

Is Rock Engineering Addressing Risk Appropriately?

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ABSTRACT

Design requirements for engineering projects are usually clearly defined. In mining, however, many excavations are temporary or short term. 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.

In this paper it is suggested that, instead of the usual technical design criteria such as loads, stresses, deformations, etc, 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 numerous risks considered - financial, moral, empirical, or other), can the design, which must take into account measures such as operations, monitoring and management, be carried out to satisfy these levels of risk. This approach fits in well with a structured design process and strategic planning considerations.

1 INTRODUCTION

The dominance of rock falls and rockbursts as causes of accidents in South African gold mines is illustrated clearly by the statistics in Figure 1. Even though the rates are seen to be decreasing, the risks of accidents and fatalities remain unacceptably high. In the gold mines, the rates have increased over the past two years. The implications of these statistics are that there are failures of the support systems and therefore, as stated by Stacey (2003), “... either the support is inadequate, or the support design is inadequate, or both are inadequate. With the fatality data, and the long history of high stress and seismicity, it is prudent to question whether an ethical design process has and is being followed in the design of rock support for these conditions.” Ethics in engineering design are directly associated with safety (Schinzinger and Martin, 2000), and it is therefore important to deal with risk and support design in this paper.

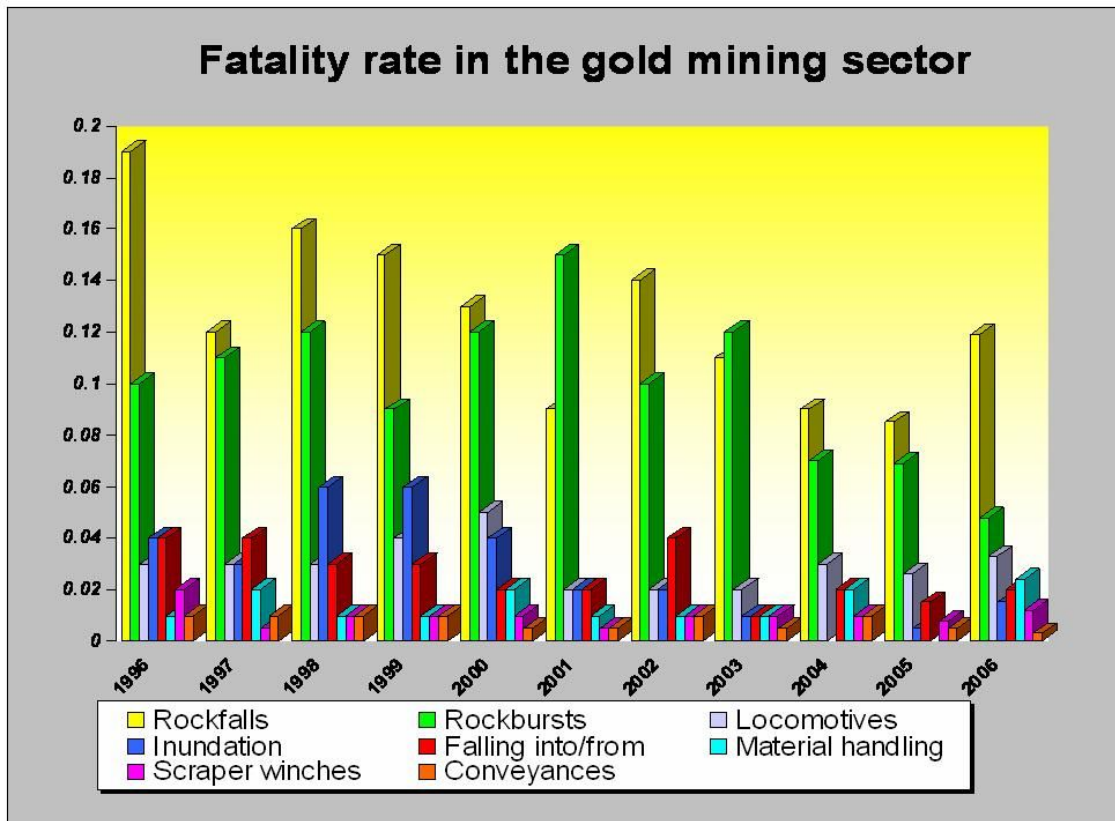


Figure 1: Fatality rates in all South African gold mines (number per million hours worked) (Adams, 2007).

