

FACTORS AFFECTING THE UNDERMINING OF SURFACE STRUCTURES
ABOVE HARD ROCK MINES IN THE CENTRAL WITWATERSRAND AND THE
WESTERN BUSHVELD IGNEOUS COMPLEX

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DECLARATION

I declare that this project report is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering (Mining) in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Signed *OBahaw* ..

Dated this *11* day of ... *October* 1991

ABSTRACT

The Mines and Works Regulations allow the undermining of surface structures under conditions which are uniformly applied in both the Central Witwatersrand and Bushveld Igneous Complex regions. There are, however, factors which are different to the Central Witwatersrand and Bushveld Igneous Complex and which affect the undermining of surface structures. Although the determination of the underground area affected by the restriction to mine under or near surface structures ("restricted area") is based on accepted engineering principles, the determination of support requirements for the protection of the surface is based on an extraction ratio or the construction of waste packs and do not consider geotechnical differences. These requirements may result in over- or underdesigned pillars, in spans between pillars either being under- or overdesigned and in the locking up of valuable minerals. The depth cut-off of 240 m below surface at which the conditions are applied, is valid.

There are similarities between the mining practices in the two environments based on the geometries of the orebodies and the strengths of the overlying strata. However, pillar design and calculation of the mine spans between pillars differ fundamentally, as the strata immediately overlying the Bushveld Igneous Complex on-reef excavations are generally weaker than the rock masses in the Witwatersrand. The pyroxenites overlying the UG2 reef are

intersected by closely spaced and moderately dipping joints and to a depth of about 70 m the effects of weathering can be substantial. As a result the pyroxenites need to be partially or totally supported as a deadweight. The presence of geotechnical structures such as dykes and faults further weakens the strata : weathering along jointed zones on their margins is severe and can extend to depths of 100 m. The determination of safe mine spans depend on the competency of the norite/anorthosite series overlying the Merensky and UG2 reefs. Graphs based on the Mohr-Coulomb failure index have been designed from which safe mine spans can be read off. The design of pillars is based on strength of material criteria and the orientation of the major jointing.

The mining on the Witwatersrand in the area and depth range of interest has resulted in mainly supercritical mine spans, especially on the South reef horizon resulting in the subsidence of the overlying strata. Formulae have been designed to calculate the theoretical height of caving in both the South and Main reef workings which, in conjunction with the graphs from which safe mine spans can be read off, can be used to determine maximum span widths.

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1. INTRODUCTION

1.1 The Phenomenon of Surface Subsidence due to Mining

Subsidence and its effects on the surface is a major problem in countries with significant mining industries. This problem has become more prominent with increased pressure for development of the surface of mining ground.

The term subsidence, as applied to the earth's surface, is defined by WHITTAKER (1989), as a surface point sinking to a lower level, and can include a structure settling into the ground or the ground itself lowering and carrying the structure with it, or even a surface layer collapsing into an underground cavity.

The process of mining of any stratified mineral, is inevitably followed by some degree of sinking of the overlying strata and consequently of the surface. In the words of the ROYAL COMMISSION ON MINING SUBSIDENCE (1927): "the descent of the superincumbent strata of a completely extracted mineral, will come down until the subsidence reaches the surface. This process, in the case of hard and relatively brittle rock, is accompanied by more or less fracturing and, therefore, by an increase in volume of the strata thus let down. It follows that the surface subsidence is never equal to the thickness of the mineral extracted. The hard and brittle rock will break up in comparatively large blocks which pile up irregularly on

each other and afford at the outset a certain measure of support to the overlying beds. The pressure of these beds gradually crushes down and partly reconsolidates the broken blocks, and, in this way the subsidence ultimately reaches the surface, but as a rule only after a greater interval. The movement, too, continues longer, and the total amount of surface subsidence is less than when the superincumbent strata consist mainly of softer and more plastic rocks".

Thus, in order for surface subsidence due to mining operations to occur, some form of underground collapse or abstraction process must precede such an event. Consequently the form of mining, degree and extent of activity coupled with geological factors play a role in causing subsidence. Mining needs to be of a sufficient magnitude before its effects become of significance to disturbing the surface. As stated by WHITTAKER (1989), the creation of an underground mining excavation results in a re-distribution of the stress field and this reacts with the rock surrounding the excavation thereby inducing movements with possible collapse potential or subsequent closure that is related to time.

Recent research has shown that the statement by the ROYAL COMMISSION is still valid and VAN DER MERWE (1984), remarks :

"When collapse of the roof takes place, the broken rubble undergoes a volumetric increase, known as bulking. The

degree of volumetric increase is governed by the bulking factor which is different for different rock types. As the collapse progresses into the roof, a stage is reached when the entire cavity is filled with rubble. The second phase of the subsidence comes into operation where, under the influence of gravity the hitherto intact but joined rock layers overlying the rubble will deflect and then fail along pre-existing geological discontinuities, forming relatively large blocks. These will come to rest on the rubble, and by their weight, compress the cavities in the rubble. This process will proceed upward until the surface is reached and subsidence will be the result".

1.2 Measures to Prevent Subsidence

The interest in mining induced subsidence is the result of the potential it has to cause serious damage to property and, indeed, to endanger lives. The South African Mines and Works Act and Regulations therefore caters for the undermining of structures and mining under or within a defined distance from surface structures is restricted.

In this country research has addressed itself to the question of surface effects due to coal mining operations. At present, the Strata Control Advisory Committee of the Coal Mining Research Controlling Committee (a statutory body which advises the Government Mining Engineer on matter relating to safety in coal mines), is carrying out a project which involves the monitoring of the surface overlying high extraction mining methods at shallow

depths. This Advisory Committee has been in existence since 1961, and has looked at supporting the surface of shallow coal mines since its inception.

The geotechnical conditions of hard rock mines differ fundamentally from those of coal mines : the strata overlying coal seams consists of material of a far weaker nature while the coal itself is also a weak material. Coal deposits in this country are normally horizontal to very shallow dipping while gold and platinum deposits are normally inclined. Coal as well as gold and platinum occur in tabular deposits in this country, but coal is normally contained in far wider seams, on average about 3 m thick. Although the approach adopted to control subsidence is similar for coal and hard rock mines, i.e. the leaving of solid pillars, the geotechnical differences are such that established formulae and mining methods for the protection of the surface overlying coal mines cannot be directly used for hard rock mines.

Very little research has been carried out into surface effects due to mining shallow, narrow, tabular orebodies such as exist in the Central Witwatersrand and the Bushveld Igneous Complex. BRINK (1979) and HILL (1981) carried out some research into the measurable subsidence which could and sometimes gave rise to damage in the Central Witwatersrand region. KOTZE (1986) reported and described occurrences of subsidences at platinum mines in the Bushveld Igneous Complex. SPENCER (1990) described

the mode of failure of crush pillars in a platinum mine and how this could affect the stability of the overlying strata.

In 1984, an Undermining Committee was appointed by the Minister of Mineral and Energy Affairs to investigate undermining and the use of the surface of undermined ground above shallow gold mines and platinum mines. Collieries were specifically excluded from the terms of reference of this Committee.

In 1989, the Working Group of the abovementioned Committee brought out a preliminary report, which was to be discussed and commented upon by the members of the Working Group. This preliminary report is attached as Appendix A and as may be noted in Section 6.2 of this Appendix, proposed guidelines have been drafted. However, they are of a general nature and do not consider the different geotechnical environments of the Central Witwatersrand and the Bushveld Igneous Complex.

