Risks associated with rockpasses in deep-level tabular mines based on historical pass performance

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Synopsis

Problems with the stability and performance of rockpasses in deep-level mines are common. This paper presents the results of an investigation into the recorded performance of rockpasses in deep-level gold mines. Records relevant to the geological environment in which the passes are excavated, their excavation details, and their historical performance are not at all well documented on mines. In general, the quality of data available from mines is poor. The investigation showed that very large spans frequently developed in passes during use, and that rock mass quality, the orientation of the pass with respect to the dip of the strata, and the magnitude of the stress acting normal to the axis of the pass were the main factors of influence. From the historical information obtained, the risks of instability in rockpasses are identified.

Introduction

Rockpasses are a key element of any mine's operations, but very little attention is given to their design compared with the design of other elements of the mine. Design, in this context, includes location, orientation, size, shape, length, method of excavation, support, system geometry, and operating principles. Other factors may also be important in specific circumstances, for example storage capacity and operating life required.

The literature on rockpasses is not very extensive, but much of it contains descriptions of failures of passes and rockpass systems. In many cases these failures have significant cost implications, both directly in terms of rehabilitation or replacement, and indirectly as loss in production. It is doubted whether, at the planning and design stage, these potential operating costs and their implications are considered.

A brief review of the generic problems experienced in rockpasses was given by Joughin and Stacey (2004), and correlations between various parameters were determined. In this paper, the analysis is extended and the risks are quantified.

Investigation of the performance of passes in deep-level gold mines

Research has recently been carried out into the recorded performance of passes in deep-level gold mines. The objectives of this research were:

- to quantify the stress regime
- to identify the geotechnical environments and their influence on pass stability
- to determine the rate of pass scaling, and
- to determine the influence of pass diameter on stability.

In order to do this, information was collected from several of the deeper gold mine shafts in the Far West Rand mining region and input into a database. It was hoped that the collection of real data would facilitate the correlation of pass behaviour with some of the factors of influence described in the section above.

Sources of data

A database of information on the ore passes was obtained from the following mines: Western Deep Levels, Elandsrand, Deelkraal, West Driefontein, East Driefontein, Kloof, Libanon, and Leeudoorn. A checklist of required information was compiled, which contained all factors that would be expected to influence the condition of passes. Disappointingly, it was found that very little readily accessible, documented information is kept on record by the mines. However, through discussions with shaft personnel, surveyors, geologists and rock engineering personnel, some useful information was

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obtained. Information on more than 200 individual passes was obtained (a pass was considered to be the pass leg between levels), although not all of the data were satisfactory. Quantitative information obtained was of estimated rather than measured accuracy. No information on passes located at depths of less than 2 000 m was included in the database.

Since very little quantitative measurement of data has been carried out on mines and since very little documentation of behaviour has taken place, the quality of data obtained was in general not good. There was substantial variation in the quality of data provided for passes at the different shafts, and consequently the data received were rated on the basis of their relative quality.

The geological information provided by the mine was used to identify the rock formations traversed by the pass and whether a major geological feature was intersected or not. The confidence in this assessment was used to grade the quality of geological information as good, reasonable or poor.

The information provided by shaft personnel was graded in a similar manner. Generally, when shaft personnel had been working with the passes for most of the life of the passes and knew their performance and condition intimately, the information was regarded as good. Conversely, in a few cases the shaft personnel had not been working on the passes for long enough to provide information that was acceptable, and the information was graded as poor.

The quality gradings from the geological information and the shaft personnel were assessed for each shaft and the poorer of the two gradings was recorded in the database. Only information having reasonable and good quality gradings has been used in the analyses below. The following subsections include the more reliable information obtained for the deep-level passes.

Geotechnical information

Geological sections through the shafts were obtained to determine the rock formations in which the passes are situated, and whether a geological feature intersected the pass. Detailed geological sections, plotted to scale, with the passes drawn in, was available from several of the mines. In other cases only the shaft geological logging was available. Geological descriptions of the rock formations were obtained from records and through discussion with geologists and rock engineering personnel. The weakest horizon traversed by the pass, and the predominant dips and dip directions of the Witwatersrand strata were recorded for each shaft. Information on the presence and amount of water flowing in each ore pass was provided by shaft personnel.

