Evaluation of risk of rock fall accidents in gold mine stopes based on measured joint data

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Synopsis

Rock fall accidents continue to be the main causes of fatalities in the mining industry. The occurrence of rock falls in supported stopes implies a failure of the support system. The failure of the support system in turn implies a failure in design. In this paper, ethical issues associated with engineering design are discussed, with particular relevance to stope support design. A risk approach is introduced that will allow designs to be carried out that are compatible with the acceptable risk defined by the mining company management. The implementation of this approach would overcome the ethical shortcomings of current support design practices.

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, they still 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 system 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.' It is therefore important to deal with support design in this paper, including the ethics of engineering design. This will be followed by considerations of the probabilities of occurrence of rock falls and the probabilities of failure of stope support. Blocks of rock involved in rock falls are usually defined by natural joints in the rock mass or a combination of such joints and stress-induced fractures. The probability of occurrence of potentially unstable blocks and rock falls can be determined using measured joint data as described by Gumede and Stacey (2007). This then leads to the evaluation of the risk of rock falls and the design of support based on risk.

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). In the Guideline for the compilation of a mandatory COP to combat rock fall and rockburst accidents in tabular metalliferous mines (DME, 2007), the requirement is clearly stated, 'Support design methodologies used must be properly motivated and documented.' 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.

This methodology represents a thorough design process and can be used as a checklist to ensure that a defensible design has been carried out. In the context of stope support design, the first four steps of this process are 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 carried out.

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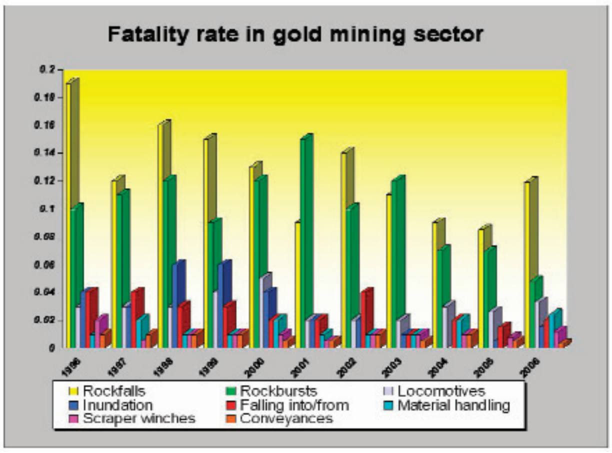

Figure 1—Fatality rates in all South African gold mines (number per million hours worked) (Adams, 2007)

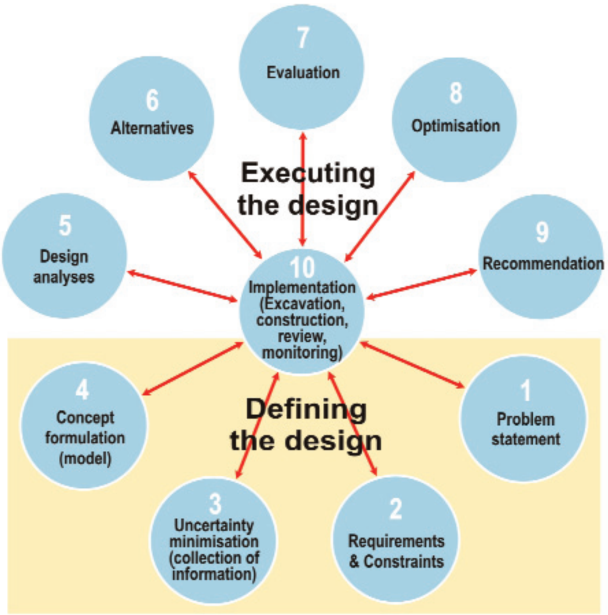

Figure 2—The engineering circle or wheel of design (Stacey, 2006)

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 cause of rock fall accidents is often blamed on non-adherence to procedures and standards by mining personnel, and poor quality control. However, as can be seen in Figure 2, the review and monitoring in step 10 is to ensure that implementation of the support, in this case, corresponds with the design. Therefore, a situation in which there is poor quality support, or omission of support, due to non-conformance with procedures, represents a failure of the design process, i.e., the support system, as designed, has not been installed.

