pillars that are too small and as such can only cause errors on the positive side.

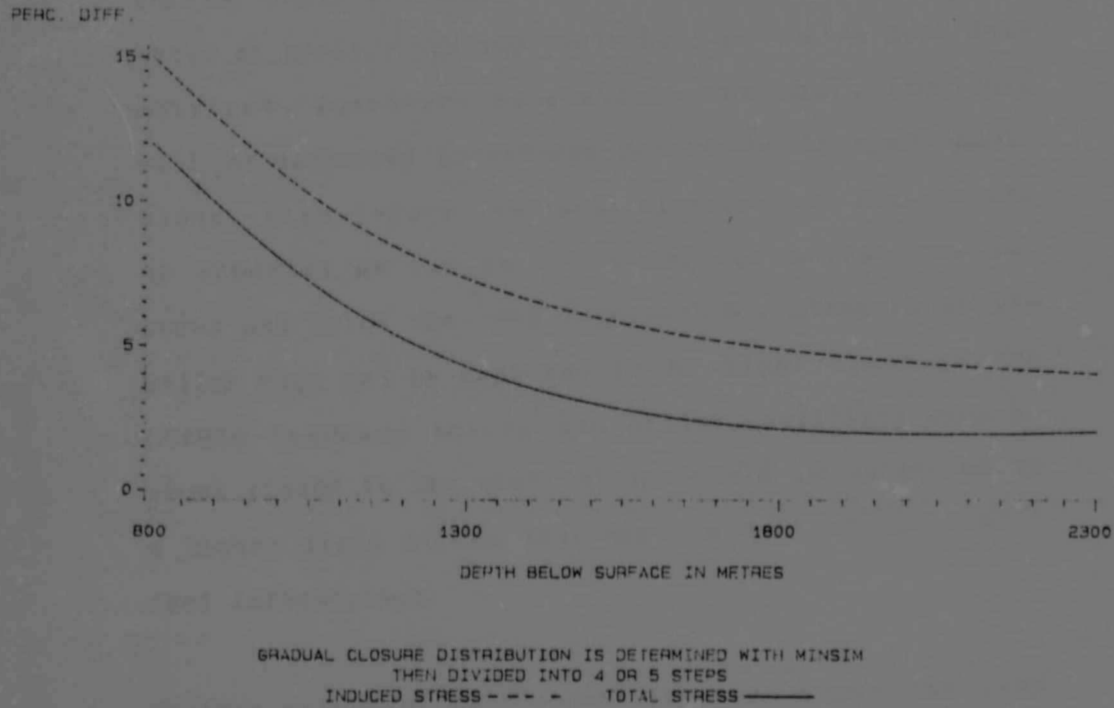

Figure 3.6 Difference in induced and total stresses calculated at the shaft-reef intersection with constant and gradual closure

CONCLUSIONS

The usefulness of closed form solutions in predicting the stress, strain and tilt distributions as the result of mining around a circular shaft protection pillar have been shown.

Maximum values of stress and strain do not occur at the shaft-reef intersection, but approximately 0,5 times the radius of the pillar above or below the reef. At shallow depth the maximum values occur below the reef, while at great depth the distributions become more symmetrical. Auxiliary excavations and shaft steelwork will be subjected to extreme conditions in these positions. High induced vertical stresses and strains can be expected as far as 1,5 times the pillar radius, above and below the reef intersection. Stresses at the pillar edge can be expected to be high. Since stress levels increase across the pillar, auxiliary excavations placed in the shaft pillar would be subjected to a higher field stress than what is felt at the shaft-reef intersection.

Maximum values of tilt generally occur above the reef level and excessively large values of this parameter are more likely to be seen at shallow depth.

Budavari's method can be used in any depth range to determine stress, strain and tilt distributions. In cases where the reef dips more than 20 degrees the MINSIM program could be used.

It was shown that there is a reasonable correlation between the finite depth and infinite depth solutions even in the moderate depth range. Mining in the first 1000 m beyond the pillar edge has been shown to have the greatest influence on the rock surrounding the vertical shaft and ancillary excavations. Finally it was shown that the total closure assumption is reasonable in the moderate and great depth ranges.

4. THE DESIGN OF A SHAFT PILLAR

Introduction

Following the calculation of stresses and differential movements around a vertical shaft and across the circular protection pillar it is necessary to analyse these results and arrive at the ultimate size for the pillar. Since the creation of a shaft pillar involves leaving ore reserves intact, the aim is to make the shaft pillar as small as possible. The optimization of the shaft pillar size involves the consideration of the extent of damage associated with certain calculated values. While it is possible to make provision for some forms of expected damage, other effects of the reduction of the shaft pillar size might be expensive or impossible to control. A separate discussion of each of the factors to be considered during the design process follows.

4.1 Design Criteria

Differential Movement

Salamon (1965), Daemen (1972) and Wagner (1983) all accepted values in the order of 1 mm/m as critical for both strain and tilt. These values apply in the compressive stress situation experienced with the vertical shaft/protective pillar combination.

Significantly different to this value are the values suggested by Van Emmenis and More O'Ferrall (1972) and Wilson (1971). Van Emmenis and More O'Ferrall stated that shaft steelwork in tension can not withstand a vertical strain larger than 0.4 mm/m. Strictly this criterion does not apply in this case since the vertical shaft should be experiencing compressive strain. Wilson, in a separate study of a number of shafts arrived at a figure of 0,2 mm/m as the strain at which damage started being visible. Wilson does not state what this value applies to.

The most important structural components of a vertical shaft are the steelwork and the concrete lining. Shaft steelwork can be designed to survive large strains and as such it is not really necessary to protect steelwork against damage. The extent of deformation that steelwork is supposed to accommodate must only be known so that structural engineers can design accordingly. Sandor (1978) states that the maximum strain that a material can withstand in compression is given by

$$\varepsilon_{max} = \sigma_{max}/E \text{ ,} \qquad (4)$$

i.e. the maximum compressive stress that can be withstood divided by the elastic modulus of the material. Sandor lists the maximum compressive stress that concrete can withstand as 20 MPa while the elastic modulus is given as 17 GPa. The maximum strain that concrete can withstand in compression is then calculated as a little more than 1 mm/m.

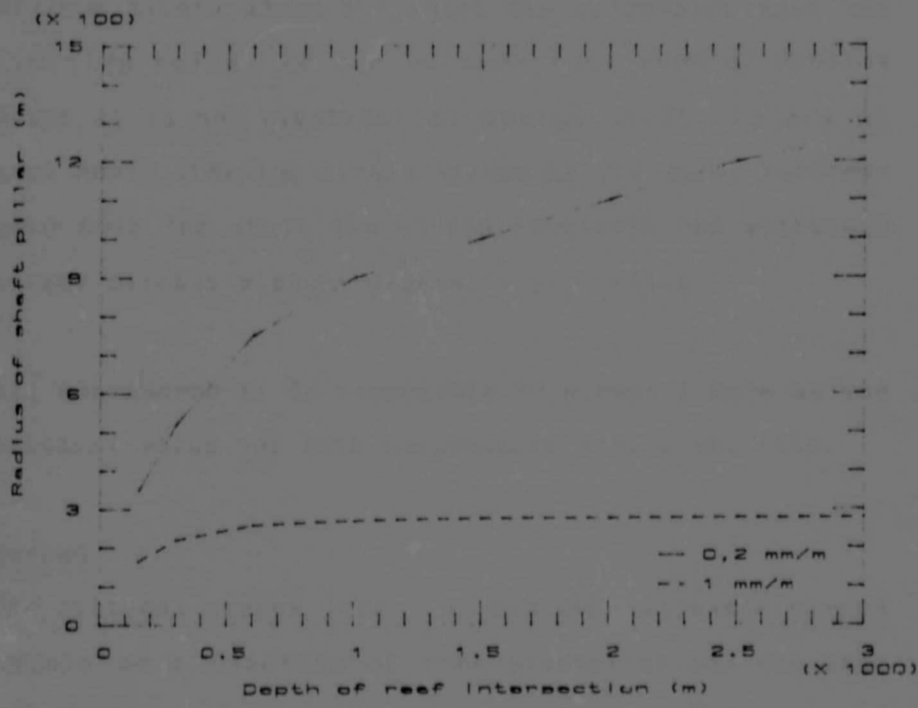

Figure 4.1 Sizes of shaft pillars according to different limiting strain values

Against this background it can be said with a fair degree of confidence that vertical shafts could withstand strain of 1 mm/m without suffering major structural damage. What about the value suggested by Wilson? Although Wilson does not state the form of damage observed it is possible that a poor quality concrete could have developed cracks under a small strain. Figure 4.1 shows shaft pillar radii calculated according to 0,2 mm/m (the value suggested by Wilson) and 1 mm/m strain criteria. In calculating these radii the maximum strain along the shaft was correlated with the limiting value. It can be seen that even at shallow depth it is not practical to design shaft pillars to such small limiting strain values as 0,2 mm/m. Furthermore both the shaft lining and steelwork can withstand larger strains without expensive protection.

