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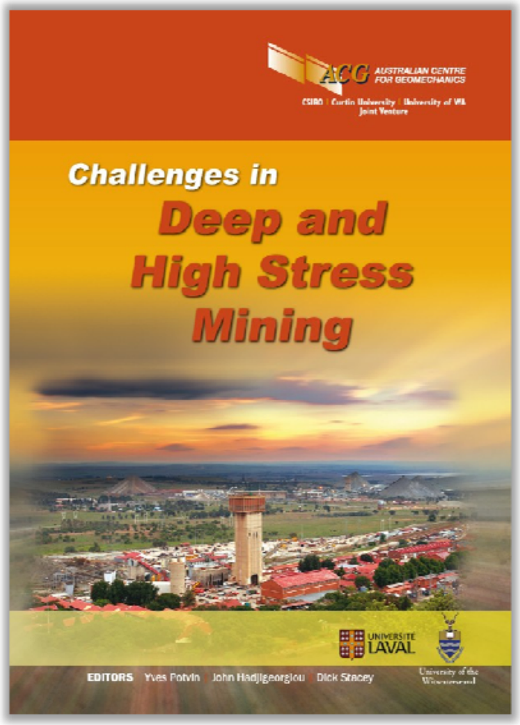

CHAPTER 1

Risk as a Rock Engineering Design Criterion

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Design requirements for engineering projects are usually clearly defined. For example, a civil engineering tunnel may be required to be stable for 100 years. Such projects require conservative design owing to their long-term nature and to the fact that they are often open to public access. The owner of the project will define the overall design objectives. In mining, however, many excavations are temporary or short-term, and not subject to public access. Additionally, in mining, conservatism is not acceptable since it may impact heavily on the economics of the mining. Risk is therefore an integral part of mining, and 'acceptable risk' therefore becomes a necessary and significant consideration in any mining project or operation.

It is suggested here that, instead of the usual engineering design criteria such as loads, stresses, deformations, quantified risks should be used as fundamental design criteria in mining. Commonly, designs are carried out in engineering terms with no input from management at executive level in terms of overall design objectives. Risks associated with these designs are often not quantified. However, if risk is the basis of the design, then executive level management should be directly involved in specifying the acceptable risk at the outset. Only once the acceptable levels of risk have been defined (there may be several risks considered — financial, moral, empirical), can the design be carried out to satisfy these levels of risk. The application of this design process is illustrated here with regard to rockfalls in a deep level mining environment. Using statistical data on the geometry of weakness planes (joints, bedding planes and stress-induced fractures) in the rock mass, and the characteristics of the support (layout and capacity), the probability of rockfalls can be determined. The exposure of underground workers to these conditions determines the probability of loss of life. If this risk does not satisfy the specified level of risk, measures can then be determined to reduce the risk to an acceptable level.

1 INTRODUCTION

Mining is a high risk business and, owing to the fact that owners have an appreciation and an appetite for risky ventures, is often successful, epitomising the risk–reward relationship. In contrast, technical specialists are generally risk averse and focus on technical excellence. Their specialist involvement has effectively removed the responsibility of the risk–reward relationship from the mine design engineer. Owing to the uncertainties that prevail within the rock engineering environment, there always exists a probability that an underground excavation may not perform as expected with respect to stability, and in the worst case a major collapse may result. Risk here is defined as the product of the probability of an event and the consequences of occurrence of that event. Risk criteria are therefore set on the basis of consequences of potential failures, which develop joint ownership of the selected rock support necessary to provide the required stability. Owing to the management input to the risk policy, there can no longer be abdication of responsibility to the technical specialist, who is not in a position to specify the acceptable risk levels, and the risk/consequence process therefore incorporates the mining business context into the design criterion. It also enables the identification of measures that can result in risk reduction. The rock support design process suggested in this paper allows the mining executives to determine the level of risk that is acceptable, which, in turn, allows the rock engineer to design the rock support that can satisfy the specified risk criteria.

At this stage, it is of value to consider some of the general precepts concerning safety and reliability identified by Wong (2005):

- "Nothing can be 100% reliable and safe" and "human beings, one day, will invariably make a mistake." Mining companies often claim a 'zero tolerance' approach to accidents. As indicated by this precept, this is not practical, and can only be an idealistic, but unrealistic aim.
- "Reliability cannot be predicted without statistical data; when no data are available the odds are unknown." Reliability can only be predicted if statistical data exist, and this is commonly not the case in mining, which is usually data shy, particularly in the geotechnical environment. This highlights the need for improved geotechnical data collection techniques.
- "Making things safe and reliable costs money. Engineers will always need to cost the price of failure for comparison." In mining, optimism prevails and there is little expectation that a disaster will occur. When it does, it usually comes as a 'surprise'. Consequently, the cost of such a disaster is rarely balanced against the cost of ensuring safety and stability.
- "A modification or a change in use of a system, or existing design, can lead to a higher risk of failure and a complete reassessment must be carried out." Design modifications may significantly alter the probability of failure. With regard to rock support, in the South African mining industry the Code of Practice requires that a risk assessment be carried out before any new support system is introduced. The design process to be dealt with in the next section also demonstrates the importance of design review.