Ethics in engineering design are directly associated with safety (Schinzinger and Martin, 2000), and safety is directly associated with risk. According to Martin and Schinzinger (1983), a 'rights-based' ethical theory is particularly applicable in engineering. This approach emphasises the right of those affected by the work carried out by the engineer to give their informed consent before being so affected. An act-utilitarianism ethical theory (Martin and Schinzinger, 1983) is also applicable, since it indicates that the safety obligations of engineers are to maximize the good consequences for all affected by engineering projects and products. It is considered relevant here to quote three of the responsibilities of registered persons in terms of the Code of Conduct of the Engineering Council of South Africa (ECSA, 2007).

'Registered persons:

- must discharge their duties to their employers, clients, associates and the public effectively with skill, efficiency, professionalism, knowledge, competence, due care and diligence;
- must at all times have due regard and priority to public health, safety and interest;
- must when providing professional advice to a client or employer, and if such advice is not accepted, inform such client or employer of any consequences which may be detrimental to the public health, safety or interests and at the same time inform the Council of their action.'

The third step of the design process is the gathering of sufficient data to minimize the uncertainty. According to Wong (2005), 'Reliability cannot be predicted without statistical data; when no data are available the odds are unknown.' Reliability can be predicted only if statistical data exist, and this is commonly not the case in the mining, particularly in the geotechnical environment. This highlights the need for improved geotechnical data collection techniques. The issue of data on jointing and fracturing in the rock mass, which define potentially unstable blocks of rock, is dealt with in the section below.

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.' With regard to support to prevent rock falls, if there is not adequate information on the geometry of jointing and fracturing in the rock mass, 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 commonly 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 (Jager and Ryder, 1999). 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. As indicated above, such cases represent failure of the support system and demonstrate that the support system is not performing as required. In terms of a robust design process, this should lead to a reassessment of the support design, but the continued occurrence of rock fall and rockburst accidents suggests that this reassessment has not taken place satisfactorily.

The stope support design procedure published by Daehnke *et al.* (2001) emphasizes 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 emphasize 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 (orientataions, spacings and lengths). It is also apparent that no such data are routinely collected on South African gold mines, and that no such data on jointing 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.

In the following sections, the use of joint data to predict the probability of occurrence of rock falls, and the probability of failure in supported stopes, is dealt with. A simple procedure is then described to determine the probabilities of loss of life using these data, and how these probabilities are affected by the stope support installed. The results of such an approach can be compared with internationally acceptable statistics on the annual probability of loss of life. This therefore defines the risk. Defining the acceptability of risk, be it loss of life or financial risk, is the responsibility of management. Currently gold mine stope support design does not take risk into account. It is suggested that this should change—management should decide on the acceptable risk, and the level of risk chosen should then determine the stope support system that should be installed. Management therefore makes the risk decision, which is correctly management's responsibility, and rock engineering personnel then provide the technical stope support design that satifies the risk determined by management.

Evaluation of the probability of occurrence of rock falls and the probability of failure of stope support

Gumede and Stacey (2007) have described the methods of collecting joint geometrical data, and the use of these data for the evaluation of probability of occurrence of rock falls of particular sizes (volumes, fall-out heights) and the probability of failure of stope support. The application of this approach requires as input data, statistical distributions of the geometrical properties of the joints and fractures in the rock mass—the orientations, spacings and lengths. The jointing characteristics will be different in each ground control district, defined as a requirement of the COP, and therefore such data must be measured in each district, in advance of stoping, for the analysis and stope support design to be valid. The availability of measured joint properties in the mines would provide the opportunity of using these data for engineering purposes, namely, the quantification of the probabilities of occurrence of potentially unstable rock blocks of various sizes. This in turn can provide essential data for the design and specification of support to prevent rock falls and therefore reduce the consequences of such events, i.e. accidents, collapses, production loss, and financial loss.