1.3 Control of Subsidence in Other Countries

In other major mining countries rules for the protection of the surface have been legislated (ADAMEK, 1985, BRAUNER, 1972, FRANKHAM, 1984). STASIKOWSKI (1986) tabulated measures taken in these countries, and a summary of these appear in Section 3.3 of Appendix A. When comparing the rules applicable in the different countries, one comes to the conclusion that there is no common

solution for the prediction of subsidence. This is mainly due to the variety of geological conditions. Therefore rules for the control of subsidence must be based on geological and geotechnical data of the areas in which they are applied.

1.4 Present Legislation

As stated before, the Mines and Works Regulations regulate the undermining of surface structures. The relevant Regulations appear in Section 2.2 of Appendix A and they stipulate that whenever, in the opinion of the Inspector of Mines, it may be necessary to protect the surface and structures on the surface, he may prohibit the owner or manager of the mine from mining any portion of the mine which may affect the stability of the surface except under such restrictions and subject to such conditions as the Inspector, with the approval of the Government Mining Engineer, may determine. In arriving at restrictions and conditions to be applied, the Inspector of Mines uses guidelines. These guidelines were established in 1946 and were revised in 1965 by the Government Mining Engineer's office. They stipulate the percentage of solid rock that has to be left in situ in the form of pillars, or, as an alternative, the percentage of mined out area which has to be packed by waste rock, to form the support for the protection of the surface.

However, the guidelines were found to be inadequate in recent years : they do not consider differences in

geological and geotechnical environments and are too rigid to be applied to different mining methods.

The main purpose of the Undermining Committee was to evaluate and revise the guidelines.

The guidelines define a "restricted area" into which the restrictions and conditions have to be applied. The determination of and the background to the definition are given in Section 2.1.3.1.

As is explained in Section 1.5 differences exist between the geotechnical environments of the shallow Witwatersrand and Bushveld Igneous Complex mines. This report investigates these differences to establish factors which affect the undermining of surface structures.

1.5 Platinum versus Gold Reef Mining

The reason for applying the same restrictions and conditions for the undermining of surface structures in both the Witwatersrand and the Bushveld Igneous Complex, is the similarity between mining practices in the two regions.

These similarities arise from the fact that :

- * geometrically the orebodies are very similar and outwardly the same basic mining methods are utilized; and

- * the uniaxial compressive strength of the overlying strata in general is relatively high (greater than 200 MPa) in both environments.

However, mining methods differ fundamentally, as the strata immediately overlying the Bushveld Igneous Complex on-reef excavations is much weaker for reasons explained below, whilst the rock masses in the Witwatersrand typically comprise uniform and continuous series of quartzites with occasional grits and conglomerates that are massive to widely jointed with subvertical, discontinuous and thinly infilled joints (TUCKER, 1986). Collapses in the shallow gold mines are typically restricted to the first few metres of a hangingwall sequence.

In the Bushveld Igneous Complex safe panel spans depend on the competent norite/anorthosite series overlying the Merensky and UG2 reefs. However, the immediate hangingwall in platinum mines typically consists of sequences of pyroxenites that, in some areas of the Bushveld Igneous Complex are thickly developed (COERTZE, 1971). These sequences are intersected by closely spaced and moderately dipping joints, which were subjected to late-phase hydrosylicate alteration, which significantly reduced their strength (VILJOEN, 1986). Shear zones also cut the pyroxenites sequences, the majority of which have little or no displacement. The pyroxenites are typically

weathered along the joints and shears to depths that are far greater than those experienced in typical shallow Witwatersrand gold mines (see Section 3.2.2).

The end result is that Bushveld Igneous Complex hangingwall pyroxenites tend to act as blocky masses which need to be partially or totally supported as deadweight, and sometimes on a block by block basis. As such, the stability of the pyroxenites is a consideration independent of the determination of safe panel spans.

This situation differs significantly from normal Witwatersrand gold mining environments where there is greater strength along the widely spaced and steeply inclined joint surfaces. As such, effective interlocking of joints bounding blocks occurs. This reduces internal stope and face support requirements and enable the immediate hangingwall stope spans to act as strong elastic beams/arches.

1.6 Overall Aims of the Study

The subsequent sections of this project report address the present situation around the undermining of surface structures and the protection of the surface.

Geotechnical details concerning the rockmass overlying the Central Witwatersrand and Bushveld Igneous Complex mines are investigated and are applied to rock mechanics considerations.

The study of factors affecting the undermining of surface structures has become more urgent with the increased pressure by industrialists and township developers to use land that is underlain by mineral deposits. The establishment of these factors and the recommendations on mining methods and support based on the factors will be useful to the Inspector of Mines when he has to consider undermining applications from the Witwatersrand and the Bushveld Igneous Complex mines.

Although some investigations have already been carried out (HILL 1981, BRINK 1979), these were concentrated on the use of undermined ground. The preliminary report of the Working Group on Undermining Guidelines also covered the topic of providing guidelines in a general sense. This project report attempts to establish factors affecting the undermining of surface structures in two mining areas, Central Rand and the western Bushveld Igneous Complex and to make recommendations on mining methods and support based on these factors.

In Chapter 2 definitions and terms associated with subsidence and a background to the existing guidelines are given.

Section 3 considers the different geotechnical details of the Central Rand and the western portion of the Bushveld Igneous Complex which are necessary for the establishment of design criteria in Section 4.

Section 4 considers the geotechnical data and deals with the behavioural characteristics of the intact rock mass. Suitable design criteria and methods for analysis of the overlying strata are established.

Section 5 applies the design criteria established in Section 4 to determine graphs and tables for different mine spans and to determine pillar sizes for the protection of surface structures.

2. REVIEW OF THE EXISTING GUIDELINES AND THEIR BACKGROUND

2.1 Background to the Existing Guidelines

Before considering the existing guidelines, it is necessary to explain in some detail definitions and terms relating to the deformation of the surface. VAN DER MERWE (1984) distinguishes between two classes of subsidences : planned and unplanned. Planned subsidences are confined to coal mines which practice high extraction mining methods, such as longwalling and pillar extraction. The type of subsidences occurring in the Central Witwatersrand and in the Bushveld Igneous Complex regions can be classified as unplanned subsidences. This class is typified by fractures in the ground due to underground mining which leads to discontinuous deformations of the surface.

2.1.1 Types of Surface Effects

Some of the discontinuous effects of subsidence due to underground mining have been identified in the Central Witwatersrand region as follows (HILL, 1981) :

- (i) Discontinuous subsidence resulting from the cantilevering of the wedge of hangingwall defined by a shallowly dipping stope and the ground surface. This behaviour is commonly restricted to an area adjacent to the stope outcrop

(within 30 m of it), and may result in the formation of a step or steps in the surface profile with open cracks (Figures 2.1.a and b).

