Introduction

Although the behaviour of rock around underground mining excavations has been understood implicitly for centuries (Agricola, 1950 (1556)), the science of rock mechanics only began formally about 60 years ago. In South Africa, research into the problems that were being experienced in deep gold mines, owing to high stresses and rockbursts, began formally in 1952 at the CSIR, and this early development was summarized by Bieniawski (1968). The first formal text on rock mechanics was published in 1957 (Talobre, 1957), and the text that perhaps became the early 'bible' of rock mechanics in the English speaking world, with particular application to the deep level mining conditions in South Africa, was published in 1969 (Jaeger and Cook, 1969). The latter text concentrated on theoretical aspects and dealt mainly with the elastic behaviour of rock. The validity of elastic analyses for predicting the overall deformational behaviour of the rock mass around deep gold mine excavations was established at an early stage through measurements (for example, Ryder and Officer, 1965). Elastic analyses continue to be used on a daily basis for planning and evaluation of mining layouts on deep gold mines.

The text by Jaeger and Cook (1969) makes only passing mention of geological discontinuities such as joints and faults and even very recent texts (Jager and Ryder, 1999; Ryder and Jager, 2002) give little attention to the importance of these features. However, particularly at shallower depths, geological structural planes of weakness play an important role in the deformational and failure behaviour of the rock, and this leads to a significant distinction between the rock material and the rock mass. Much of the pioneering work regarding rock mass behaviour arose from experience in the construction of civil tunnels and dams in Europe.

‘Rock mechanics' deals with the science of the behaviour of rock and rock masses. Testing and analysis form major activities in this science. The concept of ‘rock engineering' has developed subsequently and this deals with the engineering of excavations in rock and the use of rock for engineering purposes. The major activity in ‘engineering' is design, and this differentiates it significantly from rock ‘mechanics'. As far as rock engineering design is concerned, there are only two broad aspects that must be dealt with:

➤ evaluation of stability of excavations or foundations
➤ design of measures, such as excavation geometry and support, to achieve the degree of stability required.

These two aspects, and the further implications embodied in them, are dealt with in this paper. As an introduction, however, it is necessary to deal briefly with the characteristics of a rock mass, which is the medium in which the design must be carried out.

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Characteristics of a rock mass

A rock mass usually consists of several or many types of rock material. For example, a sedimentary rock mass may have layers of different rock types such as sandstone, shale, and mudstone, and may be intersected by intrusions such as dolerite dykes and sills. Each rock type will have its own material behavioural characteristics, which implies a range of variability in behaviour. Even within each particular rock type, there will be inherent variability of behaviour. The behavioural characteristics of rock materials can be determined by laboratory testing and this is a common and necessary activity.

For small scale excavations in rock, the data obtained for the rock material from laboratory testing might be sufficient to enable an adequate design to be carried out. However, rock is usually intersected by many geological planes of weakness and, if a significant number of these is involved in the excavation, rock material data alone will not be sufficient. Common geological planes of weakness include bedding planes, joints, faults, shear zones and contact surfaces between different rock types. The properties and number of these features will modify the behaviour of the rock mass to such an extent that the behaviour of the rock material may become almost irrelevant. In addition, the behaviour will be influenced significantly by the in situ stress field and other factors such as water, which are also usually subject to significant local and regional variability.

With the geological complexity of even a ‘uniform’ rock mass, it is impossible to define its structure explicitly as would be the case for a man-made structure such as a ship or an aircraft. One usually has information only at very localized positions in the rock mass, such as given by investigation boreholes, or in underground development, and the rock mass beyond these exposed surfaces remains unknown in detail. The behaviour of the rock mass will depend on a combination of the behaviours of the many components—the rock material properties, the discontinuity properties, the confining stresses, the groundwater conditions, etc. Exactly the same rock mass could behave completely differently at different depths (and therefore different confining stress conditions). Any mechanism of instability (and therefore of stability) will depend on the relative behaviour of the components of the rock mass. It is common that initial instability can be the result of one mechanism of behaviour, and that subsequent instability is the result of another completely different mechanism. With this bewildering complexity of rock masses, the question can be asked as to whether rational design is possible in rock engineering. The first step in addressing this question is to determine whether it is possible to characterize the behaviour of a rock mass.