Unfortunately, rock mass quality is rarely quantified on gold mines and consequently this information was not available—a substantial amount of information is usually available on strength properties for various types of rock, but very little information is available on jointing in the rock mass. Since the frequency and surface quality of joints have a considerable effect on the strength of the rock mass, it is necessary to take the jointing into account. For the purposes of the research investigation into pass performance, this was done in the following manner: the geological descriptions for the different rock formations were analysed and six general rock mass types were identified. Based on the descriptions of these types, a rock mass rating (RMR) value (Bienawski, 1989) was determined for each rock mass type (Table I). Two Ventersdorp lavas were identified—a competent lava based on the Alberton lavas, and a weak tuffaceous lava based on the Westonaria lava formation. Stratigraphic sequences containing quartzite varied from a highly competent siliceous quartzite with large bedding spacings, to transition zones or zones of argillaceous quartzites, with alternating shale layers and argillaceous partings, and therefore three different quartzites were identified. All the shale formations were grouped together as a single rock type. The relative extents of the different rock types traversed by the passes is illustrated in Figure 1.

If the pass intersects a major geological feature, it is expected that it will be more jointed at the contact and that these joints may be altered, downgrading their condition. The RMR was therefore downgraded if the pass intersects a major geological feature.

The presence of water can have an effect on the stability of passes by reducing the shear strength and confining stress on the joints. Although no groundwater was reported in any

Table I

Geotechnical description of rock types and rock mass rating

Rock type	Rock class	UCS rating	Strength	Discontinuities	Condition of discontinuities	Rockmass description	RMR
Lava 1	Igneous	300	15	35	25	Very competent lavas, with minor jointing	90
Lava 2	Igneous	150	12	18	10	Weak lavas with tuffacious layers	55
Quartzite 1	Sedimentary	200	13	35	25	Siliceous quartzite, very competent	88
Quartzite 2	Sedimentary	180	12	27	20	Quartzites, with alternating siltstone and quartzite Quartzite layers are more prominent and generally siliceous	74
Quartzite 3	Sedimentary	170	12	27	10	Argillaceous quartzites or weak conglomerates, with alternating siltstone and quartzite. Well bedded, weak joints with argillite partings. Transition zone between shale and quartzite	64
Shale	Sedimentary	140	11	18	10	Dark grey to blackish silty shale often laminated. Lamination outlined by siltstone layers. Thick bands of argillaceous quartzite with shale bands.	54

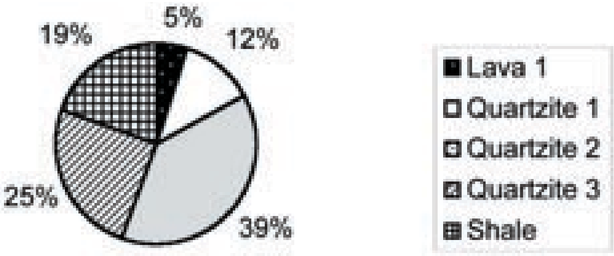

Figure 1—Relative extent of occurrence of rock types in passes

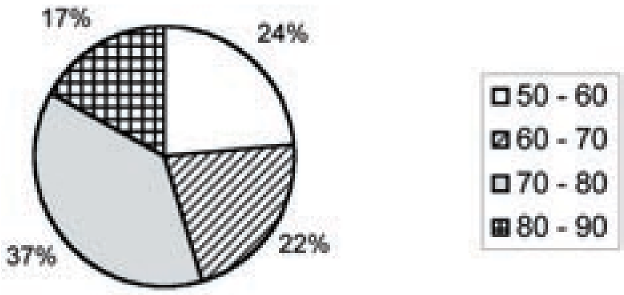

Figure 2—Ranges of RMR used for evaluation of pass data

of the passes, mine water was frequently reported. Mine water will have less influence on the rock mass than groundwater, since it is external to the rock and the joints are less likely to be saturated. If it was reported that mine water occasionally flowed down the pass, it was treated as 'completely dry' in the RMR system and the RMR was not adjusted. Where large quantities of mine water were reported, this was treated as 'damp' and a value of 5 was subtracted from the RMR.

Four ranges of RMR were chosen for the evaluation of the pass data and the distribution of these ranges is shown in Figure 2.

Orientation of passes relative to geological strata

Shaft station plans were obtained from the survey departments on each mine for the relevant passes. The coordinates of the top and bottom of each pass were recorded, and this allowed the orientation and depth of the passes to be determined. Where possible, the dates of excavation of the passes were obtained. Records of this information were not readily available and were only provided with reasonable accuracy for recently excavated passes.

The angles between the passes and the geological strata were calculated and their distribution for the passes evaluated is shown in Figure 3.

Methods of excavation, pass sizes, pass lengths and support of passes

Ninety-six per cent of the passes analysed had been raise-bored and the remaining 4% had been raise-bored and sliped. A number of rockpasses that were excavated by drill and blast were investigated, but these passes were all very old and the data was poor and therefore not used. The most common excavated diameter was 2.1 m, but several other sized passes were recorded. The distribution of pass diameters is shown in Figure 4.