- (ii) Discontinuous subsidence resulting from block movement in which the subsided block of ground is defined by major fault and/or dyke contact planes, the stope and the ground surface. Open cracks may be observed at the contact. In some cases more than one major contact plane may define the block of ground. This form of subsidence may occur over a wide range of mining depths and is not restricted to the outcrop area. Very significant differential subsidence can occur (Figures 2.1.c and d).
- (iii) Discontinuous subsidence resulting from the ravelling or washing away of fill from a stope outcrop area. This type of subsidence is commonly called a sinkhole, but should not be confused with the true sinkholes which form in dolomitic rock formations. Sinkholes are localised occurrences restricted to the immediate stope outcrop areas. They appear as open holes, and ventilation air is commonly

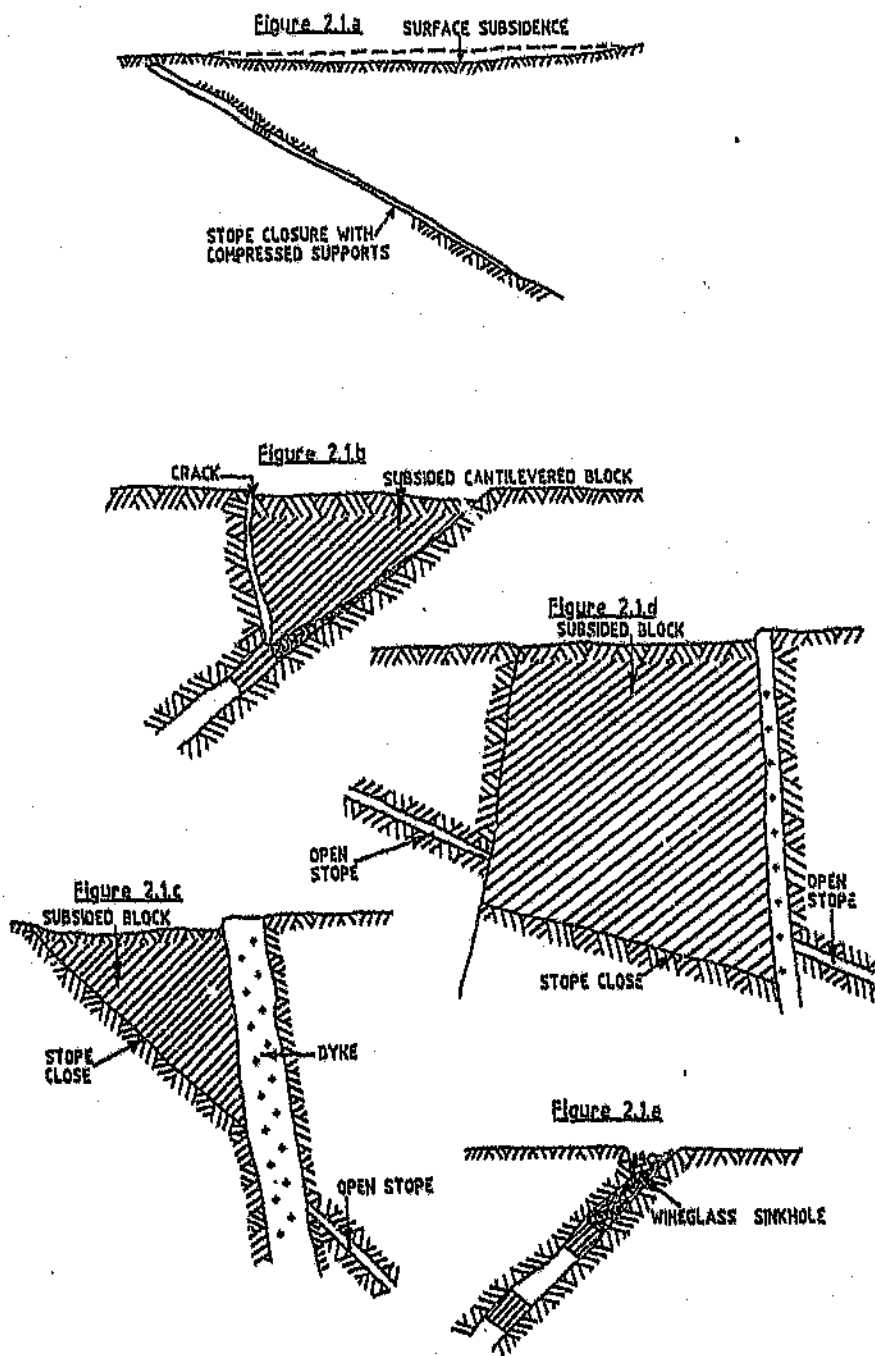


FIGURE 2.1 MECHANISMS OF SUBSIDENCE (AFTER HILL)

noticed, indicating connection with mining workings at greater depths (Figure 2.1.e).

Deformation of the surface :

The effects of ground movement on the surface are described by the following components :

- (i) Vertical displacement at a point or subsidence. The vertical displacements of surface points form a subsidence trough which frequently extends, in plan view, beyond the edges of the mined out area in all directions.
- (ii) Horizontal displacement of points on the surface which accompanied subsidence.
- (iii) Differential movements of the surface also occur. This affects the slope of the subsidence profile. Surface strains result from the differential ground displacements, and both lengthening and shortening of the surface occur.
- (iv) Curvature of the subsidence profile occurs. The subsidence profile is a curve depicting subsidence on a section drawn across the subsidence trough.

- (v) The angle of draw is the angle of inclination from the vertical of the line connecting the edge of the workings and the edge of the subsidence area. Several researchers whose works are summarised in BRIGGS (1929) and LANE (1928) refer to "draw" or "pull", when describing the movement of rock towards the excavation (Figure 2.2).
- (vi) The angle of break is the angle between the vertical line at the opening edge and the line connecting the opening edge and the point of maximum tensile strain on the surface. The strain is the most likely place where tensile cracks occur (PENG, 1986). The angle of break in hard rock mines tends to be 20 degrees and lying over the mined out area (WHITTAKER, 1989).

2.1.2 Instability Types

Two principal type of mining spans can exist : subcritical and supercritical (BRADY, 1985) :

Subcritical spans : a subcritical condition is characterised by bulk elastic deflection only. For reef plane dips of 20 to 40 degrees, the magnitude of deflection would depend on the rigidity of the rock mass,

