Predicting the stability of rockpasses from the geological structure

by T.R. Stacey*, J. Wesseloo†, and G. Bell†

Synopsis

Instability in rockpasses at deep levels often initiates as a result of stress induced fracturing of the rock on the walls of the pass. This may then progress to a stage at which the geological structure of the rock mass becomes dominant and permits large joint-defined blocks and slabs to become unstable. In this paper, a technique is described in which jointing parameters and their variabilities—orientations, spacings and lengths—are taken into account in estimating the extent of failure that may develop around a typical unsupported deep level gold mine rockpass. The results of this prediction are compared with the results obtained from a review of pass performance in the gold mining industry.

Introduction

Although rockpasses are a key element of any mine's operations, often 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.

Literature on rockpasses contains numerous 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. Problems in passes are defined as any occurrences in the pass or pass system that cause the pass or system to operate at less than its desired performance, which performance includes the production rate and designed life or planned total tonnage capacity of the pass. Three publications are referred to specifically in the context of problems with passes—those by Hambley (1987), Emmerich (1992) and Hagan and Archeampong (1999). Of the numerous problems that occur in passes and factors of influence, the following are associated with geological material, geological structure and stress level:

Collapses—these may occur within the pass owing to adverse geological structure. Such collapse material may itself block the pass and cause a hang-up, or, with continuing collapse, a large opening may result, which can lead to major instability and blockage of the pass

Scaling—scaling from the surfaces of the pass under high stress conditions leads to an increase in the size of the pass. It is aggravated by the abrading effect of the rock falling down the pass. Stress scaling will also interact with the geological material and structure—the scaling will be worse in weaker rocks and, as a result of scaling enlargement, a geological structural collapse may occur (for example, Minney, 1990)

Wear—owing to the passage of the rock down the pass, wear (abrading and plucking out of rock blocks) may lead to enlargement of the pass and ultimately geological structural collapse. Wear will be enhanced in weak rock material and in the presence of stress scaling. Wear is usually greatest on the footwall surface of the pass, but may not be when interaction takes place with weak rock materials and stress scaling

Location of passes—the quality of the rock mass in which the pass is located may have the most significant effect on the performance of the pass. Often the location of passes is dictated by other factors such as proximity to the shaft system, or proximity to the orebody, and there is little scope for choice of location. However, owing to the major influence of rock mass quality, the location of the passes should be optimized as far as possible

* *School of Mining Engineering, University of Witwatersrand.*

† *SRK Consulting.*

Orientation of passes with respect to geological structure—it has been found that failure in passes in the same rock mass quality occurs more readily for some orientations with respect to the geological structure than others. For example, in gold mines in which the rock mass is stratified, it has been found that passes intersecting the strata at acute angles are less stable than passes orientated perpendicular to the plane of the strata

Orientation of passes with respect to stress—high stress causes passes to scale or to 'self mine'. This is particularly a problem in deep mines. Scaling leads to considerable enlarging of the passes, increasing the probability of instability of the passes. Such instability can lead to falls of large slabs and blocks of rock from the sidewalls due to the geological structure, resulting in hang-ups and blockages.

It is apparent from the above that the performance of rockpasses is significantly dependent on the geological structure of the rock mass, on the orientation of the pass relative to this structure, and on the *in situ* stress magnitude. This is confirmed by the information presented by Joughin and Stacey (2004), which resulted from the collection and interpretation of data on rockpasses from a range of mines.

In the present paper, theoretical investigations into the effects of geological structure (bedding planes and joints) on unsupported pass behaviour, based on the jointing characteristics, are described. In these investigations, the influence of stress level is taken into account in a semi-quantitative manner. The aim of the investigations has been to provide a comparison of conditions, rather than absolute conditions, relevant to deep level rockpasses.