2 THE RISK/CONSEQUENCE ANALYSIS IN DESIGN

A corporate strategic planning process will identify corporate strategies that should include the levels of risk that are acceptable to the mining company. These strategies should then naturally be expected to form the bases of the criteria for all mine design and operation activities.

An example of a comprehensive design process is that developed by Bieniawski (1991, 1992) for rock engineering. Bieniawski defined six principles: (1) clarity of design objectives and functional requirements; (2) minimum uncertainty of geological conditions; (3) simplicity of design components; (4) state-of-the art practice; (5) optimisation; (6) constructability. The design methodology corresponding with these design principles is summarised in the ten steps shown in the 'circle or wheel of design' (Stacey, 2006) in Figure 1. Although this systematic process was developed for rock engineering, it is equally applicable to any form of engineering, and also, in principle, to feasibility studies and project management. The methodology represents a thorough design process and can be used as a checklist to ensure that a defensible design has been carried out.

The first two steps–statement of the problem, and requirements and constraints–are extremely important steps in that they ensure that all parties understand what is being designed and the constraints on the design. These two steps would therefore include the corporate policies on acceptable risk. The 'defining the design' part of the process (steps 1 to 4) is the most important, and the formulation of the conceptual model is probably the most critical step in the process. Such a model would include the design criteria, which must satisfy the acceptable risk.

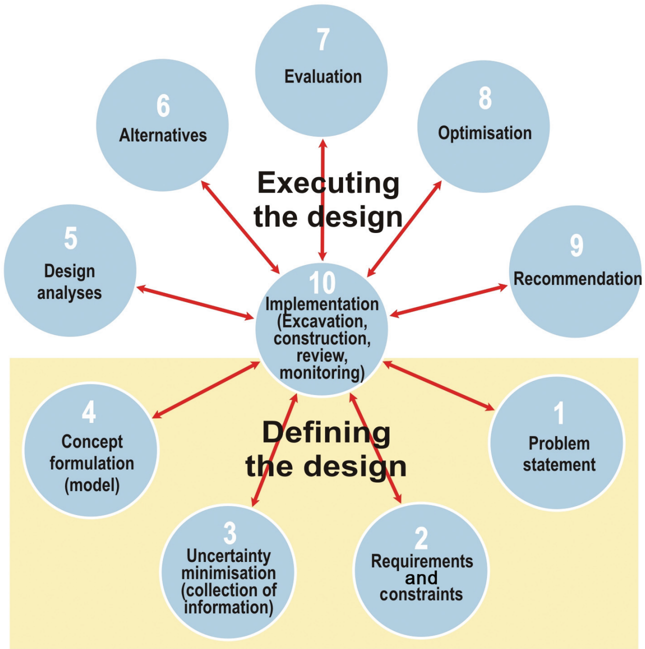

FIGURE 1 The engineering circle or wheel of design (Stacey, 2006)

Review and monitoring are extremely important aspects of design since they allow design shortcomings to be detected at the earliest possible stage, and 'prove' the design. The importance of review and monitoring in any engineering design process is emphasised by the spokes of the wheel in Figure 1. The implication is that the design must meet the stated objectives at all stages. If the resulting risks are not within the acceptable limits, the design must be revised. The similarity between this design process and the strategic planning process developed by Ilbury and Sunter (2005) has been described by Stacey (2006) and demonstrates that strategic planning and design interact closely with each other.

The traditional 'non-risk' design approach is, in summary:

- Collect all the geotechnical data that could be required for design of the underground excavation to a confidence level appropriate for the application.
- Design to a factor of safety (FOS) or probability of failure (POF) criterion commonly used by rock engineers.
- Provide the resulting rock support specification to the mine planners for their design and economic calculations.
- Apply monitoring procedures to determine the adequate performance of the supported excavation according to the expectations of the rock engineer.