Laboratory tests can quantify the behaviour of rock material. The extension of this approach to quantify rock mass behaviour is to carry out large-scale field tests. Such testing has proved to be of value in the case of specific critical structures. Examples are large-scale shear tests (for example, Thiel, 1979) and large-scale deformability tests using plate bearing equipment. The volume of rock mass influenced by these tests is still limited, however, and the tests are costly. They are appropriate for specific structures, and an example of the latter is the different types of large-scale deformability testing carried out for the caverns of the proposed Elandsberg Pumped Storage Hydroelectric Scheme (for example, Van Heerden and Maschek, 1979). A second example is specific foundation deformability testing, using an in situ cable jacking test, carried out for the arch bridge carrying the sewer pipeline north of Johannesburg (Pells, 1973). Since mining is always exposing new areas of a rock mass to deformations, however, such testing is likely to be relevant only in exceptional circumstances.

A method that has been used with some success to evaluate rock mass behaviour is to build large-scale similitude models of the rock mass and to test them under representative loading. Such models were used in the past, for example, for evaluation of the behaviour of dam foundations (for example, Oberti and Fumagalli, 1979). Again, such an approach is of little relevance to mining, in which stresses are often changing constantly as a result of the extraction process.

A form of large-scale testing is the use of the back analysis technique (for example, Yamachi and Sakurai, 1991). In this technique, deformations and changes in stress around a tunnel, for example, resulting from adjacent mining activities are measured and then used to back analyse the behavioural parameters of the rock mass. These parameters are then available for use in future design. This is an approach that has relevance in mining since new excavation, creating the ‘unloading’, or change in stress field, takes place almost daily.

Precedent experience can be used as a basis for design. When there is past experience of excavation in a similar rock mass, it can be applied to a new excavation. An example of this approach is the cavern design of the Drakensberg Pumped Storage Scheme (Sharp and Mellors, 1982), which made some use of the precedent of the Poatina Cavern in Tasmania (Endersbee and Hofo, 1963). The precedent approach is probably used implicitly, rather than explicitly, in most mining operations—mining personnel know what has worked and what has not, and therefore implement mine design decisions accordingly. This may be considered to be a simple form of the observational approach (Peck, 1969) which, formally, requires measurement and quantified observation of behaviour, from which design and construction decisions can be made.

The most popular, and hence most common method of quantifying a rock mass is to use rock mass classification. Rock mass classification is a means of taking into account the most important factors influencing rock mass behaviour, and then quantifying, or determining a numerical value for, the rock mass quality. The factors usually taken into account in commonly used classifications are the rock material strength, joint surface conditions, the joint spacings, and the groundwater. The rock quality designation (RQD) is an input to most schemes. Factors taken into account by some schemes, but not others are the confining stress and the orientations of joints. The most commonly used methods are the Q System (Barton et al., 1974; Barton, 2002), the Geomechanics Classification System (Bieniawski, 1973, 1989), the Mining Rock Mass Rating System (Laubscher, 1990; Jakubec and Laubscher, 2000) and the Geological Strength Index (GSI) (Hoek, 1999). For illustration purposes, Figure 1 shows a simplified and slightly modified version of the GSI System of Hoek (1999). This shows visual representations of typical rock masses down the vertical axis, representing the rock mass structure, and joint surface conditions along the horizontal axis. Visual comparison of
the appearance of the rock mass, taking into account the observed conditions of the joint surfaces, allows a range of values for the rock mass rating (RMR) to be determined very easily, thus quantifying the rock mass. This simple approach does not take confining stress into account, nor does it take the effect of water into account explicitly.

Rock mass classification methods have proved to be very successful in quantifying rock masses and have been correlated with excavation stability, required rock support, rock mass deformation and strength parameters, and several other parameters. These will be dealt with further in this paper.

Thorough rock mass classification, using more than one method, and taking into account variability in input parameters, should be carried out for successful engineering quantification of rock masses. The occurrence of different geological structural zones must also be taken into account, and could result in different rock mass quality ratings for different parts of a rock mass.

The design process in rock engineering

Engineering design usually involves the development of a ‘solution’ (the design) to a known ‘problem’. There is no unique solution, and different engineers will produce different solutions—some solutions will work better than others, but all solutions should ‘work’. The reason that solutions are not unique is probably because of the very wide scope of the issues involved in design.

Satisfactory engineering design involves a design process, which is a sequence of events within which the design develops logically. A defined process can serve as a checklist of activities that must be carried out to ensure that a satisfactory design results. It can be considered as quality control that ensures that all aspects that should be taken into account in the design, are taken into account.

Bieniawski (1988) discussed the design process in mining, and concluded that mine design is a process based on empiricism and practical experience that does not qualify as engineering design. This lack of thorough engineering design in mining might be due partly to the variability of the rock masses in which the mining is taking place, but is more likely to be due to the attitude in the mining industry that ‘Our mine is different, and therefore what applies elsewhere, does not apply here.’ This attitude has probably inhibited the development of good design practice and, in the rock engineering field, it is probably true to say that it is only since Codes of Practice to Combat Accidents due to rockfalls and rockbursts have been required by law that many rock engineering personnel on mines have been exposed to the concept of design, rather than the concept of analysis.