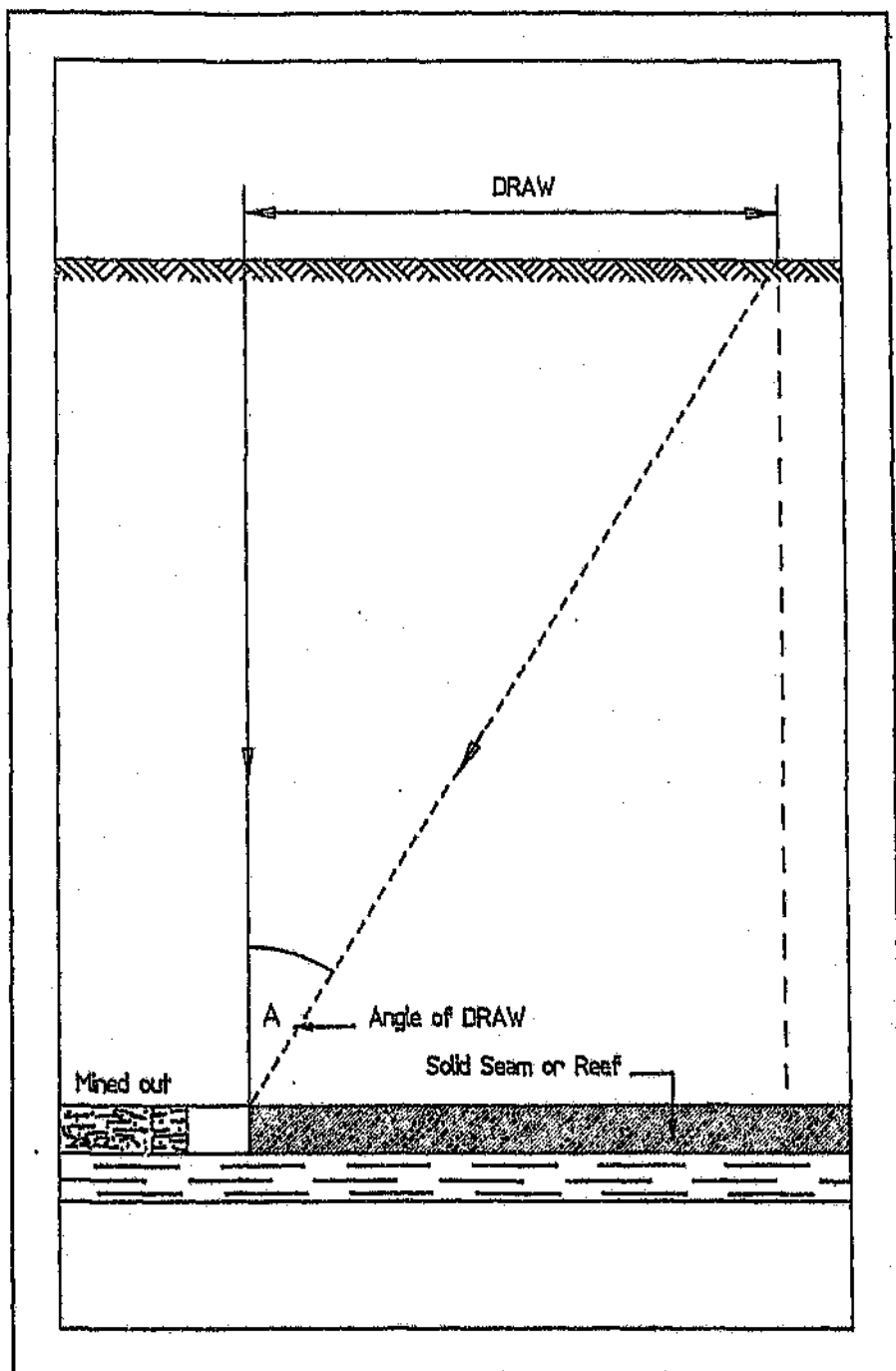


FIGURE 2.2 ANGLE OF DRAW

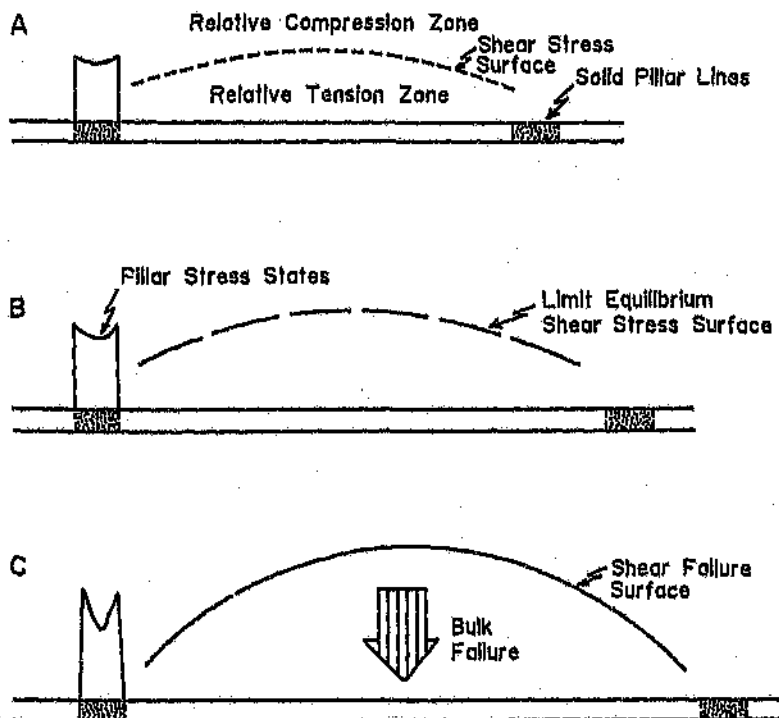
the depth below surface and the magnitudes of the horizontal field stresses. An increase in either the mined spans or mining depth would result in additional movement, increasing horizontal stresses would mostly tend to promote overall stability (Figure 2.3 A).

Supercritical spans : the transition from a subcritical to a supercritical span is usually defined by a span unique for each type and thickness of rock mass. This so-called critical span represents the point of critical stress state for the deflecting rock mass (figure 2.3 B). A small increase would result in the creation of a supercritical condition. A supercritical condition would result in partial or total failure of the overlying rock mass (KRATZSCH, 1983). This would be initiated by induced and dynamic slip along a critically stressed surface. In general terms, failure would result from excessive elastic deflection according to the Voussoir Beam Theory (BRADY, 1985)(Figure 2.3 C).

2.1.3 Existing Guidelines

In terms of Common Law rules the mineral rights holder must provide subjacent support to the surface so as to avoid damage to the surface and surface structures (VILJOEN, 1975, FRANKLIN, 1982, JOUBERT, 1952). These rules are enacted in the Mines and Works Regulations (Regulations 5.3.1, 5.3.2, 5.3.3 and 5.3.4).

2.1.3.1 Restricted Area



- A - A Subcritical Span
- B - A Critical Span
- C - A Supercritical Span

FIGURE 2.3

IDEALISED SECTIONS THROUGH SUB-CRITICAL AND SUPER-CRITICAL MINE SPANS

As has already been mentioned in Section 1.4 the guidelines used by the Inspector of Mines mention a "restricted area". The restrictions and conditions contained in these guidelines are applied in the restricted mining area. In determining the restricted area, protection along the rise, dip and strike must be provided. Where the dip of the reef is less than 20 degrees, it is usual to define this area as "within a horizontal distance of $d/2,7$ " where "d" is the vertical depth to footwall elevation of the deepest reef beneath the natural surface of the ground, and the horizontal distance is measured from the sides of the structure to be protected (Figure 2.4).

When the dip of the reef is greater than 20 degrees, the restricted area is shown on Figure 2.5 and defined as follows :

- * up dip or rise side - a horizontal distance of $d/2,7$ measured up dip, at right angles to the strike of the reef.
- * strike side - a distance of $d/5,7$.
- * dip side - no protection is required, but a nominal distance of 3 metres is specified.

The area so restricted is limited according to the depth of the reef, and normally a restricted area is only applicable to depths less than 240 m.