Mining is a high risk business and owners usually have an appreciation and an appetite for risky ventures. In contrast, technical specialists are generally risk averse and focus on technical excellence. 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 collapse and fatality may result. Risk is defined as the product of the probability of occurrence of such an event and the consequences of occurrence of that event. It is suggested that, instead of the usual technical design criteria such as loads, stresses, deformations, etc, quantified risks should be used as fundamental design criteria in rock engineering. 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 numerous risks considered - financial, moral, empirical, or other), can the design, which must take into account measures such as operations, monitoring and management, be carried out to satisfy these levels of risk. 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 the 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 STOPE SUPPORT DESIGN

Traditionally the design of stope support in South African gold and platinum mines has been carried out by rock mechanics personnel on mines in terms of the Code of Practice to Combat Rockburst and Rock Fall Accidents on Mines (COP). Support design is also one of the responsibilities expected of rock mechanics personnel by their employers. The link between the COP and rock mechanics design principles developed by Bieniawski (1991,1992) has been described by Stacey (2004). From these principles, a design methodology or process follows, which is illustrated in Figure 2. There is a strong parallel between this design process and the strategic planning process described by Ilbury and Sunter (2005).

The methodology in Figure 2 represents a thorough design process, which can also be used as a checklist to ensure that a robust design has been carried out. In the context of stope support design, the “defining the design stage” (the first four steps of this process), is extremely important – the performance objectives including constraints, the collection of information for design purposes, and the definition of the expected behaviour so that appropriate design criteria can be set and design analyses can be carried out.

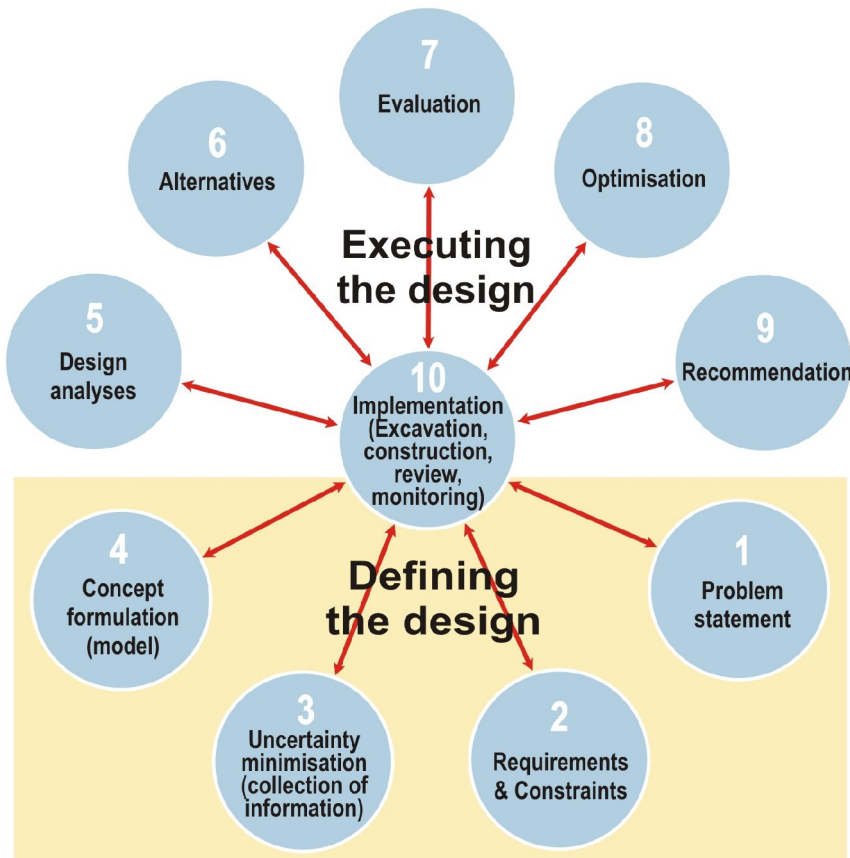


Figure 2: The engineering circle or wheel of design (Stacey, 2006)