In contrast, the risk/consequence analysis process reverses this traditional design approach and instead uses the following design process:

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

This reversal of the traditional approach to underground excavation support 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 priority. This is consistent with both the strategic planning process, in which the business objectives would be defined, and Bieniawski's design process, in which the required risk profiles will be defined as up-front performance objectives in the design process (Stacey, 2006).

In the context of the above and underground excavation and rock support, it is interesting to quote the following regarding safety and risk from Martin and Schinzinger (1983):

"Thus, for engineers, assessing risk is a complex matter. First, the risks connected to a project or product must be identified. This requires foreseeing both intended and unintended interactions between individuals or groups and machines and systems. Second, the purposes of the project or product must be identified and ranked in importance. Third, the costs of reducing risks must be estimated. Fourth, the costs must be weighed against both organisational goals (e.g. profit, reputation for quality, avoiding lawsuits) and degrees of acceptability of risks to clients and the public. Fifth, the project or product must be tested and then either carried out or manufactured."

It is to be noted that these authors link ethics and risk, and that the identification of risks is the first step.

The adoption of the risk/consequence approach effectively allows the owners to define their risk criteria, taking account of the specific consequences of rockfalls and collapses, and task the designers accordingly. A further benefit from the process is that it allows the designer to specifically identify measures that will improve the design or, alternatively, reduce the risk.

2.1 Risk in the mining context

In evaluating the risk of rockfalls in an underground mine, it is essential that these risks be seen in the context of the total mining risk. The rock engineering discipline is only one of the disciplines on the mine that function under conditions of uncertainty, and the rock engineering uncertainty is only one of several sources of uncertainty impacting on the achievement (or non-achievement)

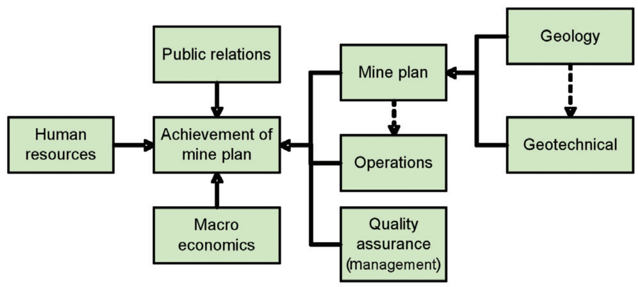

FIGURE 2 Sources of uncertainty impacting on the achievement of the mine plan

TABLE 1 Illustrative jointing parameters

Joint set	Dip (°)	Dip direction (°)	Range (°)	Spacing (m)			Length (m)		
				Mean	Min	Max	Mean	Min	Max
1	89	90	30	0.2	0.1	1	2	1	4
2	60	0	30	2	0.4	4	2	1	4
3	30	180	10	1	0.1	2	100	50	400

of the mine plan. The major aspects impacting on the achievement of the mine plan are illustrated in Figure 2.

Achievement of the mine plan depends on the following:

- That the ore resource model performs as predicted.
- That the geotechnical model performs as predicted.
- That the assumptions made with regard to productivity and costs are achievable.
- That skills in management, leadership, human resources and public relations 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 practice, the input from the different disciplines to the mine plan is often unbalanced. The input to the mine plan on geological, metallurgical and mining systems is often at a much higher level of knowledge and confidence than the geotechnical input. The uncertainties that are present, shown in Figure 2, give rise to the probability of achieving or not achieving the required target. The proper understanding of the performance in each of these areas is essential for optimising 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.

Risk models should also incorporate mitigation strategies. For the four major uncertainties mentioned above, typical mitigation measures would include the strategy regarding ore available for mining, underground excavation/stope management strategies, technology strategies 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 appropriate variances.

The next step is to subdivide the main uncertainties into subcomponents that can be measured or estimated more accurately, and distributions defined for each of these components. An understanding of the risk regime in which the mine operates allows the optimisation of the underground excavation design in terms of the balancing of risk and reward. This is done by evaluating alternative designs (as indicated in the design process, Figure 1), each with its associated design reliability, safety performance, economic performance and the risk of non-achievement of the mine plan.

The final step is to apply the process to the proposed plans to closure. In this paper, only the contribution of the underground excavation/stope support design to the risk/consequence relationship is considered.

2.2 Risk/consequence evaluation process

The reliability of the stope support design is quantified by the POF, determined by calculation using the available geotechnical information at the level appropriate to the particular level of study. A description of such a process has been presented by Gumede and Stacey (2006). For example, Figure 3 illustrates the predicted distribution of sizes of unstable blocks in a tabular stope for a stope support system consisting of elongates on a 1.5 x 1.5 m grid in a rock mass containing the illustrative joint sets summarised in Table 1 (continuous bedding, closely-spaced stress-induced face–parallel fractures, strike–parallel joint set dipping normal to the bedding). The distribution of probabilities of failure of the blocks is illustrated in Figure 4.