The lengths of the passes were calculated from the coordinates of the top and bottom of the pass, taking into account its orientation. The distribution of pass lengths involved is shown in Figure 5. Although lengths varied considerably, most were less than 200 m in length.

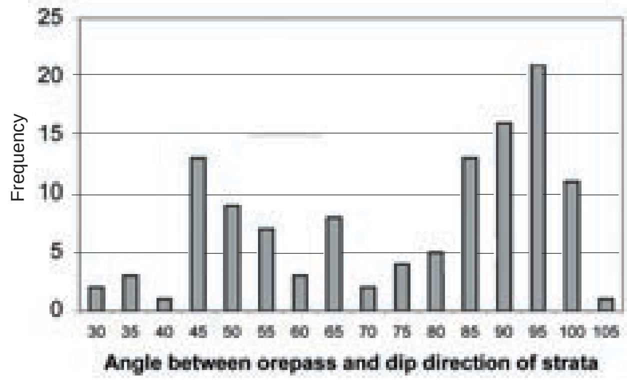

Figure 3—Distribution of angles between pass orientations and strata dip

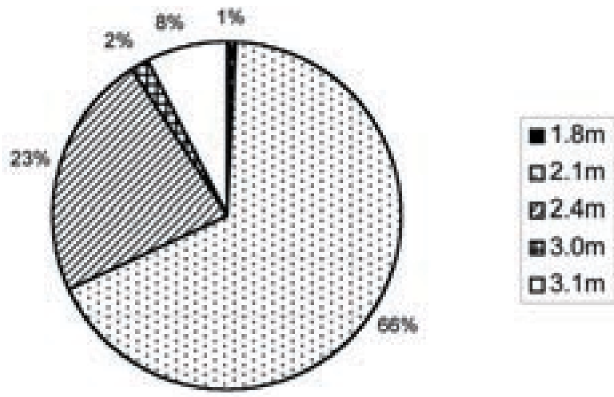

Figure 4—Excavated pass diameters

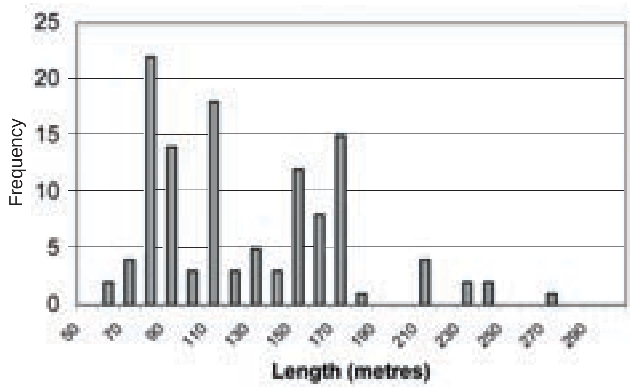

Figure 5—Distribution of pass lengths

Most passes (87%) were unsupported. It appears that this trend is changing and more passes are being supported. Details of the support originally installed, and during rehabilitation, were provided by shaft personnel. Installed support recorded included cast concrete linings (7%), precast concrete segments (3%) and long anchors (3%).

In situ stress information

In situ stress information was obtained from the stress measurement data recorded in a stress measurement database (Stacey and Wesseloo, 1998). Stress gradient tensors were calculated from the measured stress tensors and depth of measurement, and oriented to the survey coordinate systems used by the mines. Only stress measurements that were graded to be of satisfactory quality in the stress measurement database were used. Stress gradient tensors were then allocated to each of the shafts, by proximity of measurement. Unfortunately very few reliable stress measurements have been made, and those used in this analysis were often carried out a considerable distance from the shaft passes to which they have been applied.

The local stress field for each pass was determined by multiplying each term in the stress gradient tensor by the depth of the bottom of each pass. The depth was determined by the difference between the pass elevation and the collar elevation of the surface shaft. The resulting stress tensor was then rotated so that the z′-axis was oriented along the axis of the pass. Stresses on the new z′-axis were then ignored and the two-dimensional stress field perpendicular to the pass or z′-axis was analysed (σ_x,σ_y,σ_{xy}). The major subsidiary principal stress (σ_1) in this plane was then calculated. The distribution of the major subsidiary principal stress values used in the pass evaluations is shown in Figure 6.

The maximum tangential stress acting on the rockpass can then be determined as follows:

$$\sigma_\theta = 3\sigma_1 - \sigma_3$$

This represents the maximum stress on the wall of the pass, which may cause damage should it exceed the strength of rock. The distribution of σ_θ is given in Figure 7.