Jointing in rock mass

Joints and bedding planes are natural geological structures of small to intermediate scale that may occur in rock masses, and that can have a significant effect on the stability of rockpasses. For the prediction of their effect on stability, it is therefore necessary to have information on the characteristics of these structures. The characteristics that define the geometry of the jointing are the joint orientation, the joint spacing and the joint length (size). It is apparent that there has been no systematic mapping of joint characteristics carried out in the South African gold mines to define typical joint statistical parameters for the various rock types encountered. However, from joint data obtained locally and internationally, it has been established that the typical statistical distributions of joint orientations, joint spacings and joint lengths are as follows:

Joint orientation:	normal distribution
Joint spacing:	log normal or negative exponential distribution
Joint length:	log normal distribution.

These distributions have been applied in the investigation described in this paper. Since measured joint data are not available, the typical mean values and ranges in the values for a typical quartzite presented in Table I were obtained from experience (Turner, 1998).

It should be noted that the investigation has taken into account only this 'typical quartzite'. The results obtained must be interpreted in this light. It is probable that variations from the results will be obtained for different rock types such as lava, shale and dyke.

Pass geometries considered

Analyses have been carried out to take account of size of pass, pass orientation relative to the dip of the strata, and the stress-induced increase in size of pass. The last aspect takes into account, indirectly, the effect of mining depth. Three pass diameters were considered—1.2 m, 1.8 m and 2.4 m. The actual sizes taken into account are not particularly important, since the aim is to have results from three sizes from which trends could be determined.

The influence of stress (depth) has been taken into account by determining the increased size of the passes at the different depths, as a result of stress-induced fracturing of the rock (dog-earing). The sizes of the passes under stress levels corresponding with depths of 2500 m, 3500 m and 4500 m were determined using the technique described by Kuijpers (1999). Only the 1.8 m diameter pass was considered in this part of the analyses. Again, the purpose of using three different depths was to allow trends to be determined. The extent of dog-earing determined for the three depths is as follows (dog-ear depth refers to the distance from the original boundary of the pass to the tip of the dog-ear. Therefore the dog-ear span is the sum of the pass diameter and twice the dog-ear depth):

2 500 m depth: dog-ear depth = 0.65 x pass diameter
3 500 m depth: dog-ear depth = 0.92 x pass diameter
4 500 m depth: dog-ear depth = 1.10 x pass diameter

The actual geometries were determined using the factors given above for the different depths.

The effect of orientation of pass relative to the dip of the strata was investigated by considering three different orientation angles, giving angles between pass dip and strata dip of 40°, 65° and 75°.

Table I

Typical quartzite joint parameters

Joint set	Dip angle (deg)	Range (deg)	Dip direction (deg)	Range (deg)	Joint spacing (m)	Range (m)	Joint length (m)	Range (m)
Bedding	25	20–30	160	150–170	1.0	0.5–2.0	25	15–40
1	82	77–87	275	265–285	1.0	0.5–3.0	10	5–15
2	65	60–70	350	340–360	3	1.0–6.0	4	2–6
3	81	65–89	50	30–70	15	3.0–50.0	2	1–3

Creation and analysis of joint patterns

The investigations made use of an analysis technique that takes into account, specifically, the jointing in the rock mass (Haines, 1984; Stacey and Haines, 1984; Stacey, 1999). The technique is dependent on knowledge of the statistical characteristics of the jointing in the rock mass. By sampling these characteristics randomly, sets of joint traces are created in orthogonal planes. Pass geometries are superimposed on these traces, potentially unstable rock blocks and wedges are then identified, and their sizes and volumes calculated. Examples of sets of joint traces, pass geometries and identified potentially unstable blocks are shown in Figures 1 and 2. In the current application, joint trace plots were produced for a section normal to the pass axis and for two orthogonal axial sections. With three such sections it is possible to take into account potential joint-controlled failure in three dimensions.

By repeating the superposition process a sufficient number of times it is possible to determine the statistical distributions of volumes of potential failure, and of fragment sizes for each of the pass geometries identified above. The probabilities of occurrence of unacceptable volumes of failure, and unacceptable fragment sizes, can then be determined. It is also possible to determine the area or extent of potential failure. This is of particular relevance to rockpasses under high stress, since knowledge of the potential size or span of the pass under scaling conditions is important information for planning and design purposes.