All considered it is reasonable to accept 1 mm/m as the critical value for both compressive strain and tilt.

Stress

The critical stress level, or maximum allowable stress should be a function of rock properties and the size and shape of auxiliary excavations to be placed in the vicinity of the vertical shaft. According to Hoek and Brown (1980) heavy support becomes necessary when the vertical applied stress reaches 40% of the uniaxial compressive strength of the rock mass. Most excavations in the close proximity of the vertical shaft will be of a permanent nature and should be stable without major support. This condition can be maintained if the vertical applied stress is at 20% of the uniaxial compressive strength of the rock. At great depth, where the weight of the overburden contributes a large portion of the total stress, it will be impossible to meet this objective. De-stressing or heavy support might be the only methods of maintaining permanent excavations under these conditions. Figure 4.2 shows shaft pillar radii calculated to satisfy different critical stress levels at the reef intersection. In Figure 4.3 the radii of pillars necessary to guarantee a critical stress level of 100 MPa, are shown.

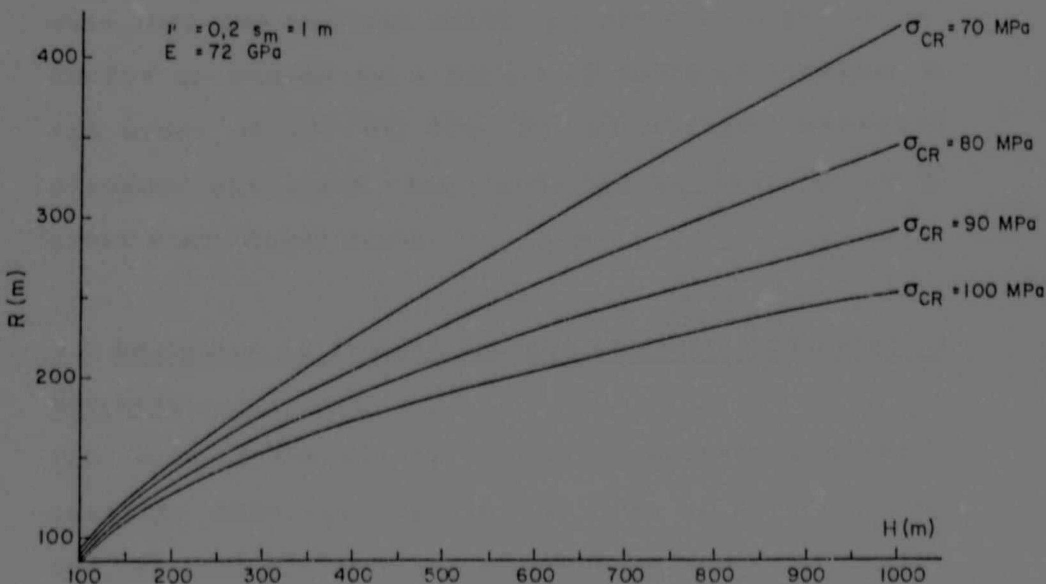

Figure 4.2 Pillar dimensions for different critical stresses

According to Hoek and Brown (1980) permanent excavations situated in a rock mass with uniaxial compressive strength of approximately 226 MPa, should not be subjected to a field stress greater than 45 - 90 MPa. Yet it is common practice in South Africa to design shaft pillars to satisfy a 100 MPa maximum at the reef intersection. Bearing in mind the facts that the stress increases across the pillar, while the stress along the shaft axis can also be higher than that at the reef intersection, it is to be expected that auxiliary excavations in the vicinity of the vertical shaft should often require heavy support. At the same time it must be said that the vertical shaft and protection pillar can suffer no damage as a result of vertical stresses of the order of 100-200 MPa. By calculating expected stresses auxiliary excavations can be placed so as to avoid high stress zones.

4.2 Designing to Protect Against Excessive Differential Movement

The size of the pillar needed to protect the shaft against excessive strain and tilt, is determined by the critical differential movement values, the mining geometry and the particular assumption about the constitutive behaviour of the rock mass. It is only practical to consider the rock mass to behave as an homogeneous, isotropic elastic continuum. The variables that enter into the calculation of the required pillar size are the effective stoping width and the Poisson's ratio. The calculated pillar radius is directly proportional to the effective stoping width while the Poisson's ratio has a minor influence on the outcome of these calculations.

Wagner and Salamon (1975) showed that at infinite depth the shaft pillar radius required to ensure that the induced vertical strain along the shaft axis remains below a given maximum is

$$R = 0,28 x s_m / \epsilon_{z\ max}^{(i)} , \qquad (5)$$

where s_m is the effective stoping width and $\epsilon_{z\ max}^{(i)}$ is the maximum allowable induced vertical strain. This equation implies that if the mining height is 1 metre and the critical strain is taken as 1 mm/m , a pillar of radius 280 metres will give sufficient protection against excessive strain in the worst possible case.

Budavari's equations can be used to calculate distributions of strain where mining is at any given depth. Distributions of vertical strain along shallow vertical shafts protected by circular shaft pillars are shown in the previous chapter. The shaft pillar radius necessary to protect the shaft against excessive vertical strain can be decided on by comparing a critical strain value with the maximum strain value to be expected anywhere along the shaft.

Wagner and Salamon (1975) indicated that for the infinite depth situation, the shaft pillar radius necessary to ensure a given maximum tilt value along the axis of the shaft is given by

$$R = 0{,}13 x s_m / t_{x\ max} \cdot \qquad (6)$$

Once again, if the effective stoping width is 1 metre and the critical tilt is 1 mm/m, the maximum pillar radius needed to protect against excessive tilt is 130 metres. Distributions of tilt along shallow vertical shafts are shown in the previous chapter. Instead of calculating the pillar radius required to satisfy the critical tilt criterion, it is also possible to decide on the pillar radius by comparing the maximum tilt calculated along the shaft with the critical value.

Since the limiting values of strain and tilt are fairly similar it is quite obvious then that at any given depth, strain rather than tilt will be the critical differential movement criterion.

4.3 Designing to Protect Against Excessive Stress

The other parameter to consider in pillar design is that of stress. This quantity is much more complex than that of differential movement and a number of variables affect the calculated stress. It is necessary to arrive at meaningful values for the relevant variables and also to consider the possible effects of the calculated values. The final objective is to arrive at the minimum pillar size necessary to maintain acceptable levels of stress.

4.3.1 Variables

The variables that have a bearing on the ultimate pillar size necessary to control stress are the following:

s_m - effective stoping width,

E - Young's modulus,

q - natural stress in the rock.

Stoping width

To design a shaft pillar for the worst possible case it is essential to assume that complete closure will take place. In addition to this it is also important to keep in mind mining on different reefs. The final effective stoping width could be taken as the sum of all the mining heights on all the different reef horizons. This statement is made without proof and deserves further investigation. Since the stoping width has a direct influence on the calculated stress it is important to use the correct value. A mine manager should never allow an increase in stoping width without reviewing the situation of the shaft pillar.

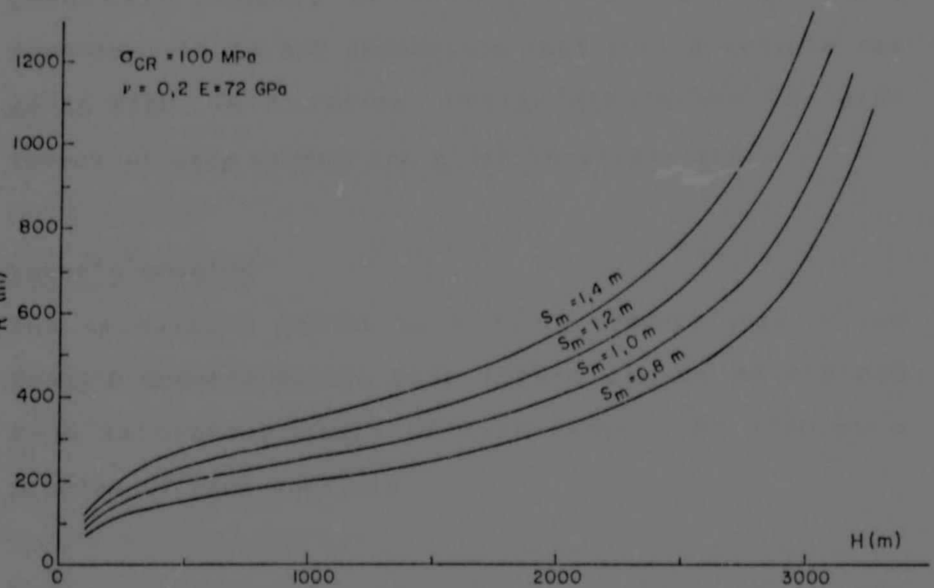

Figure 4.3 Pillar dimensions for both shallow and deep-level mines and for different stoping widths

While an increase in stoping width can seriously increase the stress in the shaft pillar it is also possible to use the influence of a decrease in this quantity to improve the stress levels in the shaft pillar and thus prevent damage. The amount of closure that occurs can be decreased through the use of backfill or stabilising pillars. The advantages of decreased stress levels in the shaft pillar can aid the stability of auxiliary excavations while the the shaft pillar radius could be reduced.