Design principles in rock engineering

Bieniawski (1991, 1992) dealt specifically with engineering design in the rock mechanics field. He defined a series of design principles that encompass a design methodology. This methodology represents a thorough design process. The design principles defined by Bieniawski will be dealt with below in the context of rock engineering in mines in which rockfalls and rockbursts occur.

**Design principle 1: Clarity of design objectives and functional requirements**

A statement of the ‘problem’ and a statement of the design objectives, taking account of any constraints that are present, to satisfy this problem, is essential to any design process. These statements clarify the design thinking at the outset. With regard to rockfalls and rockbursts, a design objective should presumably be ‘to ensure that the hazardous effects of rockfalls and rockbursts are prevented’. Since rockfall and rockburst accidents continue to occur in South African mines, and since the rock-related fatality and injury rates have not reduced, it may be concluded that this presumed design objective is not being met.

**Design principle 2: Minimum uncertainty of geological conditions**

As described in the second section above, the rock masses in which mining takes place are very variable, and rock engineering design therefore takes place in an environment of considerable uncertainty. In mining, there is usually an aversion to spending money on geotechnical investigations, with the result that geological conditions are often unknown or, at best, little known. In most South African mines, designs are carried out with inadequate knowledge of the in situ stresses, the rock material strengths and deformation...
properties, and the rock mass behavioural conditions. Minimization of uncertainty will provide an environment in which more confident design can be carried out, and hence will reduce risk.

**Design principle 3: Simplicity of design components**

A key aspect in rock engineering design is the development of a geotechnical model. This may be conceptual, but the key importance lies in the ability to identify the likely behaviour of the rock mass, and the possible mechanisms of deformation and failure. Only once this has been done, can appropriate design (failure) criteria be decided upon, design limits defined, required factors of safety or probabilities of failure defined, a design model (or models) developed, and appropriate design analysis methods decided upon. It is to be noted that all of these steps must be carried out before any analyses are conducted. This will ensure that the design is appropriate, and that it is as simple as possible. Designers often rush into carrying out complicated analyses using sophisticated analysis methods without carrying out the preparatory design thinking. These sophisticated methods often require input data, the knowledge of which is very uncertain. There is therefore a mismatch between the sophistication of the method of analysis and the lack of sophistication of the input data available. The use of sophisticated analysis methods often leads to the false confidence that a good design analysis has been carried out.

**Design principle 4: State-of-the-art practice**

The implication of this principle is that up to date concepts, analyses and methods must be used whenever they are appropriate. In the case of the South African mining industry, there have been many rock engineering research projects carried out with the ultimate aim of reducing the numbers of accidents due to rockfalls and rockbursts. This research has provided many new concepts, analysis methods and support methods, but very few of the research findings have been implemented in the industry. From this observation it would appear that not enough attention is being paid to this design principle by the South African mining industry.

**Design principle 5: Optimization**

Risk integrally involves numerous factors including safety, cost, productivity, seismicity, water, labour, etc. Therefore, to minimize risk, designs must be optimized. In addition, since conditions in which mining is taking place (economic, political, mineral price, depth, seismicity, geology, etc) change over time, it is likely that designs will need to be optimized again when conditions change. An optimized design will result from the evaluation of the output from alternative designs. Monitoring during the progress of mining will provide data that may facilitate design optimization.

**Design principle 6: Constructibility**

If the design cannot be implemented safely and efficiently it does not satisfy this principle and therefore is also not optimized. It will be necessary to review the design and repeat, either partially or completely, the design methodology.

### Design methodology

The design methodology presented by Bieniawski (1991, 1992), corresponding with the design principles, is summarized in the ten steps given in the Table above.

#### The role of analysis in design

There is often a misconception that analysis is design, and many sophisticated analyses, with little underlying validity in terms of input data and failure criteria, are often carried out. As indicated above, analysis is science, whereas design is engineering. It may be observed in the table above that ‘analysis’ occupies only one step of the overall design methodology, and is bridged by Design principles 3 and 4. Analysis is only a tool to obtain answers to the problem that has been posed. If the input information is inadequate, and the concept or geotechnical model (including the interpretation of mechanisms of behaviour and choice of appropriate failure or design criteria) is incorrectly formulated, the answers obtained from the analysis will be wrong. This illustrates that the other steps in the design methodology are in fact much more important than the analysis step—they are fundamental to a successful design, whereas the analysis simply follows from these other steps.