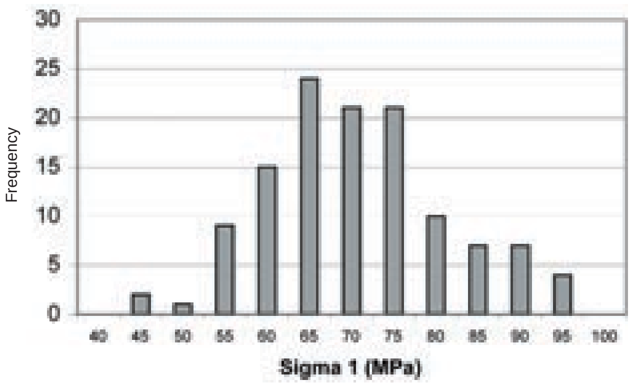

Figure 6—Distribution of major subsidiary principal stresses relevant for the passes evaluated

Stress levels are related to the depth of mining. For information, Figure 8 illustrates the range of depths at which the passes evaluated were located.

Rockwall condition factor (RCF)

The rockwall condition factor (RCF) is the ratio of the maximum tangential stress to the strength of the rock (Jager and Ryder, 1999):

$$RCF = \frac{3\sigma_1 - \sigma_3}{F\sigma_c}$$

where σ_c is the uniaxial compressive strength of the rock and *F* is the factor representing the condition of the rockpass. Since the orientation of the orepass relative to the strata has a significant effect on the behaviour of the rockpass, the value of *F* was chosen to reflect this. In the massive competent lavas and quartzites, *F* =1 in all cases. For the remaining rock types, an angle of 80° was used as a threshold value:

$$Angle > 80° : F = 1$$

$$Angle < 80° : F = 0.7$$

The distribution of RCF is shown in Figure 9.

Performance and condition of passes

A history of the performance and condition of passes was obtained from discussion with shaft personnel. When exact dates of excavation were not available, they could often be

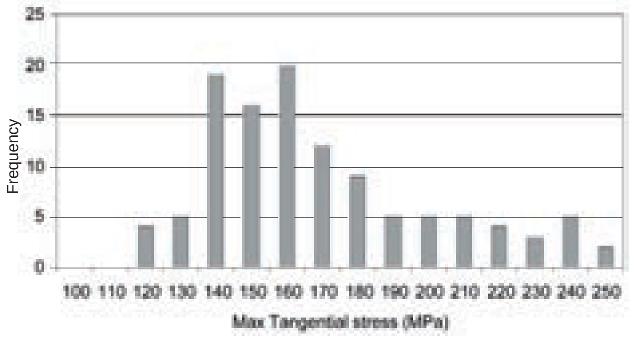

Figure 7—Distribution of the maximum tangential stress acting on the rockpass

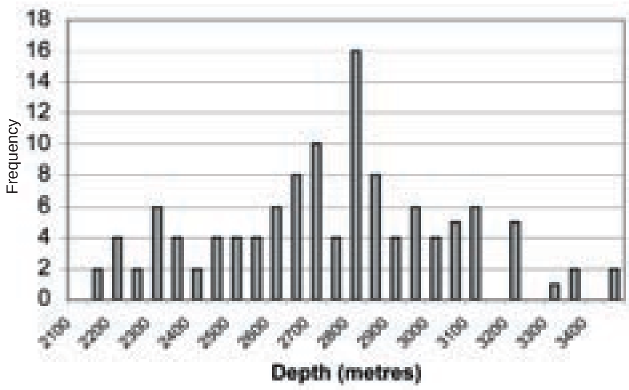

Figure 8—Distribution of depth range of passes

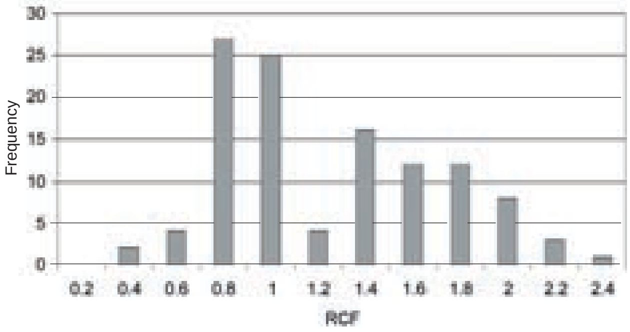

Figure 9—Distribution of the rockwall condition factor (RCF) for passes

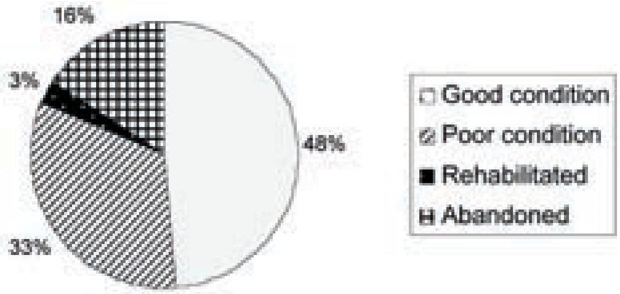

Figure 10—Status of passes

Table II

Status of passes by length

Status	Length (m)
Good condition	6350
Poor condition	4595
Rehabilitated	392
Abandoned	3074