If the performance objective (the first step in the design process) of the support system, taking into account functional requirements and constraints (second step), is to prevent rock falls, then the frequent occurrence of rock fall accidents, outlined in the introduction above, proves that this objective is not being met. One or more of three situations must be present:

- rocks are falling where there is no support;
- rocks are falling between supports;
- rock falls involve failure of the installed support system.

In all three cases the design of the support *system* must be inadequate and therefore an improved or different design approach is necessary to correct the situation and ensure safe working conditions.

The third step of the design process is the gathering of sufficient data to minimise the uncertainty. The Importance of this is illustrated by the second bullet point in Section 1 above. Gold mining operations are data limited with regard to rock engineering, and therefore the validity of rock engineering designs based on limited data, and often no data, is questionable.

With regard to the fourth step of the design process, the following statement, sourced from Martin and Schinzinger (1983) is relevant: “... kind of uncertainty that infects risk regulation comes from a *refusal to face the hard questions created by lack of knowledge*. It is uncertainty produced by scientists and regulators who assure the public that there are no risks, but know that the answers are not at hand.” If there is not adequate information for design, then a satisfactory interpretation of behaviour cannot be made and consequently satisfactory design criteria cannot be set. It follows that satisfactory support design analyses,

alternative design analyses, evaluation of the alternatives and optimization (which are steps 5, 6, 7 and 8 of the design process) can then not be carried out satisfactorily.

The design of stope support expected by the COP takes into account a mass of rock corresponding with 95% of the expected height of rock fall, determined from documented records of rock falls on the mine. *This criterion therefore designs for a 5% probability of failure of the support.* In addition, in this design process, no account is taken of the actual sizes of rock blocks, slabs and wedges that might be present in the stope hangingwall (the empirical rock fall data required in the COP do take account of observed fall thickness on a statistical basis, but not the lateral dimensions of the blocks). Therefore, the support design, based only on the expected height of rock fall, must be flawed.

The final step of the design process (step 10) involves monitoring of the behaviour. In fact, monitoring is not carried out routinely in gold mine stopes. After a rockburst or rock fall event it is common to find undamaged prop type support units lying in the stope. They have either been poorly installed, knocked out by eccentric loading, or have fallen out during seismically induced loading-unloading action. If an accident results, non-adherence to standards is often given as the reason for the accident. However, if this occurs it contradicts the design principle of constructability, the full design process has not been followed through. Such cases represent failure of the support *system*, demonstrating that the support system is not performing as required in terms of the design. In a robust design process, this should lead to a reassessment of the support design, but the continued occurrence of rock fall and rockburst accidents proves that this reassessment has not taken place satisfactorily.

The stope support design procedure published by Daehnke et al (2001) emphasises the significant influence that the orientation of the discontinuities in the hangingwall has on its stability. Daehnke et al (2001) refer to the effect of the density of fracturing in the hangingwall, as well as the frictional strength of the bedding surfaces, joints and mining-induced fractures. They also emphasise that mines should carry out their own back-analyses of fall-out thicknesses for each ground control district. These factors are directly relevant, and the implications for the stope support design process are that data must be available on the fracturing and jointing in the rock mass. Blocks in the hangingwall strata must be defined by a combination of the stress induced fractures and naturally occurring geological planes of weakness - bedding planes and joint set planes. Stacey (1989) showed that there is a significant probability of occurrence of rock falls defined by stress-induced fractures and natural joints. As a result of this work, the recommendation was made that investigations should be instigated to gather information on the characteristics of joints. However, it is apparent that there is a general lack of data on the characteristics of these planes. It is also apparent that no such data are routinely collected on South African gold mines. Although data on joint orientations have appeared in the literature, it appears that no data on joint spacing and length parameters have been published in the South African literature. Recent work by Gumede (2006) has demonstrated that such data can be collected and used successfully to determine the probability of occurrence of rock falls and the probability of failure of stope support.