On South African gold mines the stoping width is generally 1 metre or within 20 percent of that. However, it is not impossible that mining heights can go as high as 6 metres. Pillar dimensions for different stoping widths are given in Figure 4.3.

Young's modulus

The calculated stress is directly proportional to the Young's modulus value. This figure can be determined from laboratory tests of core samples or through a process of back analysis.

For the purposes of computer modelling it is appropriate to test a small core sample in the laboratory. It is true that the bulk behaviour of a rock mass is likely to be different to the properties indicated by laboratory tests. At this stage it is uncertain what the degree of difference is. Since the effective elastic modulus is always lower than the modulus of the intact rock, the employment of the laboratory results can only lead to the creation of a shaft pillar that is larger than required. A higher modulus will yield higher calculated stresses for the same pillar radius. To reduce these stresses the radius has to be increased.

Natural stress in the country rock

At any particular depth only one variable affects the vertical component of the pre-mining stress. This is the density of the rock. While the vertical component of the pre-mining stress is usually determined by the weight of the overburden, the horizontal component is the sum of a large number of complex phenomena. The most reliable method of establishing pre-mining stresses is through the stress relief method. If results from such tests are not available it is advisable to rely on the outcome of past measurements. At great depth the ratio of horizontal to vertical pre-mining stress tends to one. At shallow depth the horizontal component can be considerably larger. If the reef is also inclined at a large angle this component could affect the pillar and thus the shaft system.

DISCUSSION

From the distributions of strain and tilt shown in the previous chapter, it can be seen that the maximum values of these variables do not occur at the shaft-reef intersection and these maximum values are significantly larger than those calculated at the reef intersection. It is quite easy to imagine that damage to shaft steelwork and the concrete lining can result if this phenomenon is not considered. The same is true for stress. Maximum values of this parameter occur at positions approximately 0,5R above and below reef level. When service excavations are placed, the zone with the lowest stress should be selected if it is practically possible.

The effective stoping width is open to much abuse. The use of small effective stoping width values can be justified for a number of reasons. An increase in the effective stoping width will cause directly proportional increases in strain, tilt and stress. The reasons for using smaller effective stoping width could be planned backfill or the fact that expected closure will not be complete. If backfill is to be used to reduce the stoping width, the properties of the fill material must be well known and a later reversal of the decision to use fill must not be considered. At shallow depth full closure is unlikely to occur before back break sets in. It would be reasonable to use a smaller effective stoping width at shallow depth provided this value is in line with true closure.

CONCLUSIONS

The value of 1 mm/m has been accepted as a reasonable limiting value for both vertical, induced strain and induced tilt. The critical stress value of 100 MPa, often used in the design of shaft pillars, might be too high. Under the normal circumstances experienced in South African hard-rock mines, service excavations should be placed in stress fields of less than 90 MPa whenever possible.

The practice of designing shaft pillars for a given value of any parameter at the shaft-reef intersection could lead to damage in vertical shafts. Maximum values of stress, strain and tilt do not occur at this level and the maximum values can be up to twice as large as the values at the reef intersection. It is advisable then to consider the distributions of all three parameters along the entire length of the shaft and also across the shaft pillar. These distributions can best be calculated with Budavari's method.

5. OBSERVATIONS OF DAMAGE THAT OCCURRED IN SHAFTS AND ANCILLARY EXCAVATIONS PROTECTED BY PILLARS

A study of experiences with actual shaft pillars can lead to a clearer understanding of the damage that occurred in the past. The mining conditions associated with damage could give an indication as to the possible causes. Actual pillar sizes are compared with those designed according to Budavari's method. A listing of the cases to be discussed follows. In each case the vital statistics are given.

Where no stoping width is mentioned in the relevant literature, a value of 1,0 m was assumed. The writer accepts that this value does not necessarily apply in all of the cases listed above. However, in most of these cases the mining height is between 1,0 and 1,4 m. The Poisson's ratio does not have an important influence on the outcome of the calculations.

It is assumed that in all cases the area around the pillar is extensively mined out. It was shown in paragraph 3.4.2 that mining within a radius of 1000 m from the pillar edge has the largest influence on the shaft system. Where the extent of mining and type of support is known, the significance of such information will be discussed.

In Table 5.1 the fourth column (ER/CR %) is the ratio of effective pillar radius divided by the calculated pillar radius as a percentage.

TABLE 5.1
LISTING OF TEN SHAFT PILLAR SIZES, PERCENTAGES OF ACTUAL RADIUS/CALCULATED RADIUS AND RELATED CONDITIONS

Shaft	Effective pillar radius (m)	Calculated pillar radius (m)	ER/CR %	Condition of shaft and shaft pillar
A	38	466	8,15	Stable
B	41	255	16,1	Total collapse of pillar at shaft-reef intersection
C	61	100	61,0	Stable
D	104	230	45,2	Frequent rockbursts in stopes
E	107	405	26,4	Stable
F	149	472	31,6	Stable
G	163	250	65,2	Damage to auxiliary excavations. Punched into footwall.
H	203	460	44,1	Damage to auxiliary excavations
I	244	360	67,8	Damage to auxiliary excavations
J	91	191	47,6	Stable

The following values were used in the place of the normal variables:

Young's modulus: 70 GPa
Poisson's ratio: 0,2

To arrive at the calculated pillar radii, critical stress and strain values of 100 MPa and 1 mm/m respectively were used. The closed form solution used for this purpose applies where the dip is smaller than 20 degrees. In cases where the dip exceeds 23 degrees a MINSIM simulation was also carried out and used to reinforce indications that pillars were under designed. Where multiple reefs were mined, the stoping width was taken to be the sum of the stoping widths of all the reefs.

Each of the ten cases listed above will now be discussed so that the very basic statistics mentioned can be seen in perspective.

<u>CASE A:</u>

Actual pillar size: 38 m radius

Radius calculated with closed form solution: 466 m

In this case three reefs had been extensively mined out around the shaft pillar with stoping widths of up to 6 metres in isolated areas. The dip of the main reef is 35 degrees. This very old shaft was abandoned at one stage for a period of 14 years. There was very little support in the stoped out areas. Some pillars had been left but had decayed with time. When this shaft was re-opened after its abandonment the pillars were considered to be wholly inadequate for the protection of the shaft. Viewed against the calculated pillar size it is clear that this was the correct decision. However, before it was decided to remove the pillar, no damage had been experienced.

Since the reef mined here dips at 35 degrees it was necessary to simulate the shaft pillar with the MINSIM program. Three stages of mining was simulated. The extent of mining went from 250 m beyond the pillar edge to 570 m. After the third stage the maximum vertical strain calculated along the shaft exceeded 2 mm/m. The total vertical stress at the reef intersection reached 190 MPa. Both of these values are excessive and indicate that the shaft pillar is not large enough.

Two reasons can be given for this anomaly between the actual pillar (that proved to be adequate) and the pillar that is theoretically considered to be of sufficient size:

(i) Stabilising pillars in the stoped out areas can carry a large portion of the load which would otherwise have been on the pillar,

(ii) It is not certain that the method of adding the stoping widths in the various reefs is valid.

CASE B:

Actual pillar size: 60 m on strike by 90 m on dip

Radius calculated with closed form solution: 255 m

This case dates back to approximately 1910 when mining on the Witwatersrand reached the depth where the previous configuration of pillars could no longer accommodate the pressures. A few serious cases of total collapse of pillars occurred during this period. When timber support was introduced the situation immediately improved. It was during this period, when miners were updating support systems according to experience, that these shaft pillars collapsed completely at the shaft-reef intersections of the two upper reefs. The damage that resulted caused great financial losses to the mine since the vertical shaft had to be closed down for a number of months. At that early time in the history of underground mining in South Africa this shaft pillar was considered to be large. Against present theory this pillar was actually completely inadequate. The size of the pillar and the absence of additional support must be blamed entirely for this disaster. It is obvious that the geomechanical effects of multiple reef mining was not understood at that time.