The process described above is a manual one and is somewhat tedious to implement. However, it has been found that manual process has a benefit in that it allows the user to obtain a good engineering feel for the rock mass as well as to apply some engineering judgement in the interpretation of the joint trace plots. This important engineering feel could be lost if automatic, computerized identification of potentially unstable blocks was practised.

It must be understood that major features such as faults and dykes are not taken into account in the modelling described here. They will have detrimental effects on stability in the specific locations where they intersect, or are close to, the rockpass.

Results

The results of all the analyses were condensed into two types of outputs per geometry. These are graphs that represent the probability of occurrence of an increase in the cross-sectional area of the pass, and the probability of excedence of a certain fragment size. It is to be noted that an increase in the size of the pass implies some instability of the pass. From these graphs, information was extracted that allowed the predictive data relevant to deep-level passes to be determined as shown in Figures 3 to 6. These indicate the following:

- the influence of pass diameter on stability and scaling (Figure 3)
- the influence of pass orientation, relative to strata dip, on stability and scaling (Figure 4 for no dog-earing, and Figure 5 taking into account dog-earing occurring at various depths)
- the influence of depth (stress) on stability and scaling (Figure 6).

Discussion of results

The analyses described above have taken into account geological structural effects. They have not taken into account the effects of changing stress conditions and corresponding changes in rock fracturing as scaling occurs. In other words, they do not take into account the ongoing growth in the size of passes, which may, and often does, occur with ongoing tipping of ore and waste rock. In such cases, the influence of the excavated diameter of the pass