Having determined the reliability of the stope support design, the assessed POF value is then carried forward into

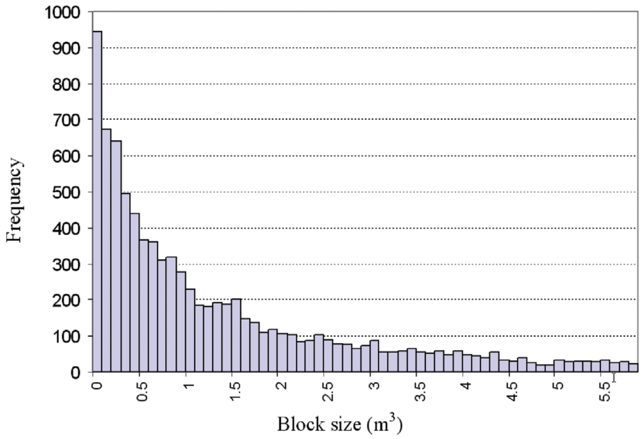

FIGURE 3 Predicted unstable rock block size distribution

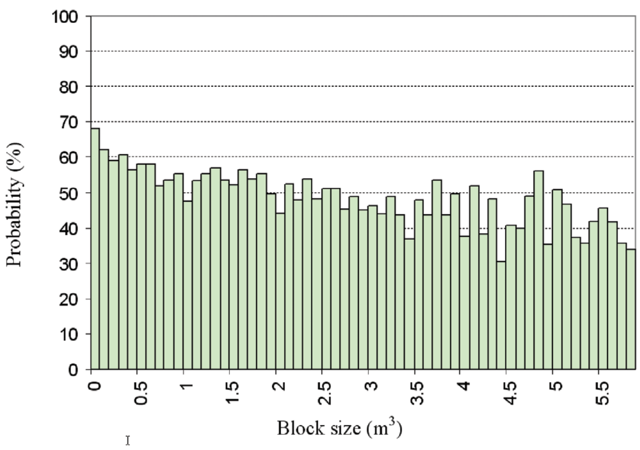

FIGURE 4 Probability of failure of potentially unstable blocks

the risk/consequence or event tree analyses, where the risk of a defined incident is evaluated. The risk/consequence analyses can, however, also be performed independently to determine the appropriate 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 rockfall or major collapse can be categorised by the following consequences:

- Injuries or fatalities.
- Damage to equipment.
- Economic impact on production.
- Force majeure (a major economic impact).
- Industrial action.
- Public relations, such as stakeholder resistance due to social and/or environmental impact.