3 PROBABILITY OF OCCURRENCE OF ROCK FALLS AND PROBABILITY OF FAILURE OF SUPPORT

Haines (1984) described a technique for the generation of joint traces using statistical distributions of joint properties obtained from field mapping data. The superimposition of an excavation geometry onto the joint traces allows potentially unstable block geometries to be identified. Repetition of this process many times then allows the probability of occurrence of potentially unstable blocks to be determined. Similarly, the probabilities of occurrence of potentially unstable blocks of certain sizes (both surface area and volume) and, of particular

relevance here, of the height of rock fall, can be determined. The application of this procedure has been described by Stacey and Haines (1984), Butcher (2000) and Stacey et al (2005) and has been shown to provide satisfactory results. It therefore provides a powerful tool for the analysis of potential stability in stopes using measured joint data.

The use of this process to predict the heights of potential rock falls for Ventersdorp Contact Reef (VCR) and Carbon Leader Reef (CLR) stopes is described by Gumede and Stacey (2007). The agreement between the predicted thickness at the 95% probability and the corresponding published data on empirically determined thicknesses was good for the VCR stopes (1.8m predicted, 1.4m empirically determined by Roberts, 1999). In this case there is a substantial set of empirical data (50 rock falls). The summarised updated empirical data presented by Daehnke et al (2001) indicated a height for rock falls of 1.2m and a height for rockbursts of 1.8m. The joint trace model interpretation does not differentiate between static and dynamic conditions, simply predicting potentially unstable blocks. Therefore, the agreement between observed and predicted heights of falls is excellent. For the CLR stopes, a 1.0m thickness was empirically determined (Roberts, 1999) and 2.2m was predicted. In this case, however, the empirical data set was limited, containing only 23 rockfalls, and its validity is therefore somewhat doubtful. Updated empirical data from Daehnke et al (2001) indicated a height of fall of 2.2m for rockburst conditions. Again therefore, there is excellent agreement between the empirical data and the joint trace model prediction.

The determination of the probability of occurrence of rock falls is only part of the necessary procedure to determine the effectiveness of the support. It is also necessary to determine the probability of failure of the support installed. The program JBlock (Esterhuizen, 2003) can be used both in the probabilistic assessment of gravity driven rockfalls and the evaluation of support effectiveness. To illustrate the application of the approach, the joint statistics published by Dunn and Stacey (2006) have been used. These data are summarised in Table 1; the data on lengths were not available in the published data set and have therefore been estimated. The stope is assumed to dip at 30° towards 315°, and a 3m stope face area in a 30m panel is considered.

Table 1: Jointing statistics

Joint Set	Dip (deg)	Dip Direction (deg)	Range (deg)	Spacing (m)			Length (m)		
				Mean	Min	Max	Mean	Min	Max
1	79	103	10	3.17	0.67	8.37	5.0	3.0	10.0
2	39	93	10	2.7	1.2	4.8	3.0	12.0	6.0
3	80	142	10	5.04	1.37	13.3	9.0	5.0	15.0
4	89	222	10	0.8	0.13	1.92	1.5	0.7	2.0
5	89	70	10	1.55	0.4	3.33	2.5	1.2	4.0