CASE C:

Actual pillar size: 61 m radius

Radius calculated with closed form solution: 100 m

This shaft pillar was at very shallow depth. At the end of the life of the portion of the mine served by this shaft it was decided to remove the shaft pillar. At this stage the pillar was not showing any signs of taking strain.

The reef mined here dipped at 4 degrees. The reef is overlain by dolomites which are overlain by shales. The surface over this mine is very hilly and deeply dissected. The dolomite carries much underground water. Where the dolomite is exposed to the surface it is often decomposed to considerable depth.

On the whole, the country rock around this shaft cannot be classified as being competent. Two reasons can then be suggested for the stable situation around this shaft. The first is that the actual pillar is fairly large compared with the calculated pillar size. The second reason is in the geometry of the mining around this shaft pillar. Due to the mechanism that formed this particular deposit, the mineable reef occurs in narrow shoots. It is natural then that mining would have been carried out in narrow stopes. This particular geometry creates relatively small minimum spans. A stable situation results.

It is also interesting to note that cages in this shaft ran on rope guides, so that the influence of poor ground conditions will not be felt in the shaft.

CASE D:

Actual pillar size: 104 m radius

Radius calculated with closed form solution: 230 m

Two reefs were extensively exploited around this shaft. The reefs dip at 40 degrees and are approximately 13 metres apart in the plane perpendicular to the reef. This shaft pillar was designed using the angle of draw method. In this case the angle was 80 degrees. After 20 years there was still no sign of pressure in the shaft pillar. This pillar is small compared with the size calculated according to Budavari's method. With the MINSIM program this pillar was modelled so that mining extended to 763 m and 1196 m from the pillar edge. The maximum vertical stress calculated was 214 MPa and occurred 20 m below the reef intersection. The maximum vertical strain was calculated as 2,3 mm/m. This value was situated 40 m below the reef intersection.

For lack of any further information, it can only be assumed that the supporting action of the pillar was assisted by remnants in the area adjacent to the pillar, where the influence of solid support is most effective.

Frequent rockbursts in the stopes around this pillar need not necessarily be blamed on the shaft pillar but might have been a result of high shear stresses induced by the effects of the pillar edge.

CASE E:

Actual pillar size: 159 m on strike by 227 m on dip
Radius calculated with closed form solution: 405 m
This vertical shaft and shaft pillar were also stable until the reserves around the pillar were depleted. Mining had been carried out on a dip of 40 degrees.

A MINSIM model of this shaft pillar indicates that it will become inadequate when the minimum unsupported span around the pillar reaches 1090 m. At this stage the maximum vertical strain along the shaft is calculated as 1,7 mm/m. The vertical stress at the reef intersection is 140 MPa and increases to 168 MPa at a position 50 m lower down.

The following auxiliary excavations were situated in the pillar protection area:

a) the incline shaft hoist chamber,
b) reef passes and stations,
c) some reef drives and
d) a small ventilation fan chamber.

A dyke 25 metres thick bounded the western edge of this pillar. On the eastern side of the shaft pillar, previous stoping had been solidly filled with sand. Closure in these stoped out areas was not yet complete when pillar extraction started.

The relatively large size of this pillar and the stabilising influence of back-filling resulted in a stable situation, even though two reefs had been mined.

CASE F:

Actual pillar size: 229 m on strike by 305 m on dip
Radius calculated with closed form solution: 472 m
The area around this pillar had been extensively mined out when it was decided to extract the pillar. Mining was on a dip of 23 degrees. The proximity of a water barrier pillar, within 160 metres of the shaft pillar might have added considerably to the stability of this pillar.

CASE G:

Actual pillar size: 213 m on strike by 393 m on dip
Radius calculated with closed form solution: 250 m
This is also a very old shaft as is indicated by the facts that the buntons are wood and the guides are ropes. The dip of the reef is 21 degrees. Stopes are

extensively mined out with a few small remnants. In this case the actual pillar was fairly large compared with the calculated radius. Consequently no damage ensued. The following reasons can be suggested for the stable situation:

(i) The size of the pillar is fairly large compared with a pillar designed for a worst possible case.

(ii) The pillar is not at great depth so that the closure will not be very large. This means that the induced stress on the pillar will not be large.

(iii) Damage that might have resulted in the vertical shaft would have been absorbed by the compressible wooden buntons. Rope guides also serve to prevent any displacement due to mining being felt in the shaft.

CASE H:

Actual pillar size: 305 m on strike by 425 m on dip

Radius calculated with closed form solution: 460 m

Here mining was carried out on a dip of 22 degrees. Two reefs 36 metres apart were mined at moderate depth. Excessive faulting and dykes were encountered in the hanging above the reefs. Signs of stress were evident in the shaft pillar. Deterioration of the old pump chamber and sumps, situated close to the shaft in the shaft pillar, had set in. It was necessary to build concrete walls and install steel support in the pump chamber while additional support and concrete abutments were necessary in the sump area. The ore-pass system in the pillar also became unusable due to excessive scaling.

In this case it is clear that the shaft pillar was under high stress. A MINSIM type model indicated that the pillar was under very high stress on some of its boundaries while other areas in the shaft pillar were not experiencing extreme levels of stress. The fact that sumps, pump chambers and the ore-pass suffered damage, while other large auxiliary excavations in the shaft pillar were stable indicates that there could be a problem with the design of these excavations. Alternatively it is also possible that geologically disturbed ground played a part in damage that occurred in some of these excavations.

<u>CASE I:</u>

Actual pillar size: 244 m radius

Radius calculated with closed form solution: 360 m

The original shaft pillar created in this case was designed with the analogue computer, forerunner of MINSIM. No reference could be found on the design of auxiliary excavations. The fact that these excavations showed signs of stress before mining was started around this shaft pillar is a definite indication that the stress concentration effect was not taken into account. The collapse of these excavations also affected neighbouring excavations. Shaft stations were affected by the severe rock movements that took place.

The poor ground conditions that finally resulted can definitely be blamed on the clear water sumps, conical settlers and water distribution tunnels. All these excavations were situated in the shaft pillar. While the conical settlers were initially being excavated, instability was experienced. To improve this condition, the original layout was revised so that only half the number of settlers were cut.

During subsequent mining east of the shaft pillar poor hangingwall conditions were experienced. Off-reef excavations also showed signs of sidewall failure.

When the conical settlers, clear water distribution tunnels and clear water sumps showed evidence of sidewall failure, it was decided to install support. Only a limited amount of rockbolt support was successfully completed. Some of these excavations were then lined with concrete while others were supported by square timber sets.

After this considerable sidewall movement took place in haulages in the vicinity of the northern boundary of the shaft pillar.

After further mining a severe burst occurred in the stopes associated with a large dyke to the west of the shaft pillar. Movement along this dyke affected haulages at the dyke intersection.

After this a period of steady daily deterioration set in. No sudden violent failure occurred. Deterioration started with heaving of the footwall, followed by sidewall collapse and then hangingwall collapse. Pillars between sumps failed successively, with each pillar failure resulting in additional stress on remaining pillars. No major movements were observed in the shaft during this period. A total shortening of 22 cm had resulted at the reef intersection during the life of the shaft. Guides in the shaft were cut to accommodate this movement. No damage occurred in the concrete lining of the shaft.

It is evident that at this mine the host rock is less competent than elsewhere in South Africa. The writer does not know what method was used to design these auxiliary excavations. If this design was based on experience then it can only be assumed that this experience did not necessarily apply in the particular area where this mine was situated.

This case will be classified by the writer as one where the strength of the rock was overestimated. From the fact that these excavations showed signs of stress during initial formation, can be deduced that the method used to design these excavations was not appropriate.

CASE J:

Actual pillar size: 91 m radius

Radius calculated with closed form solution: 191 m

This shaft pillar was stable until the depletion of ore reserves in the area surrounding the pillar.

Mining around this pillar was done on a dip of 42 degrees. Several dykes and faults intersected the pillar area. Some development had been carried out in the pillar area. The hangingwall of the reef was quartzite while the footwall consisted of shale. This shaft which was sunk in 1904 still had the original timber intact in 1956.

This shaft pillar was fairly large against the calculated size. The stable mining conditions around this shaft are not only due to the size of the pillar, but also because of the large proportion of solid remnants in the surrounding area. Of the area within a 300 metre radius around the shaft only 50 percent is mined out. A further stabilising factor is the fact that in this mined out area, some wastepacking had also been done.