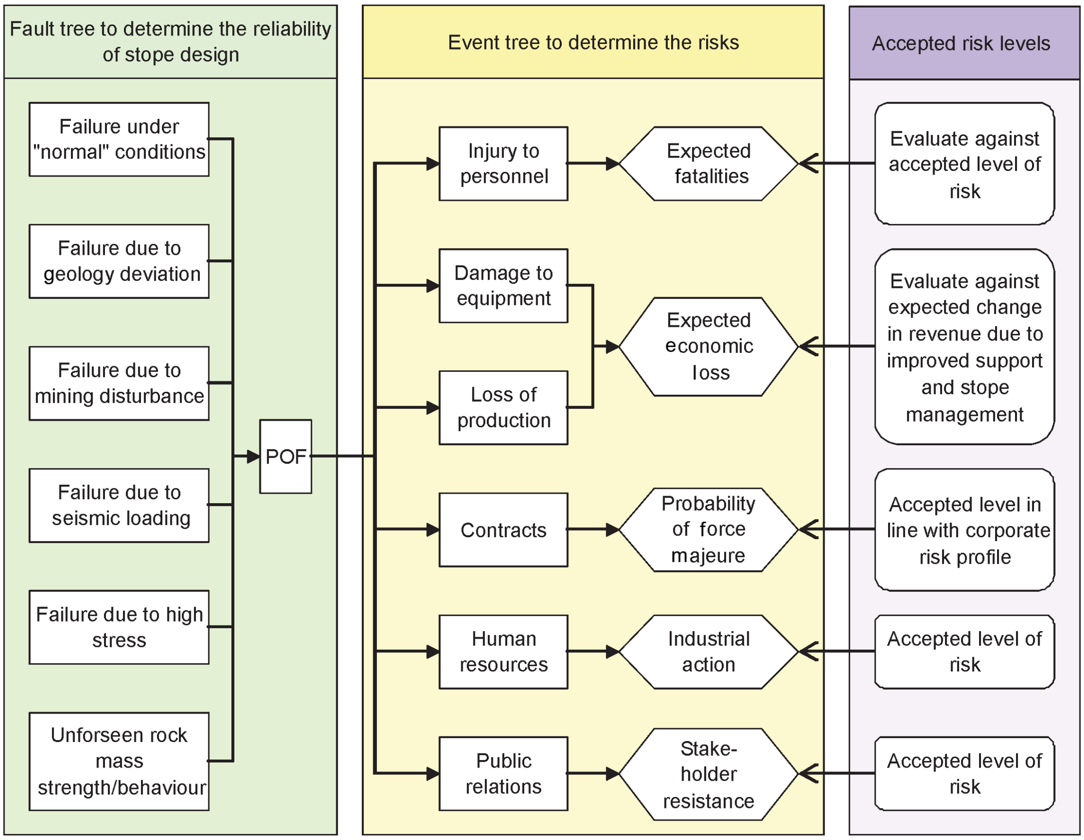

FIGURE 5 Risk evaluation process

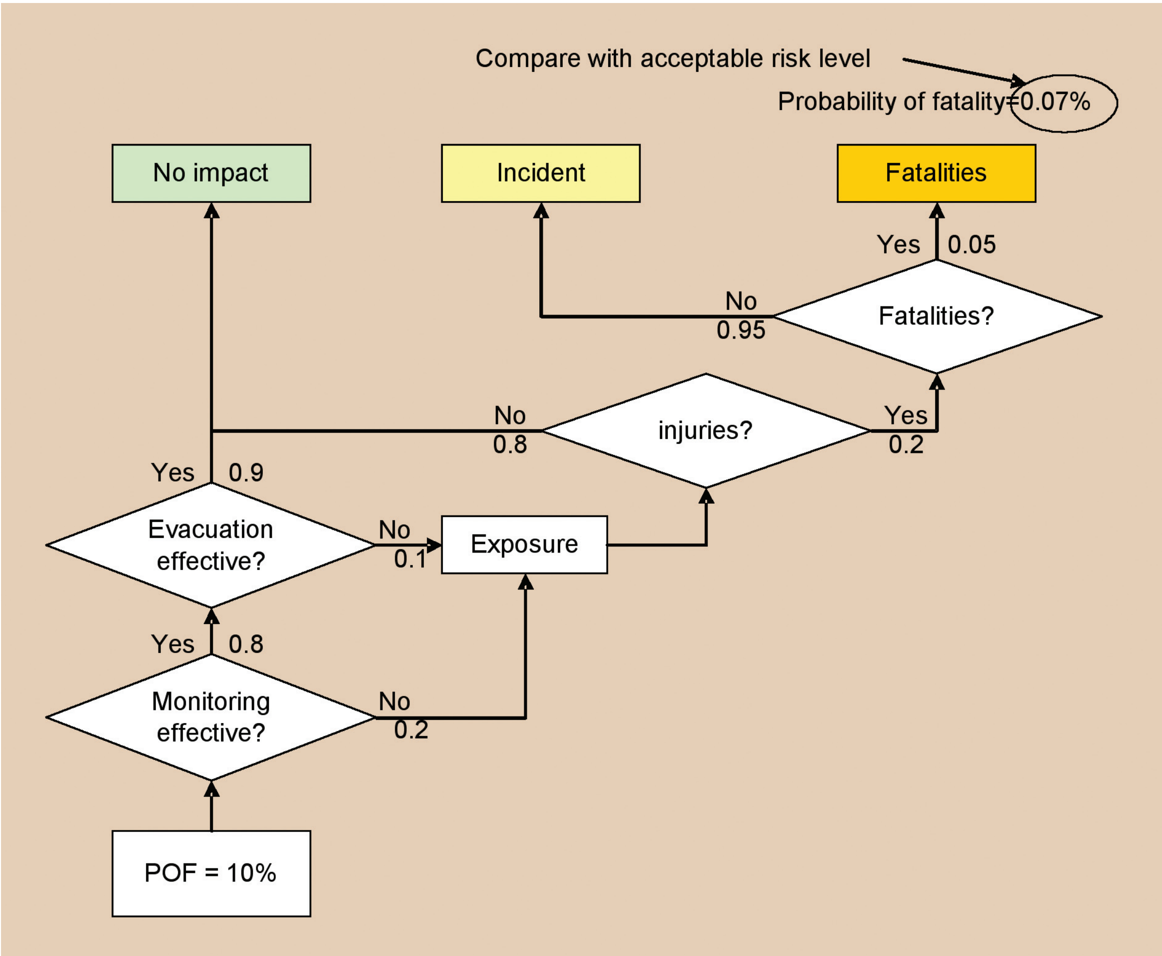

FIGURE 6 Simplified event/consequence tree for injuries/fatalities

Three of the six consequences are 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 it is therefore incumbent on mine management to take proactive decisions on acceptable risk criteria. These objectives are independent of any technical input, so that the mine designs can be developed by the technical staff to achieve those objectives.