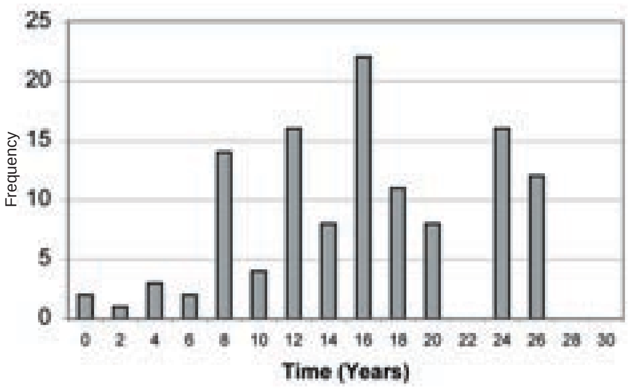

Figure 11—Time that passes have been in use

obtained approximately from the shaft personnel. The dates of abandonment and rehabilitation of passes were obtained. The status of the passes is illustrated in Figure 10.

More than 50% of the passes had stability problems, and 16% had been abandoned. The status of passes is shown in Table II, compared by summing the lengths of individual passes.

The time that passes have been in use was calculated from the excavation date to December 1998, or until the pass was abandoned or rehabilitated. The distribution of time in use is shown in Figure 11.

The scaling of passes is rarely measured on mines, and if it is, this information did not appear to be kept on record. Of all the passes for which information was obtained, most of the shafts had at least one measurement of scaling, but measured data on scaling was provided for only about ten passes. The shaft personnel provided estimates of scaled size for the remaining passes from their own observations. Scaling is colloquially known as 'dog earing' owing to the shape of the breakouts formed. The span of the dog earing (defined as the distance from the tip of one dog ear to the tip of the other), which was reported by shaft personnel, was recorded in the investigation. Figure 12 and Figure 13 show the distribution of this parameter. In Figure 12, the dog ear spans were grouped into four ranges, which represent the extent of damage. Forty-three per cent of the passes analysed had negligible damage, 19% had substantial scaling, and 38% had excessive scaling.

The fact that the maximum span of about 60% of the passes have doubled, or more, in size and that more than 20% of the passes have been abandoned, illustrates the severity of the pass problem at deep level.

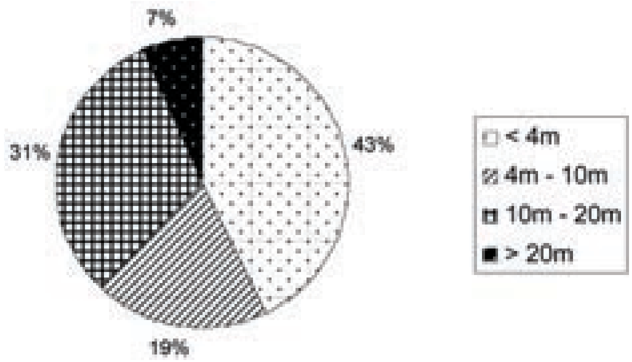

Figure 12—Distribution of ranges of dog ear spans

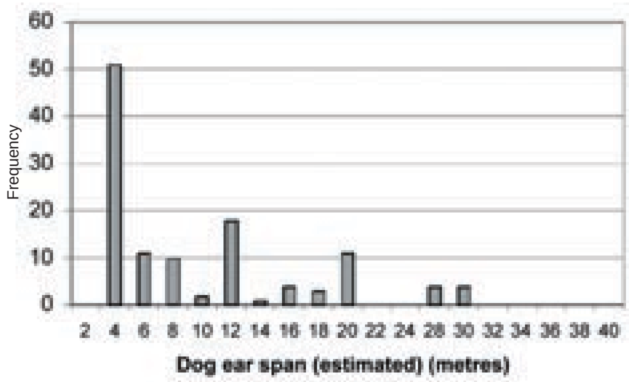

Figure 13—Distribution of estimated dog ear spans

Probability and extent of scaling

Initial attempts to correlate pass performance with influencing factors were unsuccessful, and it was only after the rock mass quality was quantified (RMR) that any reasonable correlations could be obtained. RMR was used in all of the analyses. Owing to the fact that most of the data was based on opinions or estimated values, the quality of correlations is poor.