A ILLUSTRATIONS OF RESTRICTED MINING AREAS WHERE THE DIP OF THE REEF OR SEAM IS LESS THAN (SAY) 20° FROM THE HORIZONTAL

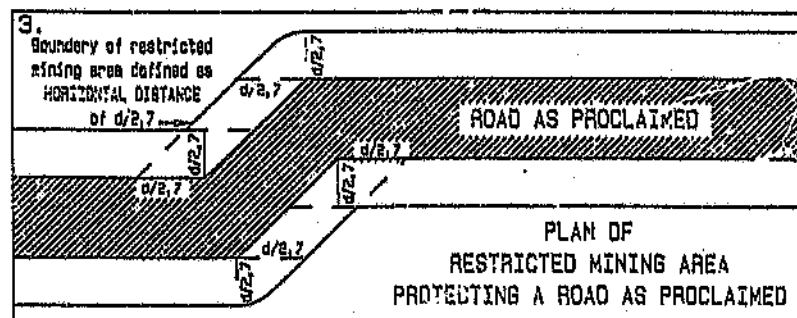
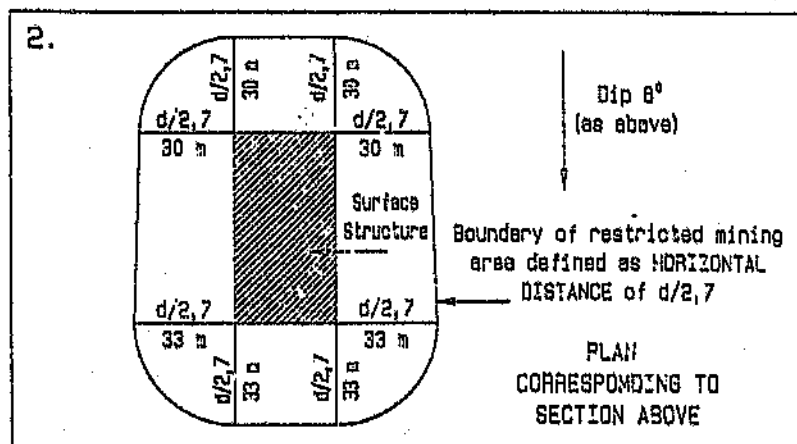
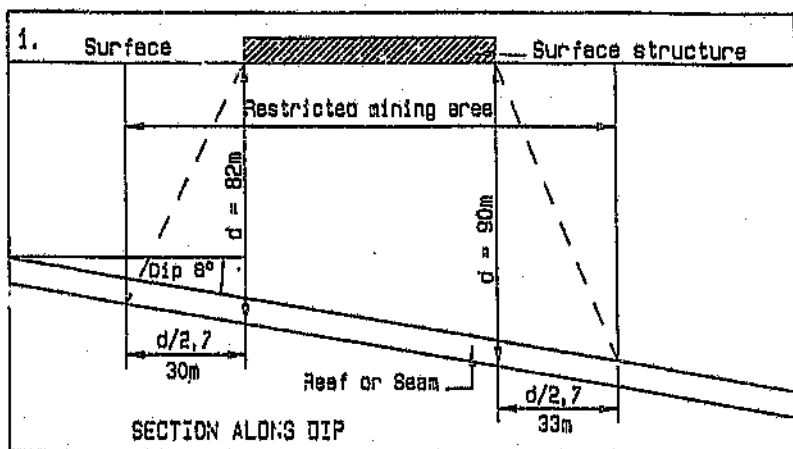


FIGURE 2.4

RESTRICTED AREA REEF DIP $< 20^\circ$

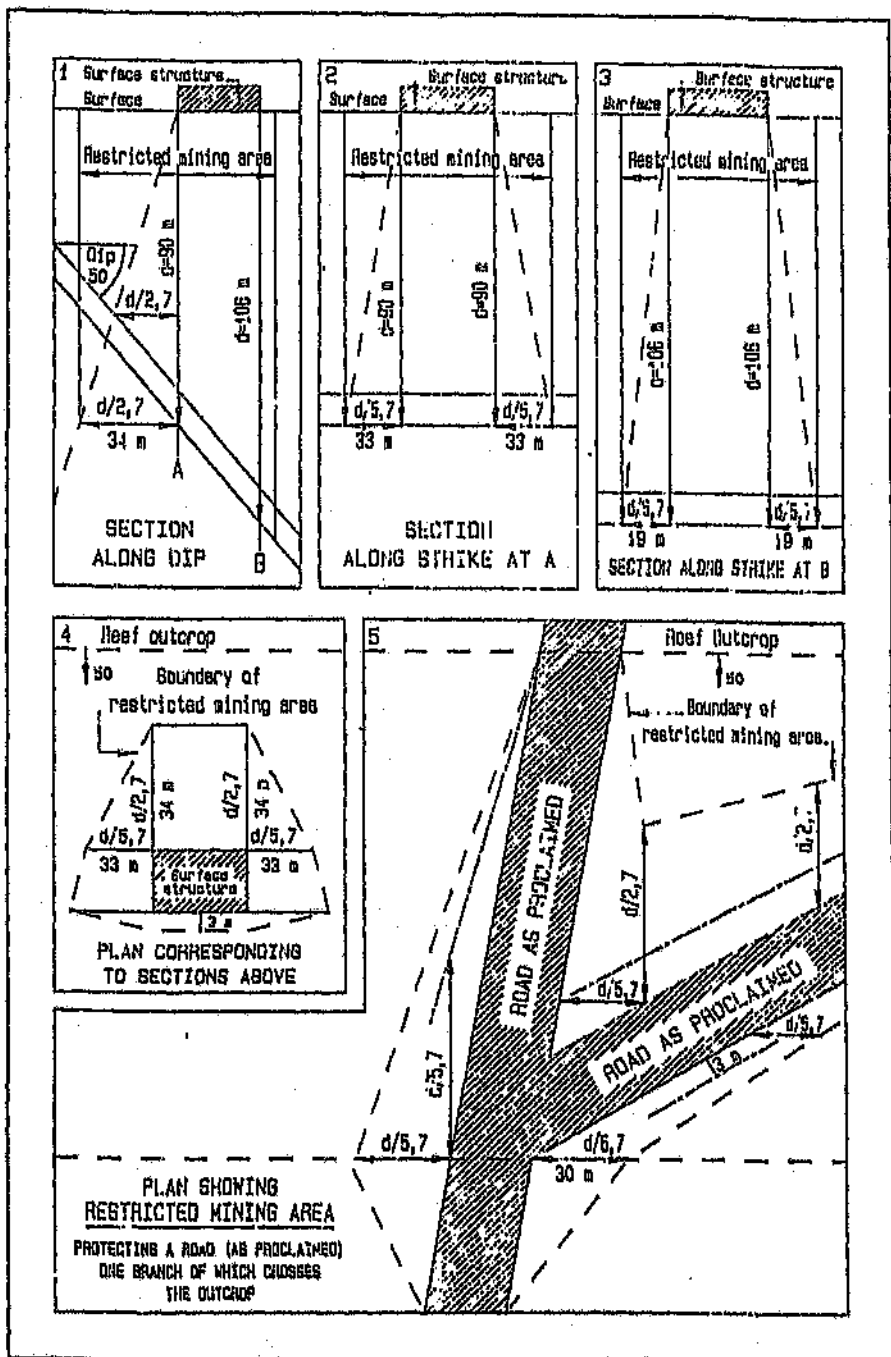


FIGURE 2.5

DETERMINATION OF RESTRICTED AREA : $\text{DIP} > 20^\circ$

As may be noted on figures 2.4 and 2.5 the restricted area is determined by the angle of draw.

Investigations around the turn of the century by the Dortmund Board of Mines in the Westphalian coalfields, revealed that the angle of draw in overlying marl, never exceeded 20 degrees from the vertical.

It is also relevant to the present guidelines on undermining surface structures, to note that the conclusion drawn by the Board that the angle of draw is always found to be positive, i.e. slanting over the solid reef or seam.

RICHARDSON, (1907), refers to an angle of draw, A, for moderate dipping reefs, lying halfway between the vertical and the normal to the plane of stratification:

$$A = \left[\frac{\pi}{2} - \frac{1}{2} \right] d = \frac{1}{2}(\pi - d) \quad - (2.1)$$

Hausse (1907) proposed a formula for German coal fields :

$$A = \tan d = \frac{1 + \cos^2 d}{\sin d \cos d} \quad - (2.2)$$

where d = dip of the reef

RICHARDSON (1907) states that this formula is applicable for reefs with dips greater than 30 degrees.