#### The role of review in design

It is good practice to carry out design reviews at particular stages in a design process, or at regular intervals in on-going operations. Measurement and observational data, which should be available in a good design process, will indicate whether the design is performing as expected or desired. If it is not, it may be that the mechanism of behaviour is different from that envisaged, or that the design criteria adopted are inappropriate, or that actual input design parameters are different from those adopted for the design. The design should then be revised or repeated. In simple terms, if unexpected behaviour is occurring, then the design must be changed to obviate such undesirable behaviour.

#### Prediction of behaviour

Engineers are taught to design any structures they may create. The detailed rock engineering design process given above may be simplified to the following:

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**Table: Design methodology**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Statement of the problem (performance objectives)</td>
</tr>
<tr>
<td>2</td>
<td>Functional requirements and constraints (design variables and design issues)</td>
</tr>
<tr>
<td>3</td>
<td>Collection of information (site characterization, rock properties, groundwater, in situ stresses)</td>
</tr>
<tr>
<td>4</td>
<td>Concept formulation (geotechnical model)</td>
</tr>
<tr>
<td>5</td>
<td>Analysis of solution components (analytical, numerical, empirical, observational methods)</td>
</tr>
<tr>
<td>6</td>
<td>Synthesis and specifications for alternative solutions (shapes, sizes, locations, orientations of excavations)</td>
</tr>
<tr>
<td>7</td>
<td>Evaluation (performance assessment, design review)</td>
</tr>
<tr>
<td>8</td>
<td>Optimization (performance assessment)</td>
</tr>
<tr>
<td>9</td>
<td>Recommendation</td>
</tr>
<tr>
<td>10</td>
<td>Implementation (efficient excavation, monitoring, design review, design revision)</td>
</tr>
</tbody>
</table>

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Presidential Address: Rock engineering—good design or good judgment?

- definition of the problem
- identification of possible solutions to the problem
- definition of suitable design criteria for each solution, and decision on the factor of safety (or probability of failure) to be applied
- determination of input parameters for the design process (for example, strength, deformability)
- execution of design calculations to produce a design which satisfies the set criteria.

Owing to the varying ideas of different engineers, this process could result in a variety of designs, with varying degrees of conservatism, all of which will be solutions to the problem. Decisions become easier as the conservatism of the design increases. As an example of this, consider an excavation in a reasonably sparsely jointed, stratified rock mass. Design criteria that could be applicable are beam stability, wedge/block stability, rock mass stability, and possibly stability against stress induced failure. In a civil engineering situation, in which very long-term stability, and hence conservatism, is required, conservatively designed support, possibly using a large factor of safety, will probably easily satisfy the requirements of all of these criteria.

In contrast, mining cannot afford to be conservative. Rock engineering solutions must be close to the stability limit (for example, a factor of safety close to unity) to ensure that costs are minimized. Some failures should occur to prove this, but these failures should not occur unexpectedly. Therefore, unlike civil engineering in which stability must be ensured, mining rock engineers must be able to predict stability (or instability), and this represents a real and exciting challenge. Answers to questions such as the following for mining operations, are not at all easy:

- Will an open stope of this dimension be stable?
- How much will the sidewall move in the next two years?
- To what minimum dimension will I have to undercut this orebody to be sure that it will cave?
- Will a slope of this angle be stable in the open pit in the medium term?

To answer these questions satisfactorily in terms of a good rock engineering design, the rock engineer must have a thorough understanding of the characteristics and behaviour of the rock mass (i.e., minimization of uncertainty), knowledge of the correct mechanism of failure, or potential failure (i.e., a satisfactory geotechnical model), appropriate methods of analysis, experience and, if available, information on precedent behaviour.

In the following sections, two commonly used methods of predicting behaviour will be dealt with. These are firstly, theoretical prediction of behaviour using numerical analyses with a rock mass failure criterion, and secondly, prediction of stability using rock mass classification methods. Finally, the use of rock mass classifications to determine rock mass behavioural parameters will be discussed.

**Behaviour prediction using theoretical methods**

There are numerous sophisticated numerical stress and displacement analysis computer codes available for analysis and prediction of the behaviour of rock masses. Most of the codes have rock mass failure criteria built into them, usually the Mohr-Coulomb and Hoek-Brown criteria, and there is therefore the temptation for users to adopt these criteria whether they are appropriate or not. This would bypass the majority of Design Principle 5 and omit the most critical step in the design process. In addition, the results obtained from numerical analyses are usually very dependent on the input parameters. These values are almost always not well defined, and the values adopted are often based on assumptions and judgement. In most cases nowadays, input parameters are derived from rock mass classification data (this is dealt with in a subsequent section). If no pre-existing or precedent data exist about behaviour at a mine, this theoretical approach may be the only option. However, the power of such theoretical analyses may lead to unfounded confidence in the quality of the predictions. It should be understood that such predictions can be seriously in error.