Several parameters were analysed to determine their effect on pass stability, all passes for which there was reasonable or good quality data being used in the analyses. The passes were grouped into ranges of RMR, and trends were analysed within each of these ranges. Passes that had been in use only for a short period of time, (<3 years) were excluded from the analyses.

Data from 114 passes were used to determine whether there was any relationship between the excavated pass diameter and development of scaling. In this analysis the original diameters of the passes were plotted against dog ear span. No obvious trend was observed from this analysis and it would appear that, once a pass has started scaling and becomes enlarged, the original diameter is no longer of any consideration.

To determine whether it would be possible to evaluate the rate of scaling in passes, analyses were carried out using data from 119 passes. Time in use was plotted against dog ear span for each range of RMRs, but no obvious trends were observed. This indicates that there probably are other factors that have a greater influence on pass stability. The rate of scaling could not be determined from this analysis.

From the analyses carried out, the main factors of influence appear to be the maximum tangential stress acting on the pass and the relative orientation between the pass and the strata. These two factors are dealt with below.

Table III

List of distributions of maximum span grouped by rock type and angle between the rockpass and the dip direction of the strata

Category	Mean	Standard deviation	Distribution	N	Length
Quartzite 1 & lava1	3.05	0.22	None	19	2010
Quartzite 2 (angle>80)	3.38	0.71	Weibull	25	2737
Quartzite 2 (angle<80)	8.48	4.42	Weibull	20	2669
Quartzite 3 (angle>80)	13.22	10.89	Weibull	9	1280
Quartzite 3 (angle<80)	20.11	5.97	Weibull	18	2084
Shale (angle>80)	10.23	4.08	Weibull	13	1845
Shale (angle<80)	14.20	3.88	Loglogistic	10	1108

Table IV

List of distributions of maximum span grouped by ranges of RCF

Category	Mean	Standard deviation	Distribution	N	Length
RCF < 0.7	3	0	None	14	1404
RCF 0.7–0.9	4.88	2.44	Exponential	33	3537
RCF 0.9–1.4	10.35	7.14	Exponential	31	4364
RCF >1.4	15.89	6.87	Weibull	36	4428

Probability distributions for the various rock types and the relative orientation between the pass and the strata

The geotechnical descriptions of the various rock types are provided in Table I. The data was grouped into the various rock types and sorted by the angle between the dip direction of the strata and the orepass. For the very competent lava 1 and quartzite 1, it was found that no problems were being

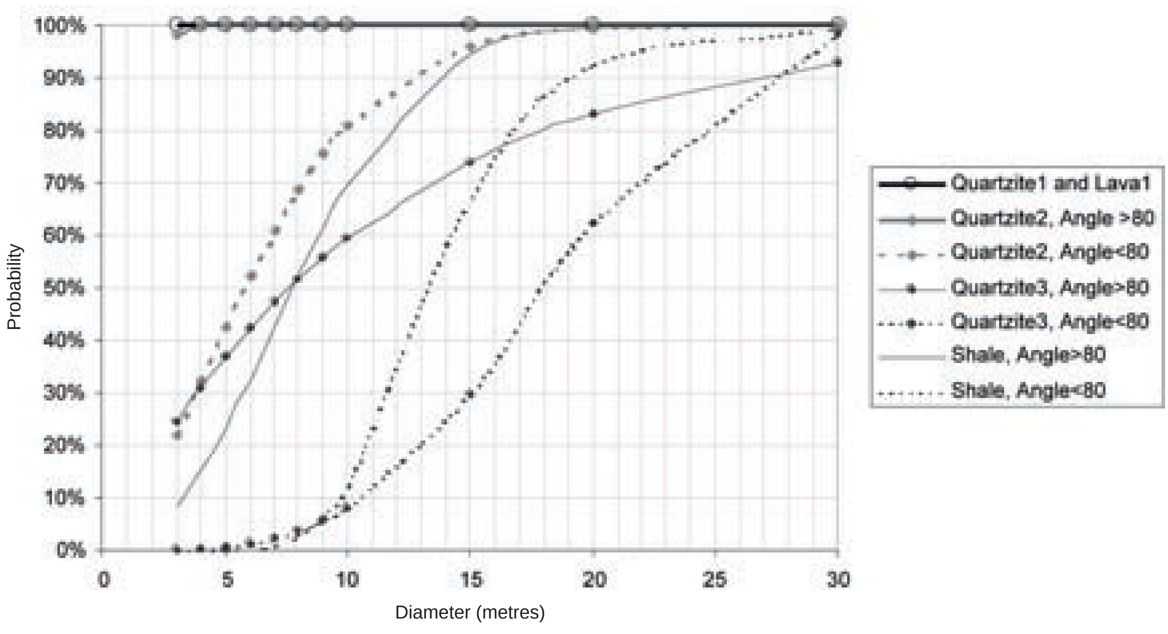

Figure 14—Probability of a rockpass not exceeding a given diameter for various rock types and favourable versus unfavourable orientations