JBlock uses the joint set statistical data to generate possible keyblocks in the hangingwall and these are then randomly “placed” in an excavation with a known support element layout. The

program then determines whether the identified keyblock will cause failure of the support elements (and the corresponding failure mode), or fall between them. JBlock does not take into account complex failure modes, and therefore results obtained from its use may be considered to be under-conservative. Using the jointing parameters in Table 1, the probabilities of occurrence of rock falls can be determined using JBlock. The results show that the great majority of the rock falls will occur between supports rather than failing the supports. The product of the probability of occurrence of unstable blocks and the probability of failure of the blocks represents the total probability of rock falls. For elongate support on a 1.25m grid, the probability of occurrence of rock falls with a volume of 0.02m^3 and greater is significant at about 24%. The volume of 0.02m^3 was chosen as the limiting value since its mass is approximately equal to that of a bag of cement. It is expected that a rock fall of this mass would be likely to cause serious or even fatal injury, particularly in a rockbursting situation. The evaluation of the risk associated with such rock falls is considered in the next section.

4 EVALUATION OF THE RISK OF ROCK FALLS

The comprehensive stope support design procedure described by Daenkhe et al (2001) is a deterministic one that does not take into account satisfactorily the fact that most rock falls occur between supports. These authors do, however, recognise the importance of areal support since they state, "The predominant reason leading to falls of ground in stopes is inadequate areal coverage." The probabilistic approach described in the section above has shown that it is possible to determine the probability of failure of blocks and wedges in supported stope hangingwalls, including failure between supports and failures involving failure of the support elements themselves. It is a natural extension of this analysis then to deal with the probability of occurrence of an accident as a result of a rock fall (whether under gravity or in rockburst conditions). Such an analysis takes into account the probability of occurrence of rock falls in the stope face area and the exposure of the mineworkers in this area. The annual probability of occurrence of such an event can then be used as a risk criterion that can be compared with internationally acceptable risk levels.

The example evaluation is carried out for the 90m^2 stope face area involving the 30m face length and a distance of 3m adjacent to the face. The stope support consisting of point supports (elongates) at a spacing of $1.25\text{m} \times 1.25\text{m}$ is initially considered.

Assume the following:

- that there are 11 miners in this stope face area for a period of 6 hours during the day shift;
- that there are 1 to 2 miners in the area for a period of 3 to 4 hours on the night shift;
- that each miner occupies an area of 1m^2 ;
- that this underground work takes place for 25 days a month and 12 months per year;
- that a block with a volume of 0.02m^3 (representing a mass of about 50kg) represents the smallest block that will cause injury. From the analysis above, the probability of failure of a block with a volume of 0.02m^3 and greater is 24%, or 0.24.

The total exposure hours per year can be calculated as follows:

$$\text{Total hours per year} = 365 \text{ days} \times 24 \text{ hours} = 8760 \text{ hours}$$

$$\text{Day shift exposure} = 12 \text{ months} \times 25 \text{ days} \times 6 \text{ hours} = 1800 \text{ hours}$$

$$\text{Night shift exposure} = 12 \text{ months} \times 25 \text{ days} \times 3.5 \text{ hours} = 1050 \text{ hours}$$

$$\text{Face area} = 90\text{m}^2$$

Area occupied by miners on day shift = 11 miners x 1m² = 11m²

Area occupied by miners on night shift = 1.5 miners x 1m² = 1.5m²

Probability of annual occurrence of a rock fall accident

$$\begin{aligned} &= 1800/8760 \times 11/90 \times 0.24 + 1050/8760 \times 1.5/90 \times 0.24 \\ &= 0.0065 \end{aligned}$$

An accident resulting from such a rock fall has a strong likelihood of being a fatality and this degree of safety is likely to be unacceptable. Acceptability of risk is dealt with below.