The success which can be achieved in the prediction of instability or behaviour using numerical analyses depends on the skill of the user, the correct interpretation of the input data necessary, and the use of the ‘correct’ failure criterion (it is very important that Design Principle 3 is followed diligently and that the potential mechanism of failure is correctly taken into account). This usually implies that some form of calibration against observed behaviour is necessary.

As a consequence of issues recorded above, the record of good absolute prediction of behaviour using these techniques has not proved to be very satisfactory. This is illustrated very well by the exercise in subsidence prediction above coal mining that was carried out in Australia (Kay *et al.*, 1991), the ‘new situation’ results of which are shown in Figure 2. It is clear that there is a substantial difference between the alternative predictions and between predicted and actual behaviour. In this example, the quality of input data available, including ‘calibration’ data, was good, and may be considered to have been better than exists in most mining situations. Those carrying out the analyses could also be considered to be expert users of the computer programs. One of the conclusions from this work was ‘mathematical modelling of subsidence can result in spurious predictions and should be undertaken with an appreciation of empirically...
predicted subsidence and the importance of the various (computer) program inputs. The outputs from this exercise also showed that very different results could be obtained by different, competent analysts, using the same sophisticated software.

In experienced hands, numerical modelling can be very useful for determining potential behaviour. It allows sensitivity analyses to be carried out quickly (a recommended approach) and in this way the problem can be bracketed. It is particularly advantageous if some observed behaviour can be back analysed to ‘calibrate’ the numerical model. This will give greater confidence in the predictions made.

**Prediction of stability using rock mass classification methods**

Rock mass classification methods have been correlated with stability of underground openings. For example, the development of the Q System was based on the availability of about 200 case studies of underground openings, and this database has grown to about 1 200 cases. Similarly, correlations between stability and opening size have been established from case study data for the Geomechanics System and the Mining Rock Mass Rating System. Representative graphical relationships for these three methods are shown in Figures 3 to 5. In Figure 5, the size of the opening is indicated by the hydraulic radius, which is defined as the plan area of the opening divided by its perimeter (the span of a square opening is four times its hydraulic radius).

Adjustments are made to the mining rock mass rating to cater for weathering of the rock, for joint orientations, for blasting and for stress.

It is quite clear from Figures 3, 4 and 5 that each approach will predict different stable sizes of openings. The RMR and Q relationships are essentially for civil engineering applications, where stability is desired. The mining rock mass rating relationship is aimed at caving, where instability is desired. It has been found from experience that, using Figure 4, the onset of caving is predicted with a factor of safety of about 0.7. This corresponds with the line between stable and transitional on Laubscher’s stability diagram in Figure 5. Thus, experience and engineering judgement is required in the application of these relationships for prediction of stability.

It is to be noted that, in spite of the availability of many sophisticated numerical analysis methods that could be used for theoretical prediction of cavability, Laubscher’s stability diagram remains the primary tool for prediction of the undercut dimension required for on-going caving.
Rock mass behavioural parameters determined from rock mass classifications

Numerical stress analysis programs require, as input, values of rock mass parameters. Since rock mass parameters are extremely difficult to determine satisfactorily in the field, rock mass classifications have provided a very convenient way of obtaining input parameters. Correlations have been developed between the rock mass quality (Q or RMR) and:

- the rock mass modulus of elasticity
- a rock mass strength, and
- rock mass strength parameters:
  - cohesion and angle of friction
  - Hoek-Brown m and s parameters.

Once the rock mass quality has been determined by classification, these parameters can be obtained from the correlations, and very sophisticated analyses can then be carried out to predict stresses, deformations and failure or potential failure, and to design support requirements. The relationship between rock mass quality and deformation modulus, based on work carried out by Serafim and Pereira (1983), is shown in Figure 6.

This graph shows a significant amount of variability due to the inherent variability in the testing methods and the rock masses. Therefore, the choice of an appropriate value for the modulus is a matter of judgement. Since the predicted deformations may be directly proportional to the modulus, the choice of the wrong modulus will result in the wrong deformation being predicted. However, available to the user now is a ‘automated’ system for GSI classification (Rocscience, 2002), with built-in correlations giving, directly, values for the deformation modulus, the rock mass strength, and the rock mass strength parameters (cohesion, angle of friction, Hoek-Brown parameters). This is an excellent tool for the experienced user, but it does have a significant downside—the implication is that inexperienced users may now obtain rock mass parameters and carry out very sophisticated analyses very easily without paying any attention to a diligent design process.