The risks are related to the POF via the stope management process. The risk evaluation process is illustrated in Figure 5 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 stope support design, and the evaluation of the risks against the specified risk criteria. The risk/consequence analysis has been described in some detail by Terbrugge et al. (2006) and will not be repeated here. The evaluation of the risk to personnel from rockfalls in a deep level stoping environment will be dealt with in the next section.

3 THE EVALUATION OF RISK TO PERSONNEL

The risk of personnel exposure is evaluated using the event tree model shown in Figure 6. The potential for injuries and fatalities can be managed by instituting strict stope management procedures, hence changing the probability of a fatality. Without such procedures, the risk to personnel is dictated by the effectiveness of the stope support. For example, using the logic described by Stacey and Gumede (2006), the probability of annual occurrence of a rockfall accident (fatality or serious injury) can be determined as 0.011 for the stope support described in the previous section (elongates on a 1.5 m grid). The implementation of the stope management procedures, as indicated in Figure 6, shows how risk could be reduced without increasing the support installed to reduce the POF. For example, if a monitoring system with 50% effectiveness, and an evacuation procedure, also with 50% effectiveness, were to be introduced, and assuming that reportable accidents result from 50% of the rockfalls, the probability of annual occurrence of a rockfall accident reduces to 0.0014. In practice, in deep level gold mines stopes, the monitoring and evacuation steps identified in Figure 6 are at present very limited or non-existent. This indicates a potential approach that could be used to reduce risk in the future. In open pit mining, the effectiveness of monitoring for reducing risk has been definitively demonstrated (Naismith and Wessels, 2005). In the situation that exists currently in gold mine stopes, it is likely that reduction in the risk can only be achieved by reducing the probability of occurrence of rockfalls by means of improved rock support. The calculated probability of a fatality obtained from the analysis described above should be evaluated against the company's acceptable risk level. The contentious issue of the acceptable risk of a fatality is discussed in Section 4.

A similar event tree can be applied to the risk to equipment. In the South African deep level tabular mining environment, such an event can be considered to have a minor economic impact. The criterion for acceptance in this instance could therefore be considered as orders of magnitude higher than that for personnel.

4 WHAT IS AN ACCEPTABLE RISK?

Of all the risks shown in Figure 5, the risk of a fatality is the most sensitive, as most companies vow to a zero tolerance in this matter. While this may be a mission, it is not realistic. As indicated by the precepts in the introduction, an inability to accept a non-zero tolerance for design indicates a lack of appreciation of

