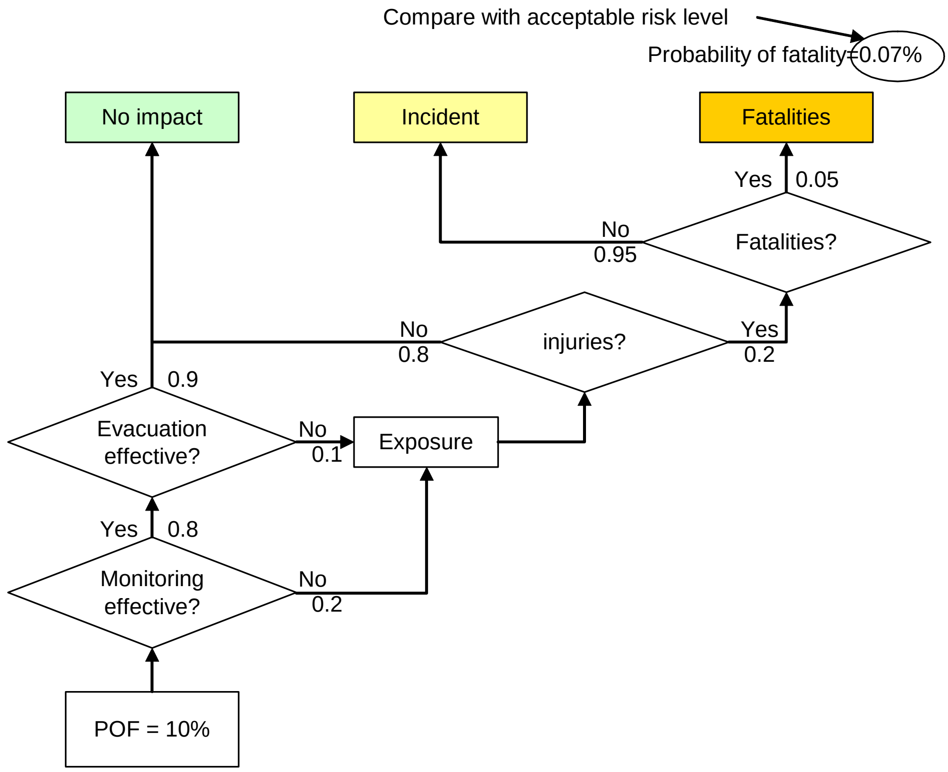


Figure 5: Simplified event/consequence tree for injuries/fatalities.

The probability of a fatality obtained from this analysis should be evaluated against the company's accepted fatality risk level. The contentious issue of acceptable fatality risk is discussed in Section 5.

A similar event tree can be applied to the risk to equipment. Due to the lower mobility compared to that of personnel, the likelihood of equipment damage by a slope failure would be greater, but the consequences less severe. As discussed above, such an event can be considered as having a minor economic impact. The criterion for acceptance in this instance can therefore be considered as orders of magnitude higher than that for personnel. Steffen (1997) recommends an acceptance level for the risk of loss of equipment at about 5%.

4 EVALUATION OF THE ECONOMIC CONSEQUENCES OF FAILURE

An example of an event tree for a major economic impact is shown in Figure 6. A major economic impact needs to be defined to quantify the risk. Typically, it is expressed as a percent impact on the NPV of the project, or alternatively, revenue can be postulated. This criterion, however, cannot be determined in isolation from the risk reward relationship for a mine, but is typically found to be optimum at the level of 5% of NPV. The same is true for determining a suitable criterion for '*force majeure*'. Again, typical values for a *force majeure* criterion are found to be 1% or less. However, under no circumstances should the design increase the risk to life beyond the accepted criterion for a fatality.