Rock support requirements determined from rock mass classification

The Q System of rock mass classification was developed specifically for the purposes of tunnel support design. As indicated above, it was based on about 200 case studies of underground openings, most of which contained rock support. It is doubtful whether, with this limited database, the approach could be regarded as a valid design method. However, the developers of the system now have a database of more than 1 200 successful applications, and the approach can now confidently be regarded as a proven design method for rock support in underground openings. It proved satisfactory for the design of support for the 62 m span underground ice hockey cavern used for the 1994 Winter Olympic Games (Chryssanthakis and Barton, 1996). The average rock mass quality Q was 8 and the permanent support consisted of 6 m long rockbolts and 12 m long twin strand cables on a 2.5 m x 2.5 m grid, and 100 mm of steel fibre reinforced shotcrete.

The rock support design tool now available for the application of the Q support design approach is a simple chart correlating rock mass quality, span and recommended support (Barton, 2002). Simplified forms of these Q value...
support recommendations, applicable to mining conditions (i.e., less conservative), are shown in Figures 7 and 8 (Stacey and Swart, 2001).

Examples of successful design, and prediction of behaviour, in rock engineering

The choice of the following case studies to illustrate rock engineering design and prediction of behaviour, is based on some personal involvement in each of them by the author.

Major construction on shallowly undermined land

Old gold mine stopes outcrop in the CBD of Johannesburg. They trend east-west and, in the vicinity of Sauer and Simmonds streets, outcrop some tens of metres south of Frederick Street. In this area the dip of the strata is steep (approximately 80°) towards the south and three reefs in close proximity have been mined. The Chief Inspector of Mines imposes strict requirements on development on shallowly undermined land and this would normally preclude development in the near vicinity of the outcropping stopes. This ‘damaged’ and therefore low cost land presented an opportunity, however, and the development of a major structure across the stope/reef outcrops was successfully motivated (Stacey et al., 1983). The rock engineering challenges in this project were:

- there was uncertainty regarding the extent of mining on the reefs, but it was believed that almost complete extraction had taken place on two reefs. The mine plans indicated that the third reef had been disturbed by a major dyke intrusion
- the conditions in the old stopes were unknown
- crown pillars had been left at surface, and it was possible that, as a result of their removal during the basement excavation, ongoing closure could take place across the stopes
- the dip of the reefs reduced significantly below about 80 m from surface and there was the risk that collapse or bulk closure of the three stopes could occur in this depth range in the future, potentially affecting the hangingwall rock mass
- since the stopes were potentially open, any construction on the footwall side was effectively on the edge of a cliff, and therefore the stability of this ‘slope’ had to be assured.

The situation is illustrated diagrammatically in Figure 9. A thorough site investigation was carried out by means of boreholes, and by access and inspection of some of the old workings to a depth of about 45 m below surface. The information obtained was correlated with information on the old mine plans. The footwall ‘cliff’ was investigated by means of an augered shaft to a depth of 25 m and a small inspection tunnel driven southwards towards the stopes.

The stabilization solution chosen was the construction of in-stope dip concrete pillars alternately 35 m and 60 m deep, with a horizontal containing pillar at the second level, about 60 m below surface, and a concrete crown pillar at surface. Long pillars were required on each boundary to ensure that loose material in the stopes was contained. The containment of the fill was required to maintain the integrity of the stope footwall and hangingwall surfaces. In addition to containing the fill, the functions of the pillars were to control the closure, and to prevent ride movements. Numerical design stress analyses were carried out to determine an appropriate width and spacing for the pillars, to evaluate their performance in the event of a collapse in the old workings below the stabilized zone, and to evaluate the stability of the footwall cliff.

During construction regular inspections were carried out to ensure that the conditions taken into account in the design remained appropriate.

It was recommended that the building be designed as three independent sections from a structural point of view, with the ‘joins’ corresponding with the traces of the reef outcrops. This would allow relative movement to take place without damaging the building in the event that any closure or ride movements occurred in the stopes.

The building was completed in 1983, and the design of the stabilizing measures subsequently served as a precedent for the construction of two further major developments on adjacent undermined land.

Large span tunnels at shallow depth

The Eastern Distributor Tunnels were constructed to ease the traffic flow in Sydney, Australia, in time for the Olympic Games in 2000. These tunnels were constructed in an urban area at shallow depth, with the maximum tunnel span of 24 m exceeding the depth from surface to the crown of the tunnel (Pells, 2002). The design of the rock support for these tunnels could rely on the precedent of the Sydney Opera House car park, in which spans of up to 17.4 m were excavated at very shallow depth (Pells et al., 1991).