To illustrate the application of the approach, the joint statistics published by Dunn and Stacey (2006) have been used. These data are summarized in Table I—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 3 m stope face area in a 30 m panel is considered.

As described by Gumede and Stacey (2007), the computer program JBlock (Esterhuizen, 2003) can be used both in the probabilistic assessment of gravity driven rockfalls and the evaluation of support effectiveness. The analyses use 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

Table I

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

be conservative. Using the jointing parameters in Table I, 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 1.25 m grid, the probability of occurrence of rock falls with a volume of 0.02 m^3 and greater is significant at about 24%. The volume of 0.02 m^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.

Evaluation of the risk of rock falls

The comprehensive stope support design procedure described by Daenkhe *et al.* (2001) is a deterministic one and does not take into account satisfactorily the fact that most rock falls occur between supports. These authors do, however, recognize 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 90 m^2 stope face area involving the 30 m 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 m × 1.25 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 1 m^2
- that this underground work takes place for 25 days a month and 12 months per year
- that a block with a volume of 0.02 m^3 (representing a mass of about 50 kg) represents the smallest block that will cause injury. From the analysis above, the probability of failure of a block with a volume of 0.02 m^3 and greater is 24%, or 0.24.

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

Total hours per year = 365 days × 24 hours = 8 760 hours

Day shift exposure = 12 months × 25 days × 6 hours = 1 800 hours

Night shift exposure = 12 months × 25 days × 3.5 hours = 1 050 hours

Face area = 90 m^2

Area occupied by miners on day shift = 11 miners × 1 m^2 = 11 m^2

Area occupied by miners on night shift = 1.5 miners × 1 m^2 = 1.5 m^2

Probability of annual occurrence of a rock fall accident = 1 800/8 760 × 11/90 × 0.24 + 1 050/8 760 × 1.5/90 × 0.24 = 0.0065

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.

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 by 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.

The risk approach is considered to be a much better, and more logical, approach to stope support design than the conventional deterministic engineering approach (Stacey *et al*., 2006). In a risk approach, rock engineers would carry out the technical analyses to determine the risks for alternative rock support scenarios. It is then the responsibility of mine management to choose a scenario that corresponds 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 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 1 m, then the probability of failure of a block 0.02 m^3 or greater reduces to 0.21 and, corres-pondingly, 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 0.02 m^3 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 optimize 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 about 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.

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 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 about current engineering design practices.

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De Beers Canada's President and CEO, is named CIM President-Elect 2007*

At its annual general meeting, held on Sunday 29 April, the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) has announced the appointment of Jim Gowans, President and CEO of De Beers Canada Inc., as President-Elect. 'With over 30 years of global mining leadership experience, Jim Gowans was a natural choice to direct the institute in 2008,' said Jim Popowich, incoming CIM President.

'De Beers Canada has been exploring Canada for over forty years, and as of this year, we will also be a fully fledged mining company,' explains Jim Gowans, 'Now is the perfect time to take on a leadership role within the Canadian mining sector.'

The President-Elect is a one-year term, followed by a year as president, then a year as past president, over which time Jim Gowans will have an extraordinary opportunity to influence change and lead the CIM into a new era as the association of choice for professionals in the minerals industries.

De Beers Canada is currently investing almost $2 billion to build two mines in northern Canada simultaneously. The Snap Lake Mine in the Northwest Territories will be commissioned for full production in the autum. Snap Lake will be De Beers' first diamond mine outside Africa, and Canada's first fully underground diamond mine. The Victor Mine in northern Ontario will be Ontario's first diamond mine and is reputed to contain among the most valuable diamonds in the world.

CIM is holding its 2007 Conference and Exhibition in Montreal from April 29 to May 2, 2007 at the Palais des congrès de Montréal. It is the foremost event for the Canadian minerals industry, where industry leaders and professionals come together to network and share knowledge. The conference theme, Energy and Mines, underpins one of the major challenges the minerals industry faces today.

Founded in 1898, the CIM is the leading technical society of professionals in the Canadian minerals, metals, materials and energy industries with over 12 000 national members. ◆

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