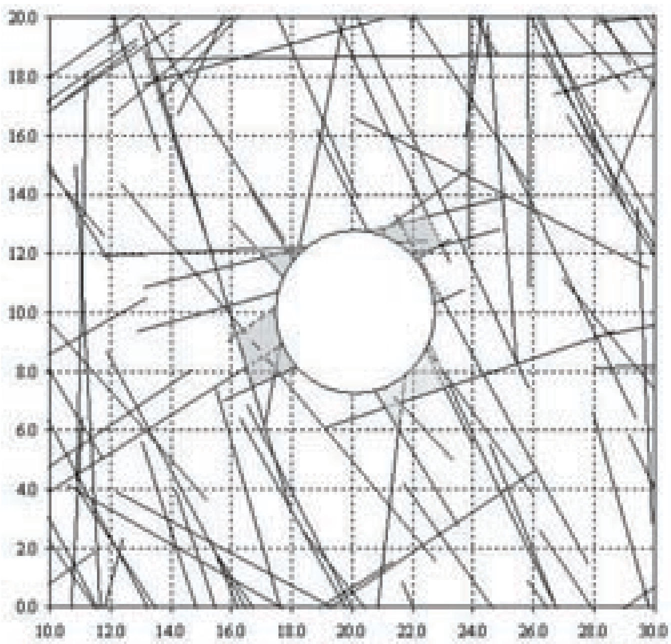

Figure 1—Generated joint traces in a horizontal section through a rockpass

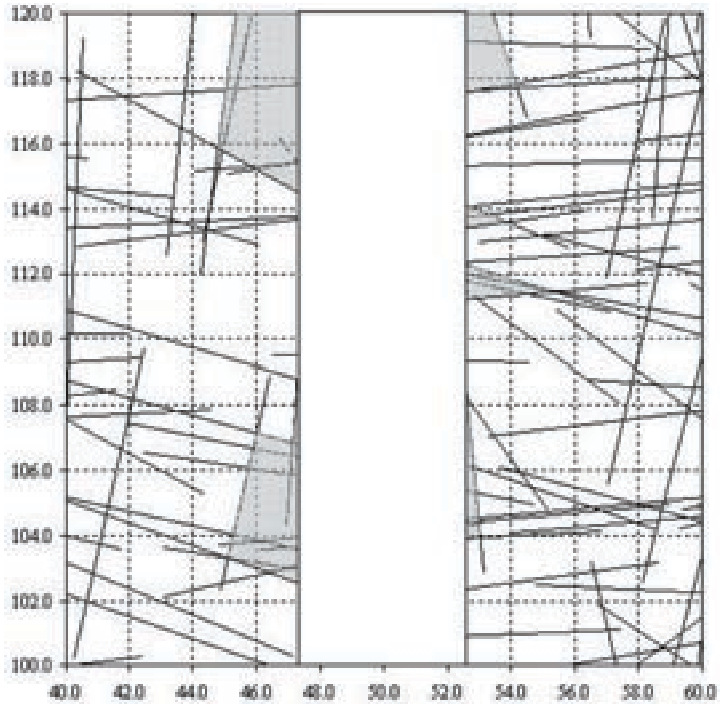

Figure 2—Generated joint traces in a vertical section through a rockpass

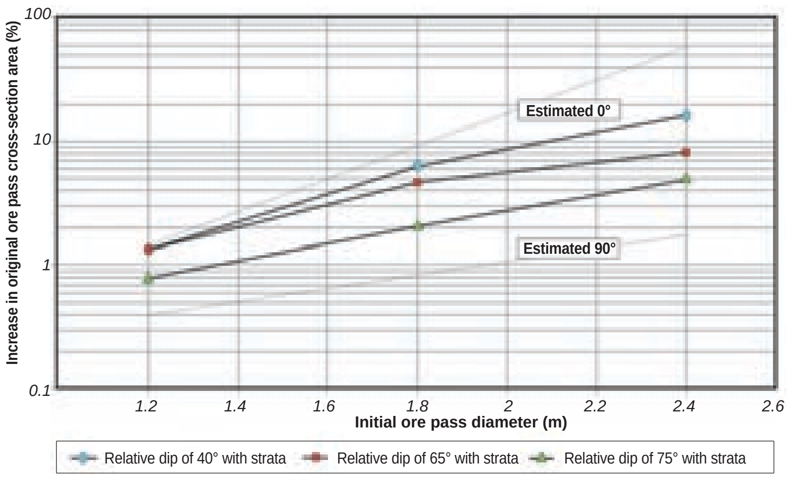

Figure 3—Influence of rockpass diameter (no dog-earing)

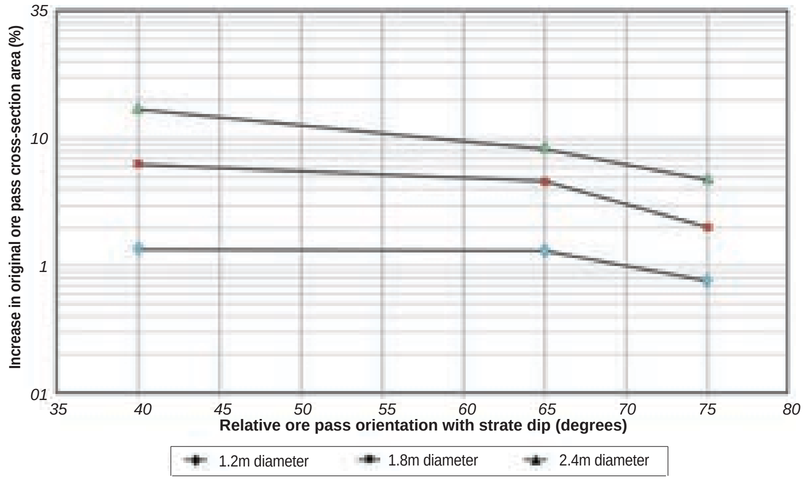

Figure 4—Influence of pass orientation relative to strata orientation with different diameters (no dog-earing)