Since the tunnels were to be excavated in an important urban area, significant site investigation took place and, in addition, the general characteristics and properties of the sandstone were well known. It was also known that a high horizontal in situ stress field was present in the area. Design could therefore be undertaken with reasonable confidence regarding the input parameters. However, because there was variability in the parameters, it was appropriate design...
practice to carry out a sensitivity study to determine the more critical factors, and this was done.

The mechanism of behaviour on which the design was based was that of the arching of a ‘cracked’ beam. The design involved the calculation of the rock support required to reinforce the beam such that a composite beam was formed and that the sag would be limited to a defined maximum value. The function of the rockbolt support was to create this composite beam by preventing or limiting shear on bedding planes by the following: introducing resistance in the form of dowel action; prestressing the rockbolts to increase the normal stress and hence the shear strength; an increase in the normal stress as a result of dilation on the joint; and an increase in the normal stress as a result of the axial force developed in the rockbolt from lateral extension (Pells, 2002). The design process was therefore logical and thorough and resulted in a rockbolt and fibre-reinforced shotcrete support system. The rockbolts and shotcrete were integrated using specially designed spider plates.

The success of the design method is perhaps best illustrated by the performance of the Sydney Opera House car park (Pells, 2002), illustrated in Figure 10. The design prediction curve represents the maximum deflections predicted and the bars represent the measured deflections. There was similar good correlation between predicted and observed deformations in the case of the Eastern Distributor tunnels. It is clear that this is a ‘correct’ design.
mesh reinforced shotcrete. This is similar to a very deep civil engineering basement excavation, and requires thorough design of the support. In this case, detailed design stress analyses were carried out to define the required lengths and capacities of the cable anchors, whilst ensuring that the behaviour of the pit walls remained regressive (movements always stabilizing) and not progressive (movements accelerating). The longest anchors installed were 45 m long, spaced 2 m vertically and 3.3 m horizontally. The appearance of the pit at an intermediate stage of mining is shown in Figure 11.

Monitoring of the deformation of the pit walls during excavation was a very important activity, to ensure that the actual deformations did not exceed those predicted by the design analyses. This was important from a safety point of view as well as from an economic point of view, to ensure that mining could continue to the full depth planned. The monitoring results showed that, except in very localized zones, for which there were geological explanations, the actual deformations were less than those predicted.

The pit was designed to be mined to a depth of 95 m, but mining stopped, for economic reasons, at a depth of 78 m. The mining method and the design were both proven to be successful.

In this case study, and the above two case studies, the design process was thorough and followed that identified above.

Fracture zone around a circular tunnel

Under high stress conditions, a circular opening usually develops sharp notches as a result of stress-induced fracturing of the rock. Owing to their sharp-pointed geometry, these notches are colloquially known as ‘dog ears’. The dog ears form on opposite sides of the circular opening and the diametral line drawn through them is perpendicular to the major stress acting normal to the axis of the opening. The appearance of a dog ear in a bored tunnel is shown in Figure 12.

Martin (1993) describes an experimental tunnel that was mechanically excavated for Atomic Energy of Canada Ltd as part of their investigations for nuclear waste disposal. This is a superb case study in which rock material and rock mass parameters, and in situ stresses, were known from measurement and testing to a high degree of confidence. Since rock properties and in situ stresses are well known, it is possible to use these data to predict the development of failure around the tunnel using different criteria, and to compare these predictions with the measured geometry and extent of failure. This was done by Martin (1997) and two of his results are compared with those of Wesseloo and Stacey (2000) and Hajibolgradamaj et al. (2002) in Figure 13. The first potential failure prediction is based on an elastic analysis using a Hook-Brown failure criterion. The second is the potential failure zone predicted using a constant deviatoric stress criterion based on an elastic analysis. The third is a non-linear analysis in which an extension strain criterion was used. The fourth is a prediction in which a cohesion weakening-frictional strengthening model was used. The actual profile of the observed fracture zone is shown superimposed on each of these results. It is clear from these examples that absolute prediction (that is, without knowing the actual behaviour) is a difficult problem even when all the required input parameters are well known.

Support design in gold mine stopes and tunnels

Gold mining in South Africa was taking place at depths in excess of 2 500 m as long as 50 years ago, and rockbursts were being experienced in these mines at least 80 years ago. In a 1980 publication (Heunis, 1980), the following statement appeared: ‘… a reduction of the rock-fall hazard, which remains a complex problem, could best be achieved at this stage by an improvement of the stope support in the immediate vicinity of the face …’ Therefore, high stress, seismic conditions and the requirement for improved support at the stope face are nothing new to gold mining in South Africa. The fatality rates in South African mines over the past almost 20 years are plotted in Figure 14, and illustrate that there has been no improvement in the fatality rate in gold and platinum mines over more than the past decade.