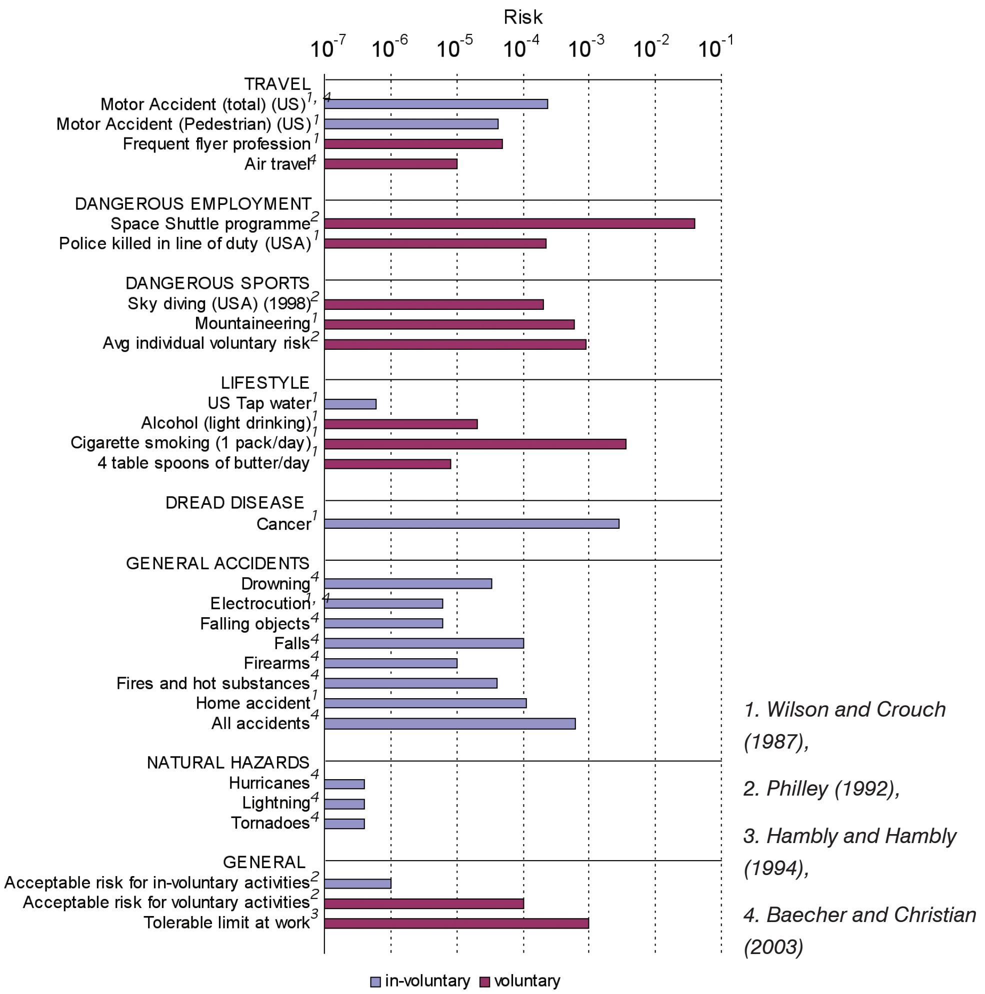

FIGURE 7 Comparative fatality statistics (Terbrugge et al., 2006)

human capabilities. Schinzinger and Martin (2000) give the following definition of safety: "A thing is safe if, were its risks fully known, those risks would be judged acceptable by a reasonable person in light of settled value principles." Regarding acceptability of risk, they quote the description due to Rowe (1979): "A risk is acceptable when those affected are generally no longer (or not) apprehensive about it."

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 approached with caution. The reason for this is 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.

Figure 7 presents some of the statistics reported in literature on the probability of a fatality per person per year. In this figure, the risks associated with many common activities like drinking water, staying at home or partaking in sport are shown. The acceptability of risk is also dependent on whether the exposure to the risk is voluntary or involuntary. Involuntary risks are risks to which the average person is exposed without choice, such as many of the dread diseases or fires. For voluntary risks, on the other hand, only those who choose to take part in hazardous activities are exposed.

For 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. According to Schinzinger and Martin (2000) individuals are more ready to accept voluntary risks, even if these are a thousand times more likely to result in a fatality than the involuntary risks. 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.

It is suggested that the data in Figure 7 could provide a defensible basis for rock engineering design. For example, a fatality risk level of between 1:1000 and 1:10000 incidentally corresponds with the upper level of the ALARP (as low as reasonably possible) region of most of the generally used guidelines, namely, the Hong Kong Planning Department, ANCOLD (Australian National Committee on Large Dams), U.S. Bureau of Reclamation and the U.K. Health and Safety Guidelines (Terbrugge et al., 2006). The latter value corresponds with the statement of Wong (2005): "It is generally accepted that risks which have a fatal injury (hazard) rate of 10 x 10^{-5} or more are unacceptable." The acceptable levels of individual risk quoted by Eriksen (2004) (for risk related to storage of explosives in Norway) are 2 x 10^{-5}/year, 2 x 10^{-6}/year and 2 x 10^{-7}/year respectively for those directly involved, those not directly involved, and those not involved.

Designing gold mine stopes to the same risk level as that prescribed for civil engineering structures may seem conservative or even unrealistic. It should, however, be realised that such risk levels could be achieved by means of a combination of factors — improved design data, appropriate and defensibly designed in-stope support and stope layouts, stope monitoring and stope management (as illustrated in section 3). More conservative stope support will be required only if alternative measures cannot demonstrably be shown to reduce the risk to acceptable levels.

5 THE ECONOMIC CONSEQUENCES OF A SIGNIFICANT STOPE COLLAPSE IN THE FACE AREA

In addition to the safety risks posed by rockfalls, they can result in economic consequences. An example of an event tree for the economic impact of a significant collapse is shown in Figure 8. A major economic impact needs to be defined to quantify the risk. This could be 'force majeure' as illustrated in Figure 8, or simply the closing down of the mining operation. However, under no circumstances should there be an increase in the risk to life beyond the accepted criterion for a fatality. Whereas, in the previous sections, the risk of a fatality or serious injury was based on rockfalls of 0.02 m^3 and greater, economic consequences will result from direct and indirect costs of accidents (Adams, 2005) as well as falls of much larger volumes of rock.