The angles of draw values obtained by using formula 2.2 are tabulated in table 2.1.

TABLE 2.1 APPLICATION OF HAUSSE'S FORMULA IN CALCULATING
ANGLE OF DRAW AT VARYING REEF DIPS ABOVE 20
DEGREES

Dip of seam in degrees	Angle of draw in degrees
30	76
40	73
50	70
60	71
70	74
80	80
90	90

The angle of draw is measured from the horizontal in formulas 2.1 and 2.2 and it may be observed that the angle of draw does not exceed 20 degrees from the vertical.

A simple calculation shows that $d/2,7$ approximates $\tan 20$ degrees x depth :

$$\frac{d}{2,7} = \tan 20 \times \text{depth} \quad - (2.3)$$

The same calculation shows that $d/5,7$ equals $\tan 10$ degrees x depth :

$$\frac{d}{5,7} = \tan 10 \times \text{depth} \quad - (2.4)$$

Formula 2.3 is based on Richardson's paper and both formulas 2.3 and 2.4 have been applied since 1946 (GOVERNMENT MINING ENGINEER, 1946 - 1987) and most likely previous to these dates as well. However, no reference could be found of the criteria on which the $d/5,7$ distance from the edge of the surface structure to the edge of the restricted area is based. One of the reasons for a

smaller angle of draw could be the fact that the hangingwall above shallow reefs dipping at small angles are more prone to gravity induced damage than the hangingwall above steeply dipping reefs.

The arbitrary distance of 3 m on the dip side of the restricted area is not based on any of the recommendations made in the references available. However, the application of the guidelines have not resulted in any reported subsidences in the restricted areas where the dip of the reef exceeded 20 degrees. BRIGGS (1929) on page 53, also expressed doubts about this rule, but stated that "it must be admitted that observations taken up to the present seem, on the whole, to indicate that there is some justification for its adoption" (referring to the negligible angle of draw on the down dip side of a pillar in a steeply inclined coal seam).

2.1.3.2 Depth at which Guidelines are Applicable

The lack of restrictions below the 240 m contour is most probably based on actual observations of surface effects. The Government Mining Engineer's annual reports between 1903 - 1927 refer many times to the appearance of surface cracks in areas where the surface has been undermined in the Central Rand area. No such reports have been published in subsequent annual reports. The reason could well be that mining took place in excess of 300 m depth in the years following 1927, and, although caving and collapsing of worked out areas still occurred, the effects

never reached surface. An example is a report of caving of an area of 180 m on dip and 330 m on strike at depths of between 218 m and 280 m at Geldenhuis Deep, which did not cause any surface disturbance. This collapse could be associated with reclamation mining, where the removal of a pillar resulted in an unsupported supercritical mining span.

Scrutiny of Departmental copies of mine plans of defunct mines in the Central Witwatersrand region, which are kept in the Government Mining Engineer's office, did not reveal any surface subsidence which could have been associated with mining operations at depths greater than 240 m.

However, subsidences not associated with current mining operations occurred at regular intervals after 1927 along the outcrop area of the Central Witwatersrand region. They were of the types depicted on figure 2.1. Section 4.2 of Appendix A describes these subsidences in some detail.

2.1.3.3 Mining Restrictions and Support Requirements

The existing guidelines stipulate that :

- * no mining is permitted in the restricted area down to a vertical depth of 30 metres.
- * normal mining operations are permitted in the restricted area at depths greater than

30 metres provided that the combined stoping widths do not exceed 38 cm for every 30 m of vertical depth.

- * where the combined stoping widths exceed this stipulated value, the measures of support summarised in table 2.2 are required on each of the reefs stoped. In this table the solid support and systematically packed waste rock support are alternatives.

TABLE 2.2 SUPPORT REQUIREMENTS AT DIFFERENT DEPTHS IN THE RESTRICTED AREA

Vertical Depth Range (m)	Solid Pillar Support ‡	Waste Rock Pack Support ‡
0 - 90	15	40
90 - 150	12	30
150 - 200	10	20

As further qualifications on this support, the pillars shall not be less than 3,5 m square and their spacing shall be equidistant. In the case of waste rock packing, the packs shall be 8 m x 8 m, spaced equidistantly and carefully built by selected stone. They shall have a suitable batter and shall be properly toed into the footwall.

Consideration would be given to limiting stoping widths, and to the existence of, or requirements for, the

superimposition of pillars on the different reefs. The Inspector of Mines would have to be satisfied that the normal method of support of the overburden cover is such that no danger would result from a sudden and violent collapse.

It should be mentioned that the requirements as stipulated in the existing guidelines are still applicable to all mining areas, except coal.

2.2 Computer Simulation Studies

Computer studies using mining simulation stress programmes were carried out with the view of correlating observed and reported subsidences with calculated results (STASIKOWSKI, 1987). The behaviour of the models was purely elastic and the analyses were continuum, and therefore did not take into account any discontinuities such as dykes and faults. Although correlation was weak, it was established that additional mining was the most obvious cause of further strata movement and the failure of support.

It was also established that regions of maximum tilt and horizontal strain are associated with crown pillars, if one is present, and with down dip abutments of the stope. These effects are less for steeper stopes. When mining takes place at depths greater than 200 m, the effects on surface are very small.

2.3 Effects of Underground Excavations on Hanging-wall Strata

The effects of underground excavations on the hangingwall strata are evaluated in Section 4.1 of Appendix A in detail. The criteria used in these evaluations, are :

- * the quality of the rock mass
- * the geological conditions
- * the prevailing state of virgin strata
- * the dimensions of the opening in relation to its depth below surface
- * the reef inclination, and
- * the type and degree of support provided.

This report uses the same criteria to investigate the factors affecting the undermining of surface structures.

2.4 Time Dependent Factors Influencing Pillars and Overlying Strata

HILL, (1981), emphasizes the fact that after the lapse of a certain period, the strata above mined out areas has come to rest. He quotes a period of 20 years. He bases this statement on the results of surface levelling over mined areas in the Central Rand region which have shown that the rate of surface movement reduces with time after mining has stopped.

The records also show that reactivation of mining, for example as in reclamation mining when solid pillars are

removed, also reactivates movement of the surface. In partial extraction systems, collapses of pillars can occur many years after cessation of mining, leading to subsidence of the surface. In this regard it is worthwhile to mention that in 1978, subsidence due to 150 metre deep old limestone workings resulted in significant damage to warehouses and industrial plant in Britain (LIMESTONE MINES IN THE WEST MIDLANDS: THE LEGACY OF MINES LONG ABANDONED, DEPARTMENT OF ENVIRONMENT, 1983). The majority of these mines were mined between 1750 and 1900. Because limestone is strong and the rocks above and below are also strong, the cavities remain "open" for many years, unlike coal mines where the cavities generally collapse within a few years.

The following reasons were found for the subsidences :

(i) Roof collapses : Collapses of workings occur as a result of the gradual deterioration of the remaining rocks. The limestone rich strata tend to be strong, although they may be weakened by jointing and by occasional layers of mudstone. Therefore the pillars of limestone continue to support the overlying strata while the roof in between the pillars collapse.

(ii) Pillar failures : At depths of 100 metres and more the weight of the rock

above is sufficient to crush pillars of weaker materials. Collapse of the roof into the room gradually expose pillars of the shale and after a period of many years the shale pillars deteriorate to the state where they crush.