Design Principle 5 (optimization) requires review of design, and Design Principle 6 (implementation) requires monitoring, and revision of design if necessary. Since design conditions have been known for a long time, and since accident rates have not decreased for about 20 years, it can be stated that 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.

Conclusions

The title of this paper asks whether rock engineering involves good design or good judgement. The information presented in the paper shows that a good design can be achieved by diligently following the correct design process, and this is demonstrated by several case studies. In particular, the identification of the mechanism of behaviour, of the appropriate failure or design criterion, and of the appropriate design analysis method, is very important in achieving the correct design.

In many situations, however, there is considerable variability in the input parameters, and the estimation of...
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appropriate input data usually involves engineering judgement. The estimation of rock engineering parameters is commonly based on rock mass classifications, and their application inherently involves engineering judgement. Good rock engineering therefore must involve both good design and good judgement.

Information in the paper illustrates that incorrect results may be obtained when inappropriate criteria are adopted, and that variability in input parameters may also significantly affect the output. The result will be that the predictions of behaviour (such as deformations, onset of failure, collapse, etc.), which are frequently required in mining situations, will be wrong. In prediction of behaviour, errors of judgement, errors in the identification of the correct mechanism of behaviour, and errors in the choice of input parameters and failure criteria, cannot be masked by a sufficiently large factor of safety. Successful, quantitative prediction is difficult and a real challenge for rock engineers, and demands very diligent attention to the principles involved in the design process.

References


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Cementation Mining Skanska—s Rowland Shaft receives five NOSA platinum stars

Cementation Mining Skanska has become the first contractor in Africa to be awarded five NOSA platinum stars for safety at one of its sites. The award was made for Cementation Mining Skanska’s Rowland Shaft at Lonmin Platinum’s Western Platinum Mine in the Marikana district in the North West Province.

Cementation Mining Skanska is sinking a 1,2 km decline with a 10 percent dip. The work includes six station breakaways, a conveyor and trackwork. The belt installation is running concurrently with decline sinking and is more than 50 percent completed. A dam and workshop has been constructed on 26 level.

The award comes as a result of much hard work and careful planning by Cementation Mining Skanska’s Master Sinker Corrie Vorster, who introduced the new NOSA safety system at the shaft. ‘The way we achieved the award was through training, training and training,’ says Vorster.

In the first four months of the 2001, prior to the implementation of the new system, Rowland had two reportables, two lost times and two dressing cases. With a Disabling Injury Incident Rate (DIIR) of 7.0 the site could only qualify for a one star rating, resulting in an unsatisfied client.

To meet these problems head-on, the new integrated system was established focusing on safety, health, environment and quality. The methodology involved risk assessment, examining procedures, providing a lesson plan, training and conducting competency assessments, all of which included health, environment and quality control.

To implement the new system, it was necessary to revisit the whole risk management programme and to apply the necessary changes.

The new system was started in August 2001 and by August 2002 the mine was awarded three stars. For the period September 2002 to March 2003 it received the much-coveted five star platinum award.

NOSA’s Five Star System is a health and management system that enables companies to control risks and improve their performance. NOSA Green Stars are awarded to companies that comply with specific health and safety management standards. Platinum stars are awarded when a company successfully implements the Integrated Five Star System, which incorporates the management of safety, health and the environment.

Sasol director appointed chairperson to the National Science and Technology Forum

The NSTF Executive Committee and its stakeholders are proud to announce the appointment of John Marriott as the new chairperson of the NSTF from 1 June 2003. Marriott succeeds Dr S.J. Lennon, who successfully served as Chairperson of the NSTF for the past three years.

Marriott, is currently a director of Sasol Technology and is also the general manager of Sasol Ltd. A chemical engineer by training, he has spent several years at the highest level in the corporate world and has simultaneously maintained an outstanding reputation in the technical world. He has forged close associations with higher education institutions in South Africa, where his management skills and technical expertise helped provide marked insights into alliances between education and industry to ensure the provision of technical and scientific skills.

The NSTF welcomes Marriott as the chairperson of the NSTF and looks forward to his expertise in issues of science, engineering and technology to ensure continued growth of the discipline in South Africa. Marriott stated that he was honoured by the appointment and looked forward to being able to contribute to the activities of the NSTF.

The NSTF wishes both Lennon and Marriott success in their new challenges in uplifting the economic growth through science, engineering and technology.