In preparing a MINSIM model for this case an interesting feature of shallow mining on a steep dip was emphasised. In the updip direction mining can only extend to the surface, in this case 590 m from the shaft pillar edge. A geometrical restriction is therefore imposed on the worst possible case that can occur. Simulation of the 91 m radius pillar indicates that the vertical stress at the reef intersection can still reach 130 MPa while the maximum vertical strain along the shaft was calculated as 1,4 mm/m. This condition occurred when mining updip of the pillar extended to surface, with 1300 m of ground removed in the strike direction and 2000 m of unsupported span downdip of the pillar. Ultimately, this pillar could have proved to be too small.

SUMMARY AND CONCLUSIONS

In the ten cases listed and discussed above, all the actual pillars were smaller than what would be designed for extreme conditions with 100 MPa and 1 mm/m criteria. One of these pillars collapsed completely and caused lasting damage to the vertical shaft. In two other cases serious damage to auxiliary excavations ensued in highly stressed pillars.

With modern analytical, numerical and laboratory techniques there is no reason why mining engineers should not be able to arrive at optimum shaft pillar sizes. It is possible to get a very close approximation of expected stresses and strains along the vertical shaft and across these pillars, using theoretical methods.

Figure 5.1 shows that pillar radii necessary to control stress are larger than what is needed to control strain (under normal South African hard-rock mining conditions). When a shaft pillar is too small it is to be expected that damage will first be caused by excessive stress. This should be observed as deterioration of auxiliary excavations.

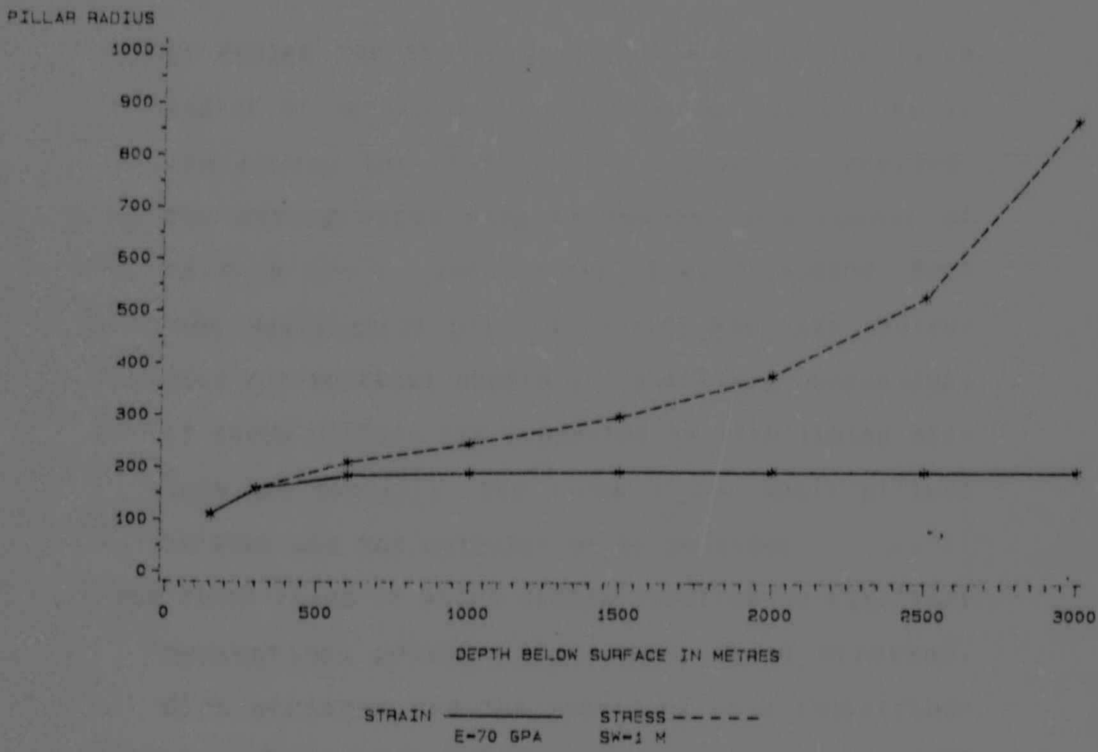

Figure 5.1 Shaft pillar dimensions for critical strain of 1 mm/m and critical stress 100 MPa

Budavari and Salamon's methods are aimed at designing shaft pillars for the worst possible case. It can be said that in most of the cases listed and discussed above, conditions did not resemble these worst possible cases as seen in theory. However, a number of these reefs were extensively mined out and it is reasonable to compare actual shaft pillar sizes with theoretical values. With this in mind the following conclusions can then be drawn from this study:

- It is difficult to show conclusively the importance of design for the worst possible case. The large number of variables that influence conditions in and around the shaft pillar can not be modelled. The strong supporting influence of a number of factors are evident in the cases discussed. Some very small shaft pillars provide adequate protection for vertical shafts and auxiliary excavations if these pillars are supported by stabilising pillars and backfill. The sizes of the shaft pillars is then not the only factor to consider.

- The three cases in which damage resulted to auxiliary excavations point to excessive field stresses. High stresses are the result of both redistribution of stresses due to the creation of the shaft pillar and also stress concentration around large excavations.
- The critical stress and strain values of 100 MPa and 1 mm/m respectively might have provided sufficient protection if these criteria had been used. (In making this statement the writer does not suggest that these values should be used irrespectively of rock quality.)

of design for the worst possible case. The large number of variables that influence conditions in and around the shaft pillar can not be modelled. The strong supporting influence of a number of factors are evident in the cases discussed. Some very small shaft pillars provide adequate protection for vertical shafts and auxiliary excavations if these pillars are supported by stabilising pillars and backfill. The sizes of the shaft pillars is then not the only factor to consider.

- The three cases in which damage resulted to auxiliary excavations point to excessive field stresses. High stresses are the result of both redistribution of stresses due to the creation of the shaft pillar and also stress concentration around large excavations.
- The critical stress and strain values of 100 MPa and 1 mm/m respectively might have provided sufficient protection if these criteria had been used. (In making this statement the writer does not suggest that these values should be used irrespectively of rock quality.)

6. MINING THE REEF IN THE SHAFT PILLAR AREA

Introduction

The set of measurements taken by Barcza and Von Willigh (1960, during mining of the reef around a vertical shaft has great scientific value. These measurements have never been back analysed with modern computer methods and much can be gained by comparing such good quality observations with the relevant theory.

This chapter also includes simulation of mining using parallel-sided, down-dip longwall faces around a vertical shaft at great depth.

6.1 Case Study of Mining in the Shaft Pillar Area Using a Number of Downdip Longwall Faces on a Shallow Dip

6.1.1 Details of this case

The Harmony Gold Mine Ventilation Shaft intersects the Basal reef at depth 1329 m below surface. The reef dips in a westerly direction at approximately 7 degrees. Stoping of the reef started during September 1954. The average stoping width in this area is 1,2 m.

The shaft diameter is 7,31 m and is lined with unreinforced concrete 229 mm thick. Near the reef intersection the shaft is brick-lined.

Measurements were made between roofbolts installed into horizontal holes drilled into the shaft sidewall. Roofbolts were placed 3,05 m apart within 15,24 m of the reef intersection, the distance increasing to roughly 60 m apart at a distance of 150 m above the reef.

6.1.2 <u>Mining around the shaft</u>

Mining around this shaft basically consisted of three longwall systems each approximately 440 m on dip, the centre to centre distances of the longwalls being approximately 250 m. The ventilation shaft is situated approximately 30 m to the south of the centre of the middle longwall.

Each longwall advanced from its centre outwards until the three longwalls were interconnected with a total span of approximately 660 m. Small pillars were scattered around the mined out area.

The layouts modelled are as follows:

31-12-1954 Three longwalls 440 m on dip with spans of approximately 20 m each.

31-12-1955 Three longwalls 440 m on dip with spans of approximately 120 m each.

31-12-1956 Three longwalls 440 m on dip with spans of approximately 180 m each.

31-12-1957 Three longwalls 440 m on dip with spans of approximately 320 m each. Only small pillars are scattered around the mined out area.

6.1.3 Determination of Young's modulus using footwall rise

Any case study in the field of rock mechanics must start with the determination of the elastic constants involved. This can be done by taking physical measurements or through a process of back analysis.

In the literature, on which this case study is based, measured strain and displacement values are given. No stresses were measured. In elastic calculations strain and displacement values are most significantly affected by the Young's modulus used. Irrespective of the method used, it is most important to determine the Young's modulus of the rock.