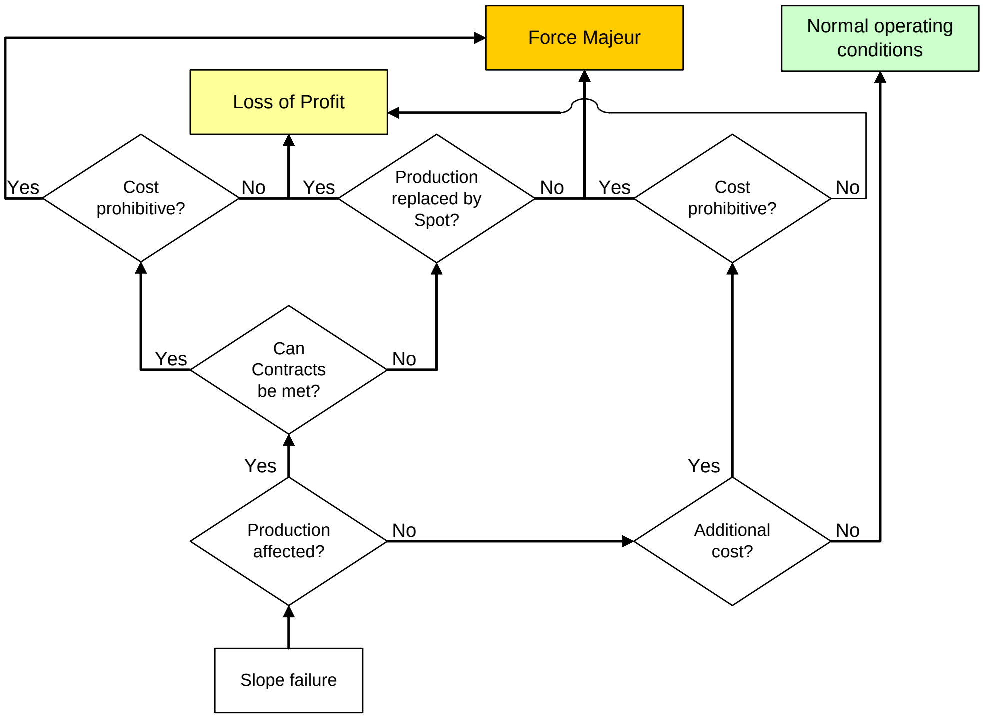


Figure 6: Event tree example for evaluation of economic consequences of failure.

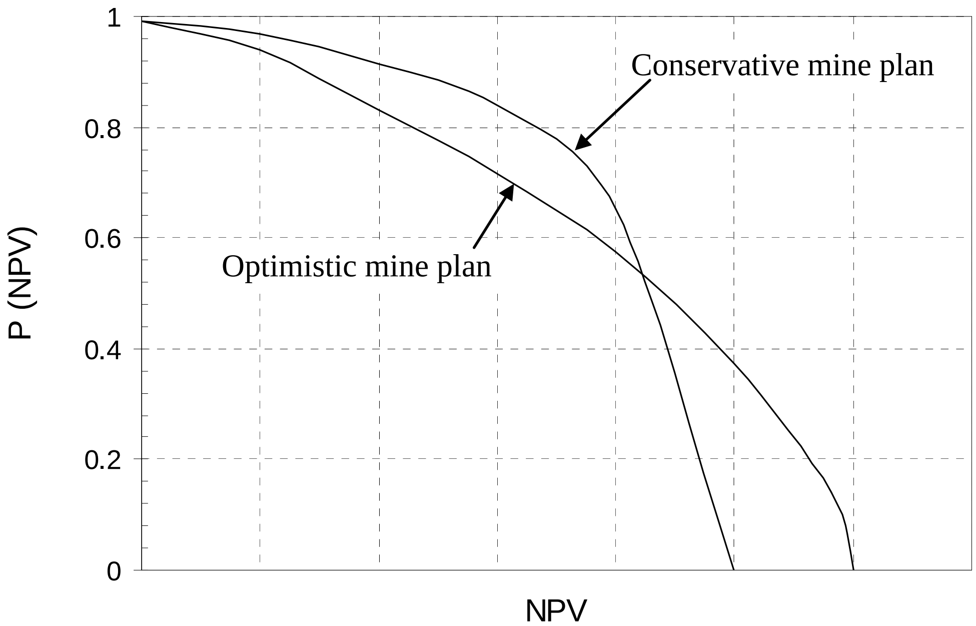
More detailed analyses enable the quantification, in risk terms, of the impact of different sizes of failure on the operation. The consequences of a failure that need to be considered include:

- **Clean-up cost**: This entails the cost of removing failed rock material to the extent that mining can safely continue
- **Slope remediation**: the slope may have to be cut back to prevent secondary failures due to steeper upper slopes, or support systems may be required.
- **Haul road repair and re-access**: The haul road and ramp may be damaged and re-access to the mine has to be taken into account. This calculation should consider the use of an alternate haul road and associated cost if only one ramp into the pit is damaged.
- **Equipment redeployment**: The cost of moving equipment to other parts of the mine where it can be used productively should be considered.
- **Unrecoverable ore**: The loss of a ramp or stack may lead to sterilizing sections of the orebody.
- **Damage to equipment and infrastructure**. The cost of replacing equipment and infrastructure. This may be a major consideration for instance where a plant is situated close to the pit crest.