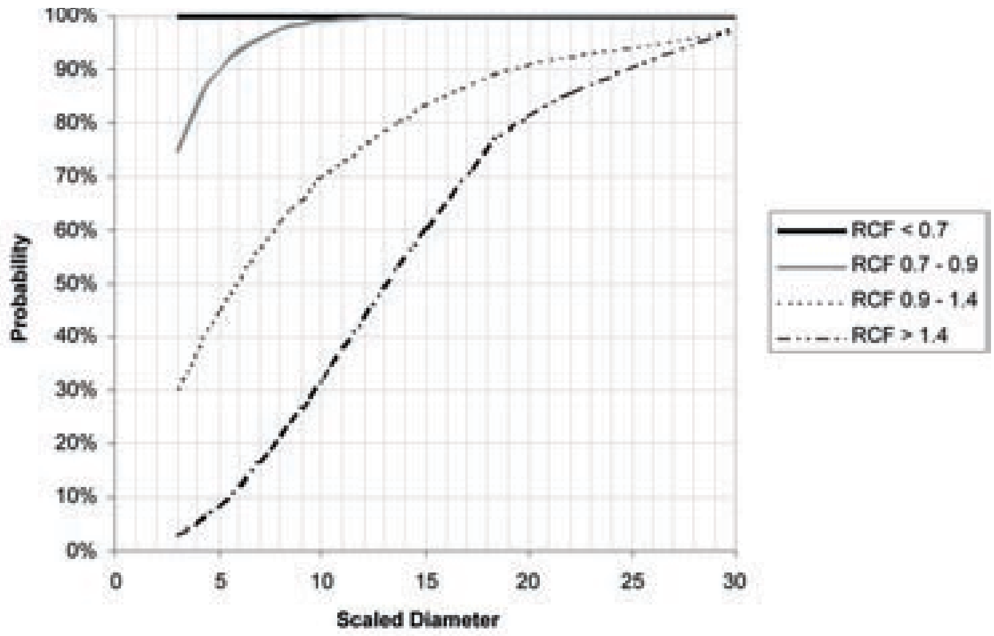

Figure 15—Probability of a rockpass not exceeding a given diameter for ranges of rockwall condition factor (RCF)

experienced. Both rock types are competent and massive (RMR > 80) and are not affected by the orientation of the strata. With Quartzite 2, an angle of 80° was found to be the threshold for deterioration in the performance of rockpasses. The weaker rock types did not have an obvious threshold for this angle, but there is a definite deterioration in performance with smaller angles. Distributions were fitted to the data in each of these groupings using the statistical program BESTFIT (Table III) and the probability of a rockpass not exceeding a given diameter was plotted in Figure 14.

Probability distributions for ranges of rockwall condition factor (RCF)

The RCF takes into account the ratio of the maximum tangential stress (σ_θ) to the strength of the rock material. The strength of the rock material is downgraded if orientation of the pass relative to the strata is unfavourable. The data was therefore sorted by the RCF value and the following critical values were found to be suitable to group the data: 0.7, 0.9, and 1.4. For each group distributions were fitted using the program BESTFIT. Table IV shows the distributions obtained for each group and the probability of an orepass not exceeding a given diameter are given in Figure 15.

Indicative extent of scaling

Probabilities of not exceeding a given rockpass size in different rock types have been dealt with above. The overall data collected, on which this analysis was based, showed a clear trend—as the RMR increases and the angle between the pass and the strata approaches 90°, the passes become more stable. These trends are shown in Figure 16. It can be seen that the slopes of the trend lines become progressively steeper as the rock mass quality improves. The change in slope has been used to derive the following simple equations that will allow indicative estimation of the maximum spans that can be expected to develop in deep level unsupported rockpasses in Witwatersrand gold mines.

$$DS = (ARS - 87)/x \quad (\text{for } ARS \le 87)$$

where

DS is the indicative dog ear span in metres
ARS is the angle between the rockpass dip and the strata dip in degrees
$x = -ae^{(RMR - 36)/b}$
RMR is the rock mass rating
a = 0.07

and

b = 9.8

From the above equations, for example, the predicted maximum span of a rockpass bored at an angle of 60o to the strata in a rock mass with a rock mass rating of 60 is 33 m. It must be noted that the quality of data in Figure 16 is poor and therefore such predictions must be regarded as indicative rather than quantitative.