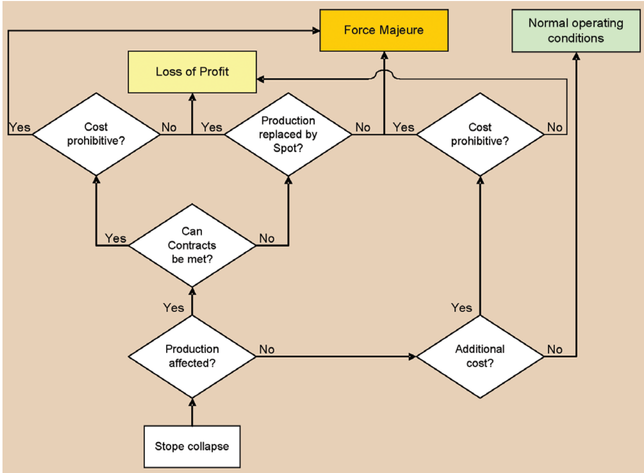

FIGURE 8 Event tree example for evaluation of economic consequences of failure

Detailed analyses will enable the quantification, in risk terms, of the consequences of accidents and different sizes of collapse on the operation. The consequences of a collapse that need to be considered include:

- Clean-up cost: this entails the cost of removing the rockfall material to the extent that mining can safely continue.
- Stope rehabilitation: the stope will have to be stabilised, reopened and resupported.
- Stope re-access: the access to the stope may be damaged and re-access to the stope has to be taken into account.
- 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 collapse may lead to the sterilisation of sections of the orebody or to increased dilution.
- Damage to equipment and infrastructure: the cost of replacing equipment and infrastructure.
- Direct and indirect costs associated with fatalities and injuries: this may include the costs of industrial and legal action.
- Disruption of production: this may impact on contracts and the costs of meeting the contracts.

The evaluation of the economic consequences of a major (or minor for that matter) stope collapse, or of a range of volumes of collapse, can be carried out using the methodology described by Terbrugge et al. (2006) and will not be dealt with here. Once these consequences have been quantified, the decision whether to accept the layout and support designs is purely a management one, weighing up the economic risk character of the alternatives within the corporate risk profile.

It is worthwhile considering the costs involved. Adams (2005) indicated that the cost of a fatality to a mine in South Africa could be as much as R2.7 million, with a lower value for injuries. In 2005 there were 41 fatalities and 1015 injuries in the stope face area in South African gold mines. The total cost of these is estimated to be R180 million, and corresponds with part of the 'loss of profit' indicated in Figure 8. Adams (2006, pers.comm.) argues that, if it is assumed that the mines have a 20% profitability, then almost

R1 billion of revenue must be generated to cover the costs of the accidents. This number is probably unconservative, since it does not take into account the costs of incidents that have not caused accidents. The magnitudes of these numbers deserve some hard management thinking — there must be significant scope to introduce cost-effective measures for reducing the risk by improving the effectiveness of stope support and by implementing stope monitoring and stope management procedures.

6 CONCLUSIONS

The outcome from the risk methodology process described above ensures that the following risks are within the required criteria set by the mining executives:

- To personnel.
- Of equipment damage.
- Of economic impact.
- Of force majeure.
- Of industrial action and negative public relations.

The methodology involves the concept that stability is not the end objective, but that safety is not compromised and that the economic impact of rockfalls and stope collapses has been optimised. A corollary to this objective is that failures are acceptable on condition that they can be managed to ensure that the acceptable risk criteria are met.

A further benefit is that the extent of geotechnical data required can be quantified — the risk/consequence analysis process can be used to assess the impact of higher quality data on the consequences of failure.

These procedures utilise all the processes and link the design outcomes to the safety and commercial requirements of the mining company in a common language of risk. In-depth geotechnical knowledge is not required by board members or management teams to communicate decisions with the technical experts, since the outcomes are reported as probabilities and in monetary terms. The executives can therefore set the risk objectives, as they should do, and these risk objectives can then be translated into technical design requirements to meet the required risk levels. A conclusion is therefore that rock engineering design can also be based on the specified risk criteria.

The major levels of cost associated with rockfall accidents and incidents indicate that there must be significant value generation in the introduction of cost-effective measures to reduce risk by improving the effectiveness of stope support and by implementing stope monitoring and stope management procedures.

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