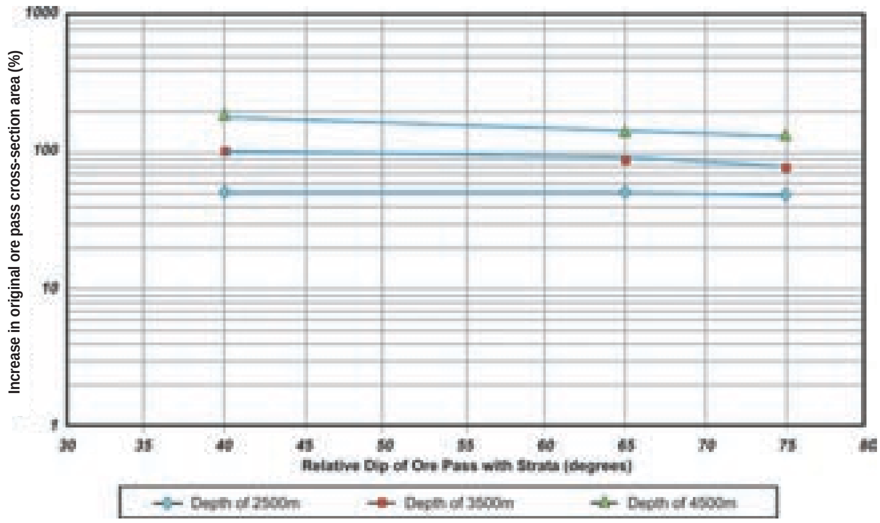

Figure 5—Influence of pass orientation relative to strata orientation on pass stability at various depths for a 1.8 m diameter pass (with dog-earing)

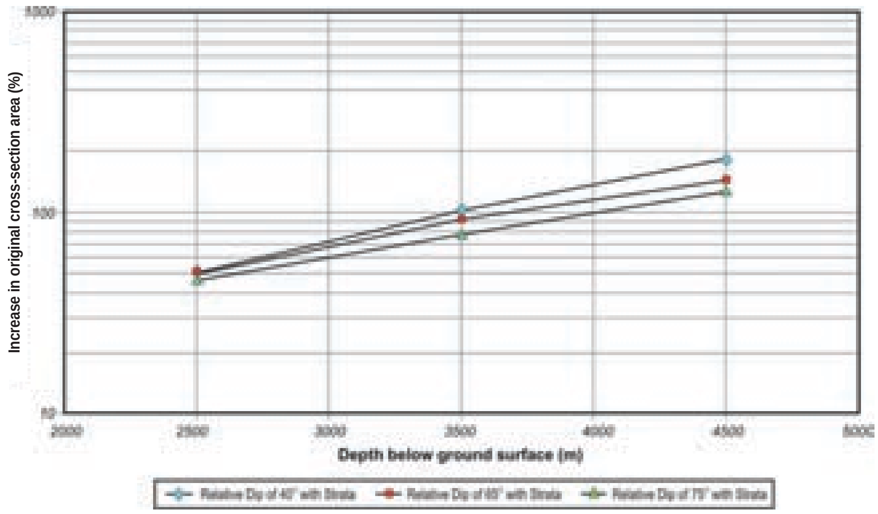

Figure 6—Influence of pass depth for a 1.8 m diameter pass (with dog-earing)

may become irrelevant, since any size will grow to the same extent. Also not taken into account is the consequential effect of block failure, that is, the loosening of further blocks after failure of the initial blocks has occurred.

The analyses also have taken into account only 'typical quartzite', and not other rock types such as the lava and shale that passes commonly intersect. Nevertheless, it is considered that the results obtained provide a reasonable, quantitative indication of some of the influences, and that this is of value in the consideration of very deep mining.