- **Cost associated with fatalities and injuries**: This may include the cost of industrial and legal action.

- **Disruption of production**: This may impact on contracts and the cost of meeting the contracts.

The evaluation of the slope design reliability and its impact on the economic risk enables comparison of different mine planning scenarios on a common base. Figure 7 shows an example of such a comparison on the basis of the probability of achieving different values of NPV. Although the optimistic mine plan may be able to unlock more wealth, the probability of achieving this is low. The probability of achieving the lower NPV's is higher for the conservative mine plan than for the optimistic mine plan. Assuming that the risk to personnel for both the alternatives is at acceptable levels, the decision whether to accept the conservative or optimistic mine plan is purely a management decision, weighing up the economic risk character of the alternatives within the corporate risk profile.



P (NPV) = Probability of achieving the estimated NPV

Figure 7: Comparison of a conservative and optimistic mine plan on the bases of the probability of achieving the expected NPV.

Figure 8 shows a comparison between different slope designs for a mine in South Africa, based on NPV and the risk of fatalities. A substantial increase is shown in the expected NPV with an increase in the slope angle up to 65˚. The increase in the NPV was, however, expected to be marginal with an increase in the stack angle greater than 65˚. The increase in the risk to personnel, however, exceeded the mine's chosen limit for risk of fatality at an angle of greater than 65˚. For the management of this particular mine, the 65° stack angle option offered a good compromise in maximising the profit without exposing the workforce to unacceptable risk levels.