When the method of back analysis is used it is essential to compare calculated values only with measurements of elastic movements of rock, since the MINSIM program which was used, models elastic movement of rock. It is generally accepted that where the hangingwall is in tension, inelastic movements occur. It is therefore not appropriate to compare hangingwall displacements or strains with values calculated according to elastic assumptions. To circumvent this problem it was decided to assume footwall rise to be elastic. Although inelastic relaxation of the footwall is not impossible, it is less likely that bulk movement of rock will occur against gravity. The writer accepts that the geology of the footwall is not necessarily the same as that of the hangingwall. However, it is assumed that inelastic movement of the hangingwall will contribute more to an erroneous comparison, than the difference in geology.

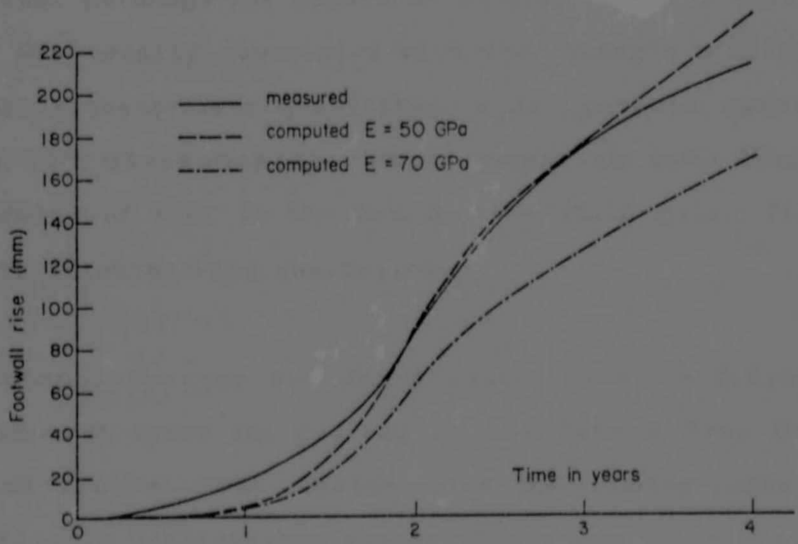

Figure 6.1 Comparison of measured and computed values of footwall rise

The MINSIM program was used to do calculations based on the assumption that rock behaves as an elastic continuum. The Young's modulus in this program was adjusted until calculated footwall rise corresponded closely with measured values. The Young's modulus value at which this occurred was 50 GPa. The correlation between measured and calculated footwall rise is shown in Figure 6.1.

In further calculations for this case study, this value will be employed instead of the Young's modulus. The author feels that there is good reason to justify this value. Although the figure of 50 GPa is lower than the 70 GPa usually associated with the Young's modulus of hard Witwatersrand quartzites, a 29 percent decrease is not unreasonable, when comparing the Young's modulus of rock in the Orange Free State gold fields with Witwatersrand quartzites.

Ortlepp, Spencer and Faure (1986) made the following statement about the geology of the Orange Free State gold fields: "The quartzites of the country rocks are typically considerably weaker than those of the other mining districts with the exception possibly of the Klerksdorp Area where weaker rocks are also common particularly in the footwall of the reefs". It is assumed that weaker can be equated with softer.

While the MINAP program had a limited application in this case study, the MINSIM program showed a continuous correlation with measured values irrespective of the extent of mining. An adjustment of the Young's modulus in the MINSIM program gives a continuous close correlation between measured footwall rise and the calculated values. See Figure 6.1.

6.1.4 Calculation of stresses and strains

For the calculation of stresses and strains the rock was considered to behave as an elastic continuum. Stresses and strains were then calculated for four different mining layouts spaced equally in time over a period of four years. The result is then to have four different sets of calculated values that can be compared with four sets of measured strains.

The applicability of the MINSIM program to early mining in the shaft pillar area deserves discussion. While the MINSIM program has certain shortcomings in its boundary conditions when used for shaft pillar design, the disadvantages in using the MINSIM model are of a different nature in this case.

Here the inability of the MINSIM program to model inelastic movement and non-homogeneous geological conditions is important. While in this case study, the lack of correlation between calculated and measured values can be ascribed to a band of softer shale, there remains an element of doubt about the ability of the MINSIM program to accurately model a hangingwall in tension. The three-dimensional capabilities of the MINSIM program is an important advantage.

The following assumptions were made in terms of constants:

Poisson's ratio = 0,2

Density of host rock = 2700 kg/cubic metre

Ratio of horizontal to vertical natural stresses = 0,5

Stoping width = 1,2 metre

When the analytical solution was applied to this model a single longwall was modelled on a 0 degree dip. This solution corresponds well with values calculated using the two-dimensional MINAP program. Both of these solutions only apply up to the point where the halfspan of each individual longwall is approximately 60 metres. Beyond this point the down-dip dimension of the mining layout becomes equal to or less than three times the strike dimension of the layout. The validity of a two-dimensional model becomes questionable at this point. The assumption that one longwall could be modelled instead of the three actually mined was tested and proved to be reasonable up to this stage.

6.1.5 Comparison of calculated values with measured values

In this comparison, stresses and strains calculated with the three-dimensional MINSIM program, are compared to strains measured in the Harmony ventilation shaft. It is essential to keep in mind the fact that the calculated values are based on elastic behaviour of rock, while the measured values include inelastic movement and bed separation.

In the footwall it was possible to get a very close correlation between measured total displacement and calculated displacement. When strains measured in the hangingwall are compared with induced vertical strains it is more difficult to see a correlation. It appears that the calculated and measured values follow each other closely at strains less than 0,2 mm/m. Closer to the reef level, i.e. within approximately 140 m, the theoretical values show a gradual increase while observed strains increase sharply in magnitude. In this region there is a poor relationship between the two sets of values. See Figures 6.2, 6.3 and 6.4 for comparisons of measured and computed data.

The most likely explanation for this discrepancy can be found in the fact that the situation modelled here is that of a hangingwall in tension. In a tensile situation inelastic movement and bed separations are free to set in while the same is not true for a compressive situation.

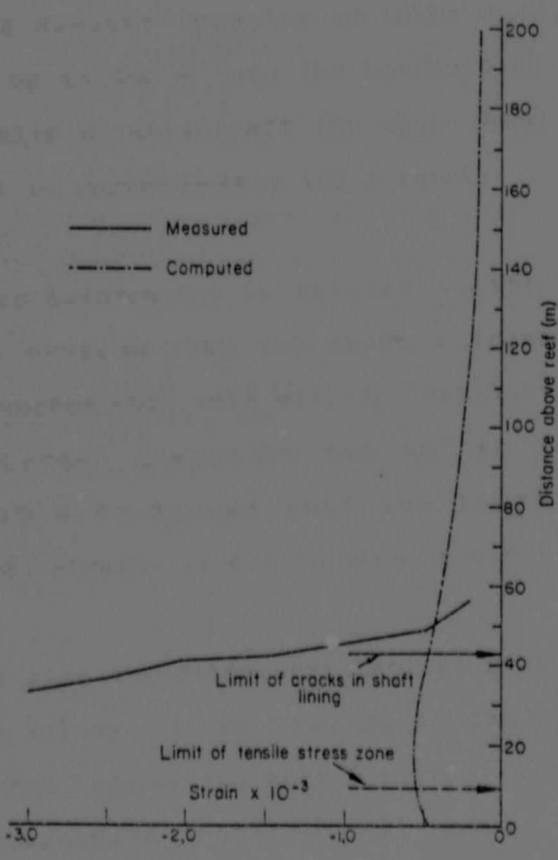

Figure 6.2 Comparison of measured and computed induced, vertical strains in hangingwall at the end of second year of mining

A closer look at the geology of the region that this mine is situated in, and the particular geology at the position where these measurements were taken, will provide a plausible explanation for the discrepancy between measured and calculated strains. Ortlepp, Spencer and Faure (1986) stated, that in this region, shale layers are common in the hangingwall of the Basal reef. On another location at this mine, soft layers stretch up to 165 m into the hangingwall of the Basal reef, while at this shaft the shale band in the hangingwall is approximately 140 m thick.

When this information is related to the diagrams, it becomes obvious that the sharp increase in measured strain corresponds well with the transition point between harder quarzites and softer layers. It is reasonable to assume that the large increase in measured strains is due to local geology.

In this case the difference between measured and calculated values, can be related to geological conditions. Van Emmenis and More O'Ferrall (1972) suggested a corresponding factor of difference between values calculated according the MINSIM model and measured values. As in this case study, it is possible to relate the poor correlation found by Van Emmenis and

More O'Ferrall to geological conditions (a series of faults).