Some of the results of particular interest are:

with an increase in the size of the pass, the potential for greater increases in the 'failed' volume is greater. For example, referring to Figure 3, a 1.2 m diameter pass, inclined at 40° to the strata, will increase in area only by about 1% due to block fallout, whereas a 2.4 m diameter pass will experience about a 15% increase. As indicated above, as soon as failure occurs, the pass will have a 'new' starting diameter and therefore block failure will be progressive. However, Figure 3 does give an indication of the relationship between rockpass diameter and stability. In this figure, the lines representing angles between rockpass dip and strata dip of 0° and 90° have been estimated

the relationship between strata dip and increase in rockpass diameter is shown in Figure 4. This illustrates very clearly that when the inclination of the pass approaches the normal to the strata, the potential failure is inhibited. These results can be compared with those determined from an analysis of the database of pass behaviour described by Joughin and Stacey (2004). One of the graphs from that paper is reproduced below as Figure 7, with data determined from the structural analysis described in the present paper superimposed on it. This superimposed line is for an initial pass diameter of 4.2 m, and the rock mass rating (RMR) for the rock mass used in the structural analysis was estimated to be 66. The trends from the *in*

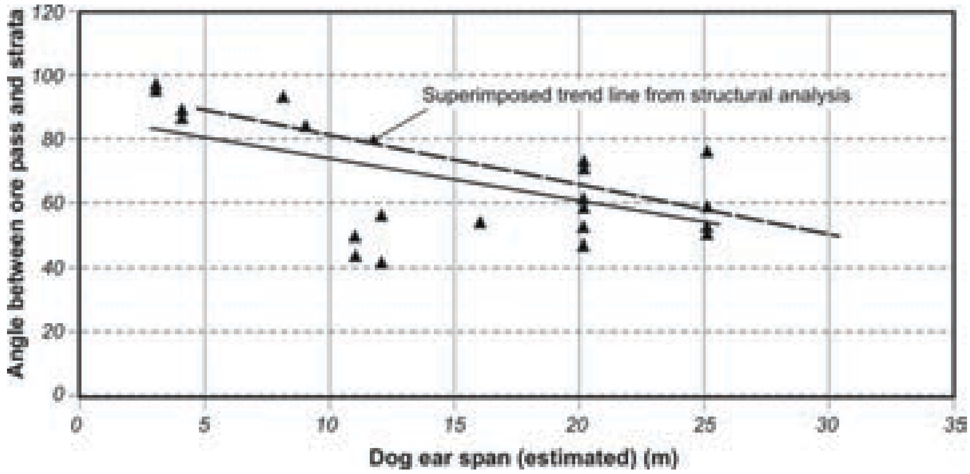

Figure 7—Estimated dog ear spans vs. angle between pass and strata (RMR 60–70)

situ data and the predicted data are almost the same, and the fact that this result has been obtained by two completely different means, gives confidence that the trend is satisfactory

when the effect of stress (depth) is taken into account by the assumption of the occurrence of dog-earing, the extent of the increase in the area of the pass is increased due to the effective increase in the pass size. This is illustrated in Figure 5. The effect of depth is most graphically illustrated in Figure 6. This shows that the increase in the pass area will approximately double between depths of 2 500 m and 3 500 m, and will nearly double again between 3 500 m and 4 500 m. This is a very simlar trend to that indicated from the database of rockpass behaviour described by Joughin and Stacey (2004)

maximum fragment sizes predicted are such that blockage of passes due to block failure is a certainty. When the pass size is enlarged, due to dog-earing, the depth has little influence on the fragment size. Under these conditions the analyses have indicated that there is an 80 per cent probability that the fragment dimension will exceed 2 m and a 10 per cent probability that a fragment with a maximum dimension of 10 m will occur.

Summary and conclusions

Geological structure and high stress are major contributors to the development of instability of rockpasses at deep and ultra deep levels in mines. A theoretical investigation into the stability of rockpasses has been described in this paper. Using typical joint set characteristics, obtained from underground experience, statistical analyses were performed in order to assess the effects of excavated pass size, pass orientation relative to the strata, and stress (depth) on pass stability, taking into account the geological structure. The results obtained show similar trends to those obtained from observations of actual pass behaviours and failures, and therefore it can be concluded that there is validity in the predictions from the theoretical approach. From the results, trends have been obtained to depths greater than have been experienced to date in existing mining operations. The application of the approach described, or similar types of approaches, could lead to improved design and location of rockpasses and, ultimately, to improved pass life and performance.

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