Conclusions

Several conclusions can be drawn from the research investigation into the performance of rockpasses at deep levels:

- the lack of measurement, observation, recording and documentation of data on rockpass performance in deep gold mines is very disappointing. Rockpasses are critical elements of the rock handling system, and as a result of the lack of quantitative data, no really satisfactory predictors of performance at very deep levels could be developed

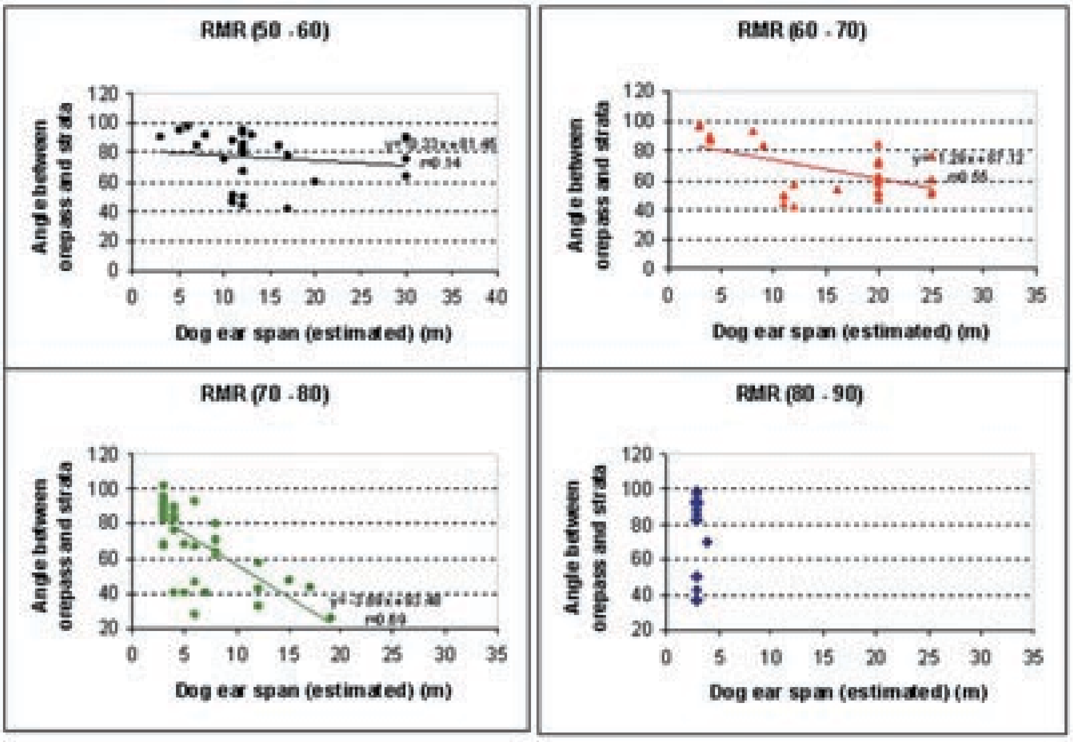

Figure 16—Relationships between pass orientation relative to strata dip and dog ear spans

using the available information, the probability of a rockpass exceeding a given diameter was determined for the various rock types and for favourable and unfavourable pass orientations relative to the strata. This exercise showed that for competent, massive rock (quartzite 1 and lava 1) no major problems have been experienced. In quartzite 2, minimal problems are experienced if the pass is oriented favourably, but for unfavourably oriented passes, the probability of the pass diameter not exceeding 5 m is 40% and 10 m is 80%. For favourably orientated passes in the weaker rock types, the probability of the diameter not exceeding 5 m is 36% (quartzite 3) and 23% (shale), and 10 m is 60% (quartzite 3) and 70% (shale). This switch indicates that severe scaling is less likely to start in quartzite 3 than shale, but if it does start, it is likely to scale more. These values do indicate a high risk of experiencing problems, but the risk is certainly higher if the passes are not orientated favourably with respect to the strata

using RCF, the effects of stress, rock strength and orientation of the pass relative to the strata are all taken into consideration. The probability of a rockpass exceeding a given diameter was determined for various ranges of RCF. If the RCF is less than 0.7, the risk is negligible. For RCF values of between 0.7 and 0.9, the risk is relatively low, with the probability of the pass diameter not exceeding 5 m and 10 m being 90% and 99%, respectively. The risk increases significantly as the RCF reduces.

These results can be used for design purposes and provide a means to determine the risks involved. They also highlight the fact that severe problems are experienced in many deep mine passes. This re-emphasises the need to design suitable linings for passes in weak material or high stress environments and to build in redundancy to allow for rehabilitation of passes without disrupting production.

Acknowledgements

Some of the work reported in this paper was carried out for the Deepmine Research Programme, and permission to publish this information is acknowledged.

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