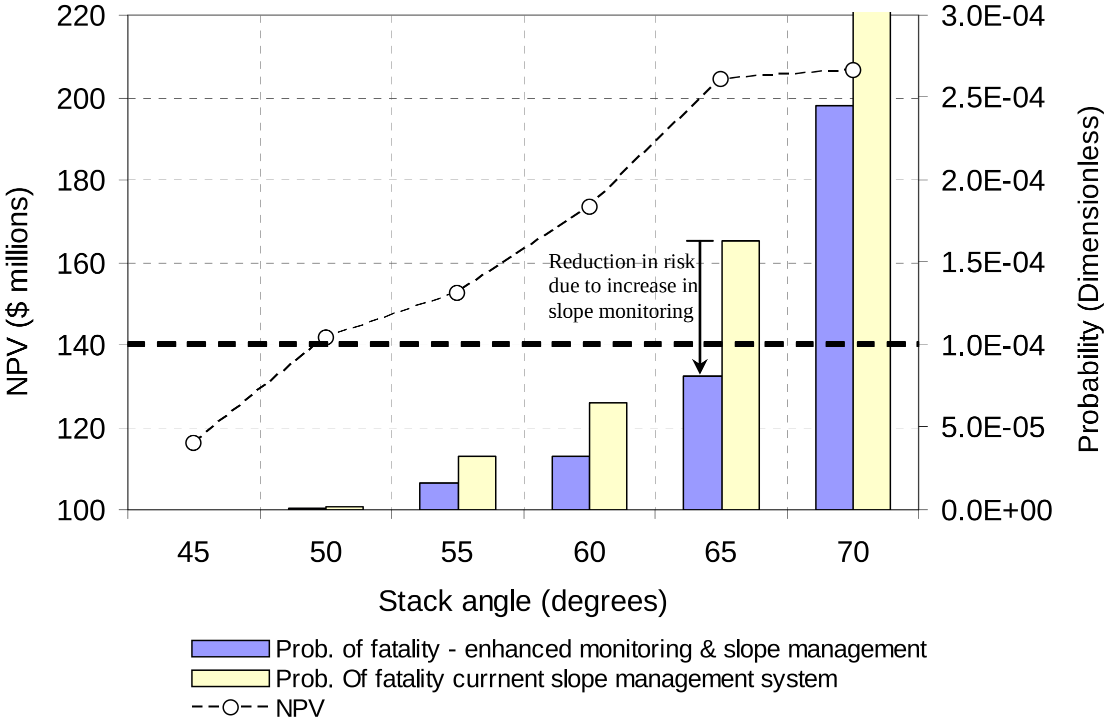
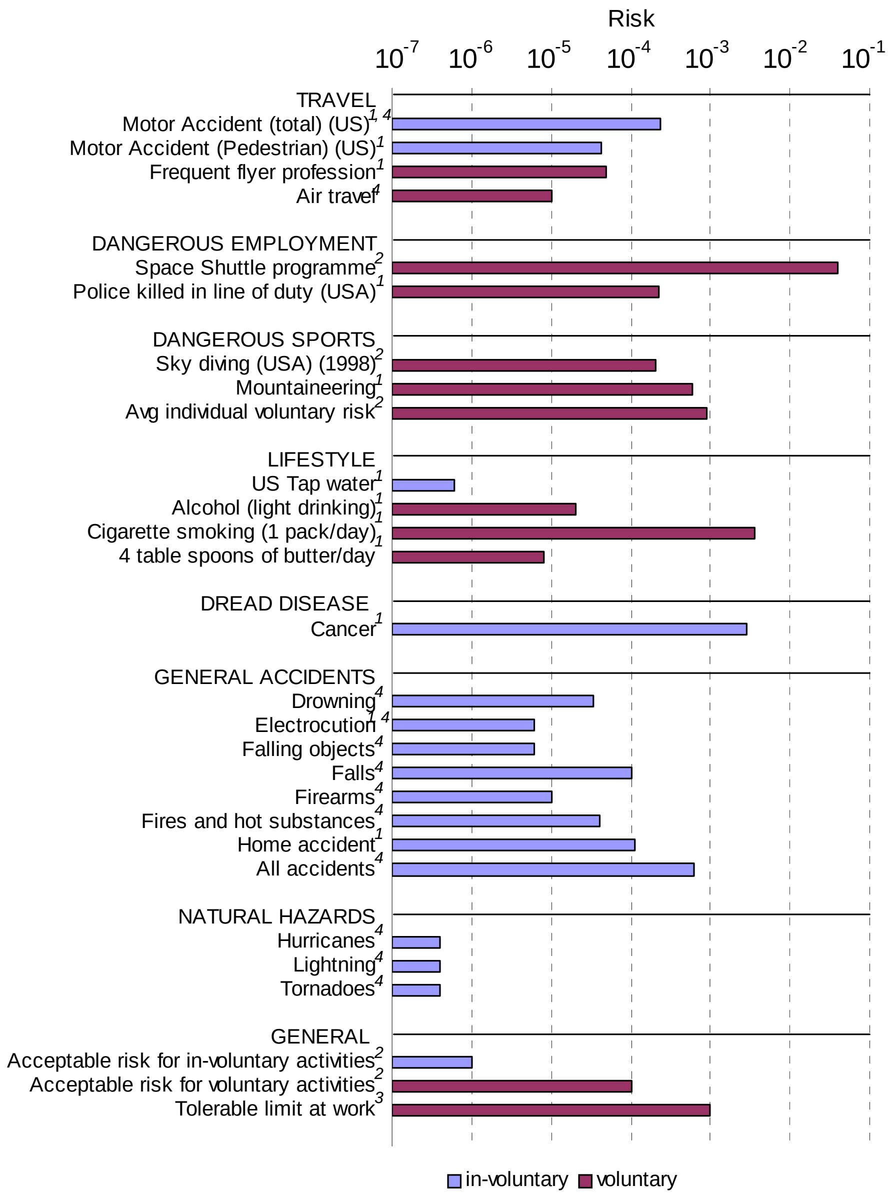


Figure 8: The comparison between different designs based on NPV profit and risk of fatalities for a mine in South Africa.

5 THE ACCEPTABLE RISK OF FATALITIES

Of all the risks shown in Figure 4, the acceptable risk of a fatality from slope failures is the most sensitive, as most companies vow to a zero tolerance in this instance. While this is certainly a *mission*, it is not a reality. An inability to accept a non-zero tolerance for design displays a lack of appreciation of the inadequacies of human ability and knowledge.

Accident statistics provide a means for quantifying risk and evaluating risk on a comparative basis. The proper meaning of accident statistics, however, is difficult to interpret and should be done with caution. This results from the fact that the outcome of statistical surveys is often influenced by the chosen methodology and assumptions for gathering and processing the data and the way the results are presented.



1. Wilson and Crouch (1987), 2. Philley (1992), 3. Hambly and Hambly (1994), 4. Baecher and Christian (2004)

Figure 9: Comparative fatality statistics.

Figure 9 presents some of the statistics reported in literature as probability of a fatality/person/year. In this figure, the risks associated with many common activities like drinking water, staying at home or partaking in sport are shown.

In Figure 9, distinction is made between voluntary and involuntary risk. Involuntary risks are risks to which the average person is exposed without choice, such as many of the dread diseases, fires etc. For voluntary risks, on the other hand, only the select few who choose to take part in certain activities are exposed. Examples of voluntary risk are extreme sports like skydiving, dangerous professions such as astronauts and unhealthy habits like smoking and excessive drinking, or drug abuse.