Although geological conditions in this area are totally different to the conditions found in the areas of interest, the abovementioned report is an indication that one has to be cautious and consider the influence of time dependent weathering effects on pillars and hangingwall stability.

2.5 Conclusions

It can be accepted that the procedure of determining a restricted area is valid and need not to be altered or revised. However, the application of uniform conditions and restrictions in areas with different geological environments in order to protect surface structures, is not a scientific method and may lead to locking up minerals where higher extraction ratios are possible. It may also cause the selection of wrong mining options which may result in subsidence.

It is therefore necessary to investigate the geotechnical and geological details in the areas of interest to arrive at valid factors and design criteria to be used for the protection of surface structures. The next section

therefore investigates the geotechnical nature of the Central Witwatersrand and Bushveld Igneous Complex regions. It will be shown that as the result of differences in the geotechnical environments of the two regions, uniform factors for the undermining of surface structures cannot be applied.

3. GEOTECHNICAL CONSIDERATIONS FOR SHALLOW MINES IN THE CENTRAL WITWATERSRAND AND BUSHVELD IGNEOUS COMPLEX

The previous section indicates that geotechnical considerations play an important role to arrive at valid conclusions. A geotechnical investigation is therefore necessary. It enables the determination of the means by which a rock mass can be modelled and establishes criteria and constants necessary for analysing the specific area. The relevant areas can then be critically appraised on an "own merit" basis.

For this report, the relevant areas of interest include the stratigraphy, lithologies, structural characteristics and material properties of the intact rock mass and reef horizons that existed prior to any mining. The stress state acting within the rock mass prior to mining and the behaviour of the surface are also considered.

The findings form the basis for the determination of the behavioural characteristics, failure criteria and techniques discussed in Section 4. These then form the basis for the analyses and conclusions in Section 5.

3.1 Central Witwatersrand Mines

3.1.1 Stratigraphy and Lithologies :

Figure 3.1 is a summary of a north-south section of a mine in the western region of the Central Witwatersrand and is

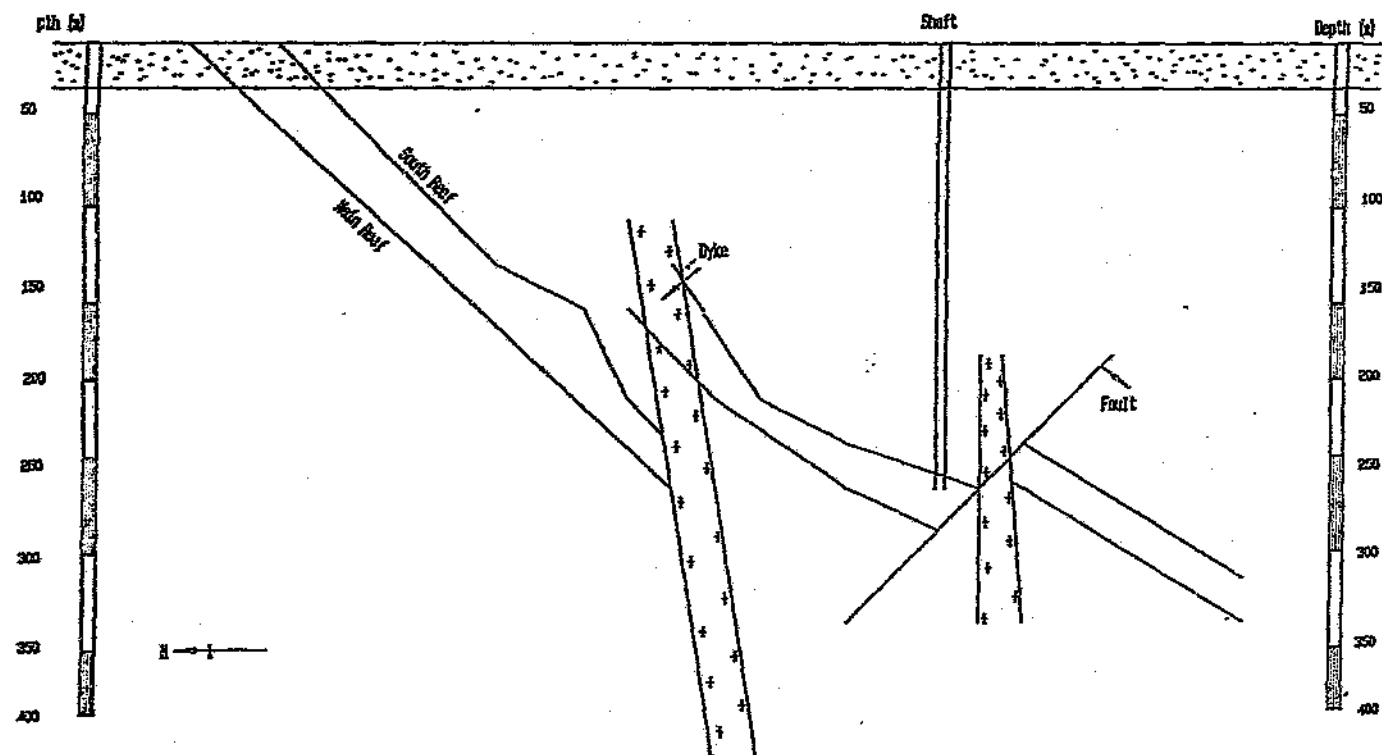


FIGURE 3.1 NORTH-SOUTH GEOLOGICAL SECTION : CENTRAL WITWATERSRAND (AFTER PRETORIUS)

typical of the geology of the Central Witwatersrand region (after PRETORIUS, 1972-73).

Rock Mass: The rock mass, overlying the South reef typically comprises a uniform series of Witwatersrand quartzites. No weak horizons, such as shale bands or persistent partings, are known within this sequence.

The surface weathered zone extends to a depth of about 12 m below surface. It comprises a typical sequence of progressively less weathered layers from a surface soil to a medium to large blocky mass with preferentially weathered joints. The latter marks the base of the original surface water table (BRINK, 1979).

South and Main Reefs: Figure 3.2 details the average inter-reef stratigraphy established for the shallow Central Witwatersrand region. The general dip direction is to the south, and vary in the range 30 degrees to 40 degrees (PRETORIUS, 1972). The thickness of the inter-reef middling varies from mine to mine but is normally in the range 25 m to 30 m. It was found that the mined horizon varies in thickness and the known minimum and maximum stoping widths are 0,7 m and 2,0 m respectively. From observations the footwall and hangingwall