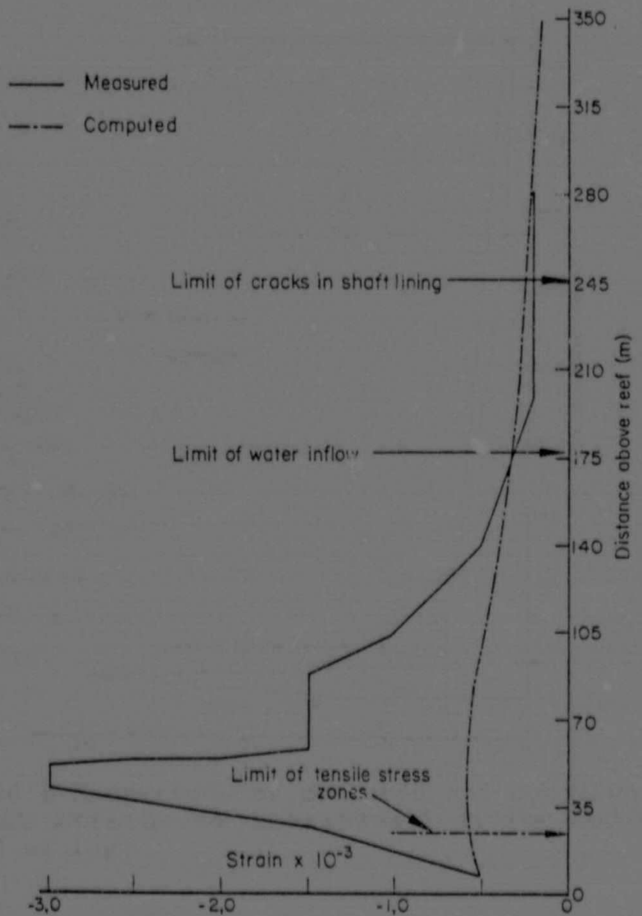

Figure 6.3 Comparison of measured and computed induced, vertical strains in hangingwall at the end of third year of mining

The upper extent of the theoretical tensile stress zone was also compared with observed strains. The stresses were calculated in the strike, horizontal dip and vertical directions. No particular correlation was obvious between the observed strain measurements and the upper extent of the tensile stress zone.

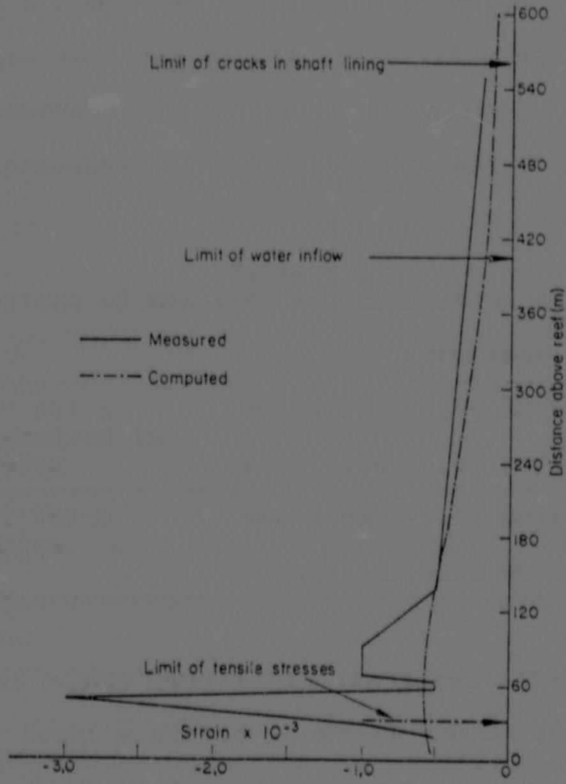

Figure 6.4 Comparison of measured and computed induced, vertical strains in hangingwall at the end of fourth year of mining

Cracks observed in the shaft lining correspond fairly closely with measured and calculated strain values of 0,2 mm/m. See Table 6.1. Water inflow corresponds well with measured strains of approximately 0,3 mm/m. The limiting value at which cracks in the shaft lining occured i.e. 0,2 mm/m, falls within the range 0,15-0,30 mm/m given by Kratzsch (1983) as the tensile strain at which fractures in concrete occur. Wilson (1971) arrived at 0,2 mm/m as the figure at which damage became visible in vertical shafts. This value was not related to the compressive or tensile situation or to any particular component of the vertical shaft.

Table 6.1
Comparison of measured and calculated strains

		3rd Year	4th Year
Strain at which cracks occurred in shaft lining	measured	0,20 mm/m	0,20 mm/m
	calculated	0,24 mm/m	0,13 mm/m
Strain at which water inflow occurred	measured	0,31 mm/m	0,31 mm/m
	calculated	0,34 mm/m	0,20 mm/m

This case study represents the first attempt to quantify the tensile strain at which water inflow is observed, while previously suggested values in terms of tensile strain at which cracks in concrete appear are reinforced.

6.2 Theoretical Modelling of Mining around a Vertical Shaft Using a Downdip Longwall System

If a theoretical study is to serve any practical purpose it is essential to simulate reality as closely as possible. The process of early extraction of the reef in the shaft pillar area is most likely to be carried out at great depth. For faster production and improved extraction the longwall system has definite advantages over the scattered mining method. For these reasons, it is appropriate to model early extraction of the reef in the shaft pillar area, at great depth using a longwall system.

The geometry of a longwall system, with two parallel faces advancing away from each other, is essentially a very simple one. For this reason an analytical solution can be applied to this situation. If the maximum span is expected to be less than the critical half-span, the analytical solution offers a fairly simple method of modelling mining conditions around a parallel-sided longwall. A program called NOPILLAR, developed by the writer and written in PASCAL, is included in appendix B. This program uses an analytical equation applicable to a parallel-sided longwall without closure as first derived by Salamon (1968).

If more than one longwall is to be modelled, a two-dimensional boundary element program such as MINAP can be used. The MINAP program can also model mining conditions after closure. For complex geometry the MINSIM program can be used.

6.2.1 <u>Calculation of stresses and strains in a vertical shaft at the centre of a longwall panel</u>

For the purposes of this study it is assumed that the worst possible condition will occur just before closure. After full closure has taken place it is assumed that the hangingwall and footwall "lock" together while stresses will return to the natural stress condition.

On a flat dip the major mining problem is expected to be that of tensile strain and stress. When the dip is steeper, the problem of ride (i.e. relative displacement in the plane of the reef) can become serious. More O'Ferrall (1983) advises that the early extraction of the reef in the shaft pillar area should not be carried out if the dip exceeds 30 degrees.

It seems appropriate, then, to simulate three different mining situations:

i) a longwall panel just before closure on a 0 degree dip (Table 6.2),

ii) a longwall panel just before closure on a 15 degree dip (Table 6.3),

iii) a longwall panel just before closure on a 30 degree dip (Table 6.4).

Results from the analytical solution and the MINSIM program are shown to correlate well (Table 6.2).

Table 6.2
CORRELATION OF RESULTS FROM AN ANALYTICAL EQUATION AND THE MINSIM PROGRAM: INDUCED VERTICAL STRESSES AND STRAINS ABOVE THE CENTRE OF A PARALLEL-SIDED LONGWALL PANEL ON A 0 DEGREE DIP

Z	STRESS (MPa)		STRAIN (mm/m)	
(m)	Analytical	MINSIM	Analytical	MINSIM
-200	-52,42	-57,4	-0,73	-0,80
-180	-56,48	-61,6	-0,78	-0,84
-160	-60,58	-65,9	-0,82	-0,89
-140	-64,58	-69,7	-0,86	-0,93
-120	-68,33	-73,2	-0,89	-0,96
-100	-71,67	-76,2	-0,92	-0,97
-80	-74,43	-78,6	-0,92	-0,98
-60	-76,54	-80,1	-0,92	-0,97
-40	-77,98	-81,0	-0,89	-0,92
-20	-78,88	-81,3	-0,86	-0,88
0	-79,46	-81,0	-0,82	-0,83

INPUT DATA FOR TABLE ABOVE:
Depth: 3000 m
Young's modulus: 70 GPa
Poisson's ratio: 0,2
Halfspan: 225 m
Stoping width: 1 m
Dip in degrees: 0

6.3 Possible Effects of Early Extraction of the Reef in the Shaft Pillar Area

6.3.1 Horizontal reef

When elastic behaviour of rock is to be used to predict the damaging effects that mining could have on vertical shafts and auxiliary excavations, it appears that the process of early extraction of the reef in the shaft pillar area, could be carried out without any adversity. Vertical and horizontal stresses are tensile, but the actual tensile stresses are not large. Vertical induced strain values are also not excessively high and no serious strain related damage should result (Table 6.2).