For open pit mining and other industrial professions, there is often a difference of opinion on whether the exposure of employees to risk in the workplace should be regarded as voluntary or involuntary. Social risk acceptance studies have shown that people will accept risk if they perceive the benefit to outweigh the risk. In our opinion, industrial risk can be regarded as voluntary, if and only if the employee has been empowered to consciously accept the risks in order to obtain the reward.

Another useful format for presenting fatality statistics is *Complementary Cumulative Probability Density Functions* commonly referred to as *F-N* charts. *F-N* charts should always be interpreted within the original context and study area for which they were developed to avoid erroneous interpretation and comparisons between charts.

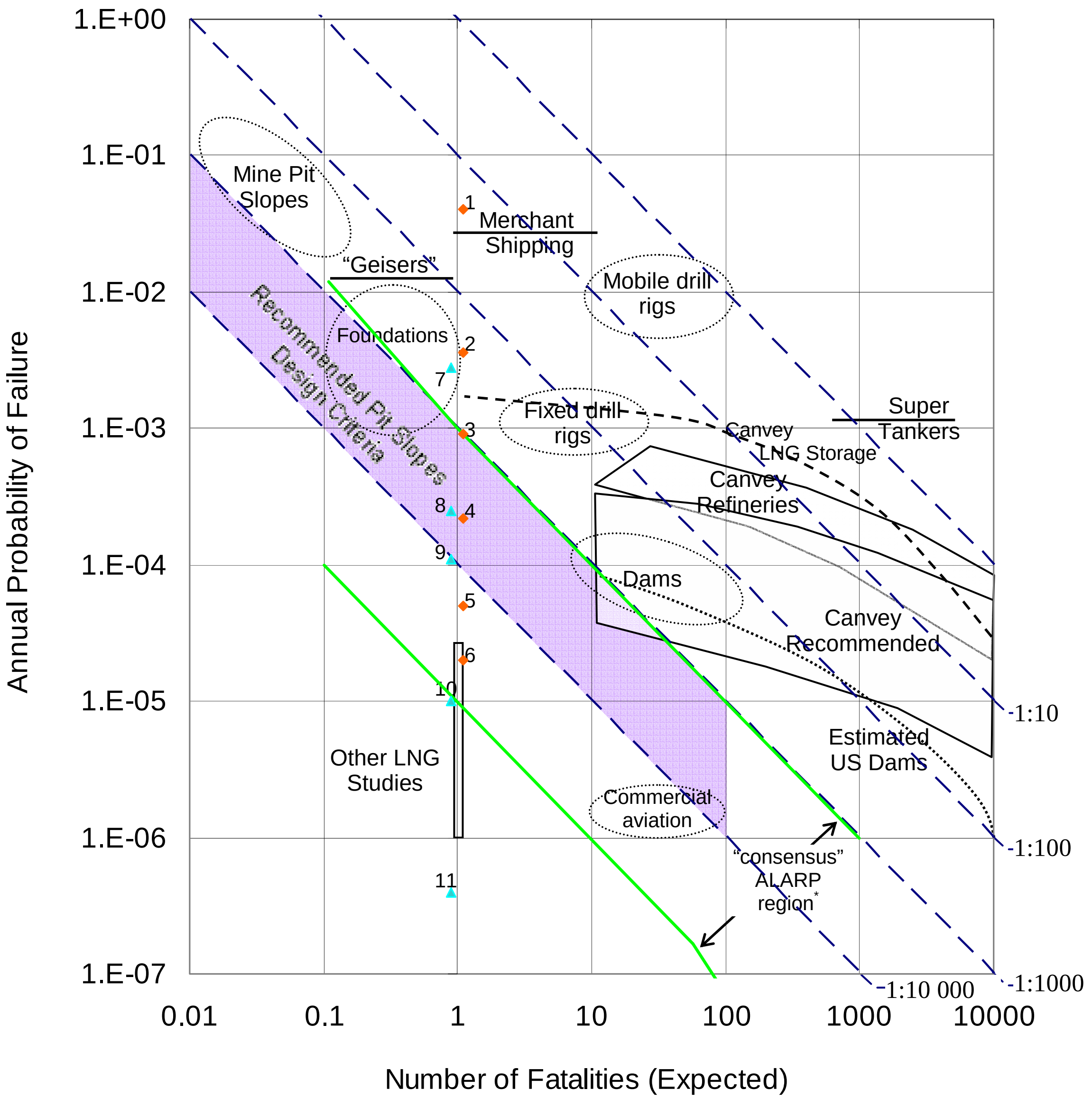
Figure 10 presents a collation of a series of *F-N* charts as well as fatality statistics from the United States. The points representing voluntary and involuntary risk were spaced on either side of the single fatality line to make them more visible.