5 SUPPORT DESIGN BASED ON RISK

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.” Wong (2005) states, “It is generally accepted that risks which have a fatal injury (hazard) rate of 10×10^{-5} or more are unacceptable.” The acceptability of risk is also dependent on whether the exposure to the risk is voluntary or involuntary. 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. The question of acceptable risk has also been dealt with by Terbrugge et al (2006) and Steffen and Terbrugge (2004), who have suggested the use of internationally accepted design criteria. They proposed the use of an annual probability of loss of life of 10^{-4} . Another approach could be to adopt the policy that employees should be as safe at work as they are at home. The latter risk is quantified in some developed countries. In the mining environment, management can and should take the decision as to whether the risk of loss of life on its mines is acceptable in terms of its company policy. It is suggested that the acceptable risk, based on corporate risk policy, should be defined in the first step of the design process (Figure 2 above), and should then be the basis of the design.

The risk approach is considered to be a more logical approach to rock engineering design than the conventional deterministic engineering approach. In a risk approach, rock engineers carry out the technical analyses to determine the risks for alternative rock support scenarios. These are then compared with the risk profile that is acceptable in terms of their company risk policies. It is to be noted that financial risk, in addition to safety risk, should be an integral part of the consideration, since rock falls usually result in loss of production, and involve costs for clearing the fallen material and for resupporting (often such rehabilitation work is also more hazardous than normal operations). Should the loss of life and/or financial risks be too high in all the scenarios considered, it will then be necessary to introduce measures to reduce the risks to acceptable levels. These measures could involve the following:

- improved support;
- improved monitoring (allowing sufficient warning of an event to evacuate miners);
- hazard awareness training;
- reduced numbers of miners;
- reduced working hours, etc.

As an example, for the risk of a rock fall accident calculated above, if the decision was taken to decrease the elongate support spacing to 1m, then the probability of failure of a block 0.02m³ or greater reduces to 0.21 and, correspondingly, the annual probability of occurrence of a rock fall accident reduces to 0.0057. If headboards were to be installed, the probability of failure of a block 0.02m³ or greater is 0.19 and the annual probability of occurrence of an accident is 0.0051. If the jointing parameters used in the above example actually were to occur at a mine, the implication is that the risk (probability of loss of life) would be far too high (much greater than 10⁻⁴, for example), and support with much greater areal coverage, or other risk reduction measures would be required to satisfy the acceptable risk profile. Logically therefore, the risk approach could be used to optimise the support design on the basis of threat to life, and cost to the mine, to achieve value for the mine. Such an approach to support design would overcome the ethical question with regard to current support design practices. It is to be noted that the support installed must still meet other engineering design criteria such as static and dynamic support resistance and deformation capacity criteria.

6 CONCLUSIONS

It has been demonstrated in this paper that joint geometrical parameters can be used to predict the probability of occurrence of rock falls, and hence the probability of annual loss of life due to these falls. Rock falls in South African gold mines usually result when unstable rock blocks are formed from the interaction of natural jointing in the rock mass, or the interaction of stress induced fractures with the natural jointing. Bedding planes or other “parting” planes will usually provide release planes, allowing these blocks to fall. The importance of the natural joints in defining the instability and as input for robust engineering design has not been given the attention that it deserves.

The acceptability of risk has been discussed, and a new approach to support design is suggested, using an acceptable risk level, defined by company policy, as the basis for the support specification. The rock engineer’s technical analyses will determine the risks for alternative scenarios, and the mine executives then have the responsibility to choose the scenario that matches the risk profiles that are acceptable in terms of their company’s risk policies. Should the risks be too high, it will then be necessary to introduce measures to reduce them to the acceptable levels. These measures could be improved support, improved monitoring and advance warning, hazard awareness training, and reduced numbers of miners or reduced working hours. If such a support design approach was to be introduced, mines would then be operating at safety levels that are acceptable in international social practice. Such an approach to support specification would overcome the “ethical” question with regard to current engineering design practices.

It is concluded that risk in rock engineering, in particular with regard to rock falls, is not being addressed appropriately. Designs are usually based on inadequate data, failures of stope support continue to occur, and support designs and design methods are not reassessed in the light of these failures. The risk of loss of life associated with rock engineering designs is rarely, if ever, quantified as part of the design process.

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