The values given above apply to massive, competent rock masses with a high Young's modulus. In practice it is highly unlikely that such perfect conditions will be encountered. In virtually any mining environment some softer layers and discontinuities can be expected. It is these geological departures from the perfect homogeneous rockmass that are likely to present problems to the rock mechanics engineer.

Normal problems associated with early extraction of the shaft pillar include:

i) bed separation in layered strata,

ii) cracking of the shaft lining,

iii) inflow of water in water-bearing strata,

iv) buckling of shaft steelwork and pipe columns due to excessive strain in the shaft.

Although it is possible to minimise bed separation in layered strata with effective support, it is not possible to avoid this kind of damage entirely. Bed separation can have two major effects on the vertical shaft and loading stations close to the reef intersection:

- excessive strain breaks the bond between shaft lining and rock. Pieces of the shaft lining and even the adjacent rock could break loose and fall down the shaft, causing considerable damage.
- excessive strain associated with bed separation can result in damage to shaft steelwork and pipe columns.

Both of these effects could be minimised or prevented. Through careful engineering based on prior knowledge of the geological and mining conditions it is possible to keep control of conditions in the vertical shaft and on the loading stations.

To control the shaft lining two practical methods are suggested. More O'Ferrall (1983) suggests the use of diamond mesh bolted to the rock beyond the lining by rockstuds. Kratzsch (1983) suggests that the shaft lining should not be bonded to the rock at all, but should be separated from the shaft sidewall by a compressible material. The shaft lining should also not be continuous. Vertical strain in the shaft can be compensated for by leaving a gap in between separate lengths of shaft lining. Kratzsch (1983) suggests that a brick lining is more resistant to large strains than concrete. It is interesting to note then, that the shaft that the case study was based on, was brick lined near the reef intersection.

A number of ways are open to the rock mechanics engineer to ensure the safety of steelwork in the shaft. Basically it is necessary to allow for some movement between buntons and sidewalls (it is not impossible to encounter a small amount of ride even when mining is on a horizontal reef) and for vertical movement. Shaft guides must be able to telescope. Pipe columns must be secured well above and below the reef using brackets through which they can move freely.

6.3.2 <u>Shallow dip</u>

All the above problems will be experienced when extracting the reef in the shaft pillar area on a shallow dip. A small ride component is likely to aggravate problems in the vertical shaft (Table 6.3).

As with the horizontal reef case the elastic movements in the rock do not indicate that the conditions in the vertical shaft should be extreme. If the extent of displacement in the rock can be estimated with the aid of a computer model, it is possible for the engineer to prepare for such movement.

The amount of ride that can be expected on a shallow dip should be fairly well compensated for with the same precautions as is taken for a horizontal reef.

Table 6.3
VERTICAL AND HORIZONTAL STRESSES AND VERTICAL STRAINS ABOVE AND BELOW THE CENTRE LINE OF A PARALLEL-SIDED LONGWALL PANEL ON A 15 DEGREE DIP

Z (m)	Vertical Stress (MPa) Induced	Vertical Stress (MPa) Total	Horizontal Stress along strike (MPa) Induced	Horizontal Stress along strike (MPa) Total	Induced Strain (mm/m)
-200	-58,3	17,3	0,1	39,3	-0,79
-180	-61,6	14,6	-2,7	36,8	-0,82
-160	-65,6	11,1	-6,4	33,4	-0,87
-140	-69,4	7,8	-11,0	29,0	-0,90
-120	-72,6	5,2	-16,8	23,5	-0,93
-100	-75,1	3,2	-23,8	16,8	-0,94
-80	-76,6	2,3	-32,4	8,5	-0,92
-60	-77,9	1,5	-42,2	-1,1	-0,91
-40	-78,9	1,0	-52,9	-11,5	-0,90
-20	-79,3	1,1	-63,8	-22,1	-0,86
0	-78,8	2,2	-71,0	-29,0	-0,83
20	-78,5	3,1	-60,5	-18,2	-0,86
40	-78,2	3,9	-49,6	-7,0	-0,90
60	-77,5	5,1	-39,2	3,6	-0,92
80	-76,0	7,2	-29,9	13,2	-0,94
90	-74,8	8,6	-25,6	17,6	-0,94

Ride in the plane of the reef at shaft-reef intersection: 152 mm

INPUT DATA FOR TABLE ABOVE:
Depth: 3000 m
Young's modulus: 70 GPa
Poisson's ratio: 0,2
Halfspan: 245 m
Stoping Width: 1 m
Dip in degrees: 15

The shaft lining can be safe-guarded in the same manner as before. In the case of a shallow dip some problems may be experienced on the shaft brow. Reinforced concrete could compensate for the stress that the shaft brow will experience.

Shaft steelwork should once again allow for horizontal relative movement or ride and vertical strain.

Table 6.4
VERTICAL AND HORIZONTAL STRESSES AND VERTICAL STRAINS ABOVE AND BELOW THE CENTRE LINE OF A PARALLEL-SIDED LONGWALL PANEL ON A 30 DEGREE DIP

Z (m)	Vertical Stress (MPa)		Horizontal Stress along strike (MPa)		Induced Strain (mm/m)
	Induced	Total	Induced	Total	
-200	-51,8	23,8	-2,8	36,4	-0,68
-180	-56,4	19,8	-5,8	33,7	-0,73
-160	-60,9	15,8	-9,5	30,2	-0,78
-140	-63,4	13,8	-14,1	26,0	-0,80
-120	-65,1	12,7	-19,6	20,7	-0,81
-100	-67,7	10,6	-26,4	14,2	-0,83
-80	-70,3	8,5	-33,9	7,0	-0,84
-60	-71,8	7,6	-42,3	-1,1	-0,83
-40	-73,8	6,2	-51,4	-10,0	-0,83
-20	-75,7	4,8	-60,8	-19,1	-0,83
0	-75,1	5,9	-64,3	-22,3	-0,82
20	-73,9	7,6	-55,2	-12,9	-0,83
40	-72 9	9,1	-46,1	-3,5	-0,85
60	-70,6	12,0	-37,5	5,3	-0,84
80	68,4	14,8	-29,6	13,6	-0,82
90	-67,5	15,9	-26,1	17,2	-0,82

Ride in the plane of the reef at shaft-reef intersection: 263 mm

INPUT DATA FOR TABLE ABOVE:
Depth: 3000 m
Young's modulus: 70 GPa
Poisson's ratio: 0,2
Halfspan: 245 m
Dip in degrees: 30

6.3.3 Steep dip

When mining on a steep dip, the problem of ride becomes a most important factor in the effects that mining can have on vertical shafts. As can be seen from the computed values (Table 6.4), the amount of ride could exceed 250 mm when a 1 m stoping width is extracted. If the stoping width is higher the amount of ride will be proportionately higher. For high speed winding to negotiate such a large displacement it is necessary to compensate for this displacement. Shaft steelwork must be designed in such a manner as to be adjustable for a large distance above and below the reef intersection. A guide rope system can cope best with this large displacement, but guide ropes can not be used in deep shafts.

CONCLUSIONS

The elastic model gives an acceptable description of the response of rock masses beyond the loosened up hangingwall. The region in which bed separation and loosening of the strata takes place, may extend beyond the theoretical limits of the tensile stress zone. The bedded nature of the hangingwall has an overiding influence on the height of this region.

The zone in which the induced vertical strain causes undesireable effects in the shaft extends well beyond the tensile stress and loosened up zones. The critical strains for tensile fracturing of the shaft lining and for inflow of water were found to be 0,20 mm/m and 0,30 mm/m respectively. Both these values are below the tolerable figure of 0,40 mm/m from the point of view of the unimpaired use of the shaft steelwork.

The magnitude of induced strain and the locations of its critical values can be determined and controlled.

The three tables of simulated values give an indication of the stresses and strains that may affect a vertical shaft along the centre line of a down-dip longwall panel. The model indicates that cracks in the shaft lining may extend for a large distance above and below the reef. Depending on groundwater conditions, these shafts will also be vulnerable in terms of water inflow. Loosening of layers in the hanging- and footwall may aggravate the situation in terms of strain and ride components.

It is clear that the conditions as calculated may be difficult to control or even intolerable. Remedial action may include backfill, satellite pillars, adjustable steelwork in the shaft and either no lining or a reinforced lining. The early mining of the reef in the shaft pillar area may not be without hazard at great depth, but it is possible to determine the effect of pillars and backfill so that ground conditions can be controlled.