The diagonal dashed lines in Figure 10 are constant risk lines, i.e. the risk along these lines can be expressed in terms of simple ratios. The upper limit of the ALARP region shown in Figure 10, for instance, is defined by a constant risk of *1* in a *1000*.

The data from Baecher (1982) reproduced in Figure 10, shows that the historical risks associated with open pit mine failures and dam failures are similar (between 1:100 and 1:1000). This is the case as the annual probability of mine slope failures is about 1000 times greater than that of dam failures, while the expected number of fatalities per failure is about 1000 times lower.

With due consideration to the data and existing government guidelines, it is recommended that open pit mines should be designed to a fatality risk level of between 1:1000 and 1:10 000. This incidentally corresponds with the upper level of the ALARP region of most of the generally used guidelines, namely, the Hong Kong planning department, ANCOLD, U.S. Bureau of reclamation and the U.K. Health and Safety guidelines.

Designing the mine slope to the same risk level as that prescribed for dams and other civil engineering structures may seem conservative or even unrealistic. It should, however, be realised that, contrary to the civil engineering structures, this risk level is not achieved by a more conservative slope, but by properly managing slope instability. *Only when the use of slope monitoring systems and management procedures are unable to reduce the risk of fatalities to acceptable levels will it be necessary to accept a more conservative slope design*.



* region defined by the upper most and lower most ALARP boundaries from: Hong Kong planning department, ANCOLD, U.S. Bureau of reclamation and U.K. HS executive guidelines.

Individual Fatality statistics U.S.A - Voluntary

1. Space Shuttle program (per flight) 2. Cigarette smoking (1 pack per day) 3. Average individual voluntary sporting risk
4. U.S. Police killed in line of duty (total) 5. Frequent flying profession 6. Alcohol (light drinking)

Individual Fatality statistics U.S.A - Involuntary

7. Cancer 8. Motor vehicle 9. Home accidents 10. Air Travel 11. Hurricanes / Lightning / Tornadoes

Figure 10: Comparison of risk acceptability criteria with statistics.

6 CONCLUSIONS

The outcome from the risk methodology process ensures that risks to personnel, and of equipment damage, economic impact, force majeure, industrial action and negative public relations are within the required criteria set by the owners. It envelops the concept that stability is not the end objective, but that safety is not compromised and the economic impact of selected slope angles has been optimised. A corollary to this objective is that slope failures are acceptable on condition that they can be managed to ensure that the above criteria are met.

A further benefit is that the eternal question of "how much geotechnical data" is required can be quantified and an audit trail can be established. The risk/consequence analysis process can be used to assess the impact of higher quality data on the consequences of failure. Coupled to the confidence levels for slope design categories into *proven*, *probable* and *inferred* as set out, a much greater reliability of data acquisition is possible.

These procedures utilise all the processes and link the design outcomes to the commercial requirements of the owners in a common language of risk. This does not require an in depth knowledge of geotechnics for board members or management teams to communicate decisions with the technical experts, as the outcomes are reported as probabilities and in monetary terms.

7 REFERENCES

Baecher, G.B. and Christian, J.T. (2003) *Reliability and statistics in Geotechnical Engineering*, John Wiley and Sons. West Sussex. England.

Baecher, G.B. (1982) *Statistical methods in characterization*. Updating subsurface sampling of soil and rocks and their in-situ testing, Engineering Foundation, Santa Barbara, California, p 463-492

Hambly, E.C. and Hambly, E.A. (1994) *Risk Evaluation and Realism*. Proceedings of the Institution of Civil Engineers and Civil Engineering, Vol. 102. pp 64-71.

Philley, J.O. (1992) *Acceptable Risk - An Overview*. Plant/Operations Progress. Vol. 11, No. 4.

Steffen, O.K.H. (1997) *Planning of open pit mines on a risk basis*. Jl S. Afr. Inst. Min. Metall. Vol.97, pp. 47-56

Vick, S.G. (2002) *Degrees of Belief*. ASCE Press. Virginia.
Wilson, R. and Crouch, E.A.C. (1987) *Risk Assessment and Comparisons: An Introduction*. Science, Vol. 236.