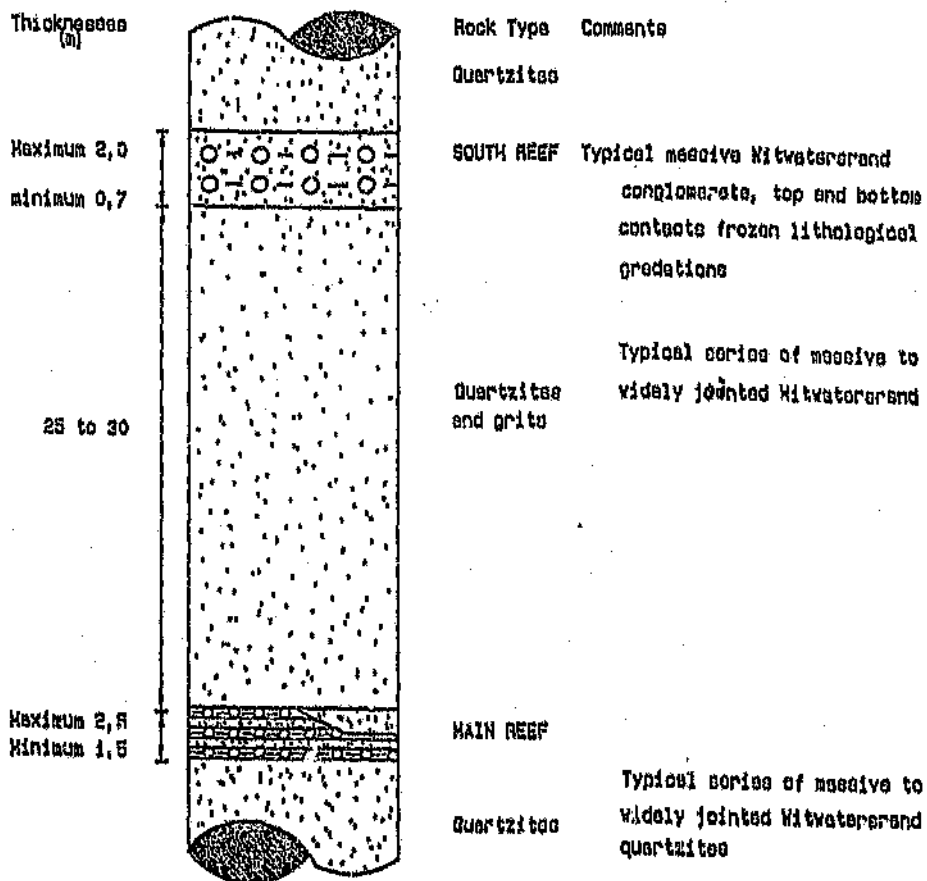


FIGURE 3.2 : INTER-REEF STRATIGRAPHY : CENTRAL WITWATERSRAND (AFTER PRETORIUS)

contacts are indistinct gradations marked by mining cutoff grades rather than discrete partings.

The observed remnant South and Main reefs have similar appearances and can be described as competent.

During inspections of Central Rand mines, minor subaerial weathering along open fracture planes could be observed around pillars and remnants in the South and Main reef horizons. In both cases the observed depth of weathering varied up to about 0,5 m, although it appeared to be better developed on the South reef horizon. It probably resulted from longterm and continuous exposure to the semi-saturated upcast air prevalent in the mines of the Central Witwatersrand in association with fracturing caused by blasting operations. In some instances fractures around blasthole sockets could still be observed.

The weathering was noted in areas where mining operations had ceased thirty to forty years ago. In areas where reclamation mining had taken place recently, the rock on pillars and remnants had a fresh appearance.

The significance of the weathering of a skin of approximately 0,5 m is the fact that it is a consideration for long term pillar design as the weathered material on the skin of the pillar has no or little strength.

Underground observations revealed that the inter-reef parting comprises a typical sequence of massive to widely jointed and competent quartzites with minor grits. No persistent partings were noted within this sequence. However, a 2 m to 3 m mining induced blocky zone was noted in the immediate hangingwalls and footwalls of both reefs. As is explained in Section 3.1.3 of Appendix A, the stability of the hangingwall of underground openings with moderate to large spans depends on the quality of the rock mass. When the quality is poor, an increase in span increases the potential of collapse of the hangingwall. The integrity of the blocky zone in the hangingwall of both the South and the Main reef can be maintained by a permanent, stiff type of support.

3.1.2 Geological Structures

Geological Features: Referring to figure 3.1 it can be stated that the subvertical and faulted dolerite dyke detailed thereon is typical of the Central Witwatersrand in that it is a persistent feature that trends

approximately east-west. The readily available surface geology plans also reveal a number of other dolerite dykes and minor faults that trend approximately north-south to northeast-southwest.

These dykes, with peripheral remnant reef, were left mostly intact to form superincumbent strike and dip orientated pillars (PRETORIUS, 1972). The majority vary in thickness between about 10 m and 40 m, a few can locally be about 80 m thick.

Joints: Dykes and faults typically have well developed and closely fractured joint zones associated with their margins. They form during the intrusion of a dyke and/or shear movement caused by displacement under pressure during the faulting process (BRINK, 1979). They can act as planes of preferential parting along which large scale rock mass movement could occur, especially in areas of high reef extraction. Underground observations at sites of major movement prove that collapses were of the type depicted on Figures 2.1.c and 2.1.d showing block movement along dykes and/or faults.

The rock mass, where not disturbed by geological structures, is widely jointed. Inherent joints and jointing patterns are neither continuous nor clustered at any particular horizon. As such, it is unlikely to unravel as a series of blocks over created mining spans.

Underground observations revealed that remnant reef horizons are also widely jointed. As such, they are considered as typical of most Witwatersrand gold bearing reefs.

Mining spans: From scrutiny of mine plans and underground observations it can be concluded that the extraction ratio of the South reef was 90 % in the area of interest (to a depth of about 250 m) and that mining activity on the Main reef horizon resulted in an extraction ration of 65 % (due to patchy grade values, PRETORIUS, 1972).

On the South reef horizon the majority of the mined spans at the depth range of interest fall within the range 100 m to 300 m. They are broken by the continuous and elongate North-south and East West orientated pillars and remnants. These comprise main. dyke material with peripheral reef and vary in thickness between 10 m and 40 m, although some are locally up to 80 m wide. Underground observation showed massive hangingwall collapses in the South reef workings.

On the Main reef horizon mined spans and pillar and remnant dimensions vary considerably. In some instances mining extended over unbroken spans of up to 100m. Elsewhere approximately square pillars with 5 m side lengths were left between 12 m and 15 m apart on dip and strike and on an approximately regular pattern.

3.1.3 Intact Material Properties

Data: In order to facilitate realistic modelling of remnants, pillars and intact rock mass behaviour in response to the mined spans, a knowledge of the properties of the reef horizons and principal rock types within the host rock mass is required.

The intact rock mass and reef horizons of the Central Witwatersrand region is probably typical and consistent with equivalent Witwatersrand sequences. As such, there is no readily available evidence to suggest that their material properties would have differed or differ significantly from those established for similar rock types elsewhere in the Witwatersrand basin. The values tabulated in Table 3.1 (BRINK, 1979) are used in modelling. However, as explained in Section 4, a rock mass is generally weaker than its constituent rock material as the mass contains structural weaknesses such as joints and faults (STACEY, 1986).

TABLE 3.1 ASSUMED INTACT PROPERTIES
PRINCIPAL ROCK TYPES

ROCK TYPE	UCS (MPa)	UTB (MPa)	E (GPa)	ν	d (T/cum)	Co (MPa)	ϕ°
Quartzite	220	20	70	0,15	2,70	30	30
South Reef	200	-	70	0,15	2,75	30	30
Main Reef	200	-	70	0,15	2,75	30	30

UCS = Uniaxial compressive strength

UTB = Brazilian strength

GPa = Giga Pascals

MPa = Mega Pascals

E = Tangent Young's
modules

ν = Poisson's ratio

d = Density

T/cum = Tons per cubic metre
 ϕ = Internal friction angle

Co = Cohesion

3.1.4 Virgin Stress State

A knowledge of the magnitude of the virgin stress state is of fundamental importance to rock mechanics considerations. For example, the magnitude of virgin stress can play a dominant role in determining the behaviour of an intact rock mass over mined spans, as well as the ultimate magnitudes of field stresses acting on remnants and pillars. That is, virgin stress largely determines the performance of an excavation, or series of excavations, during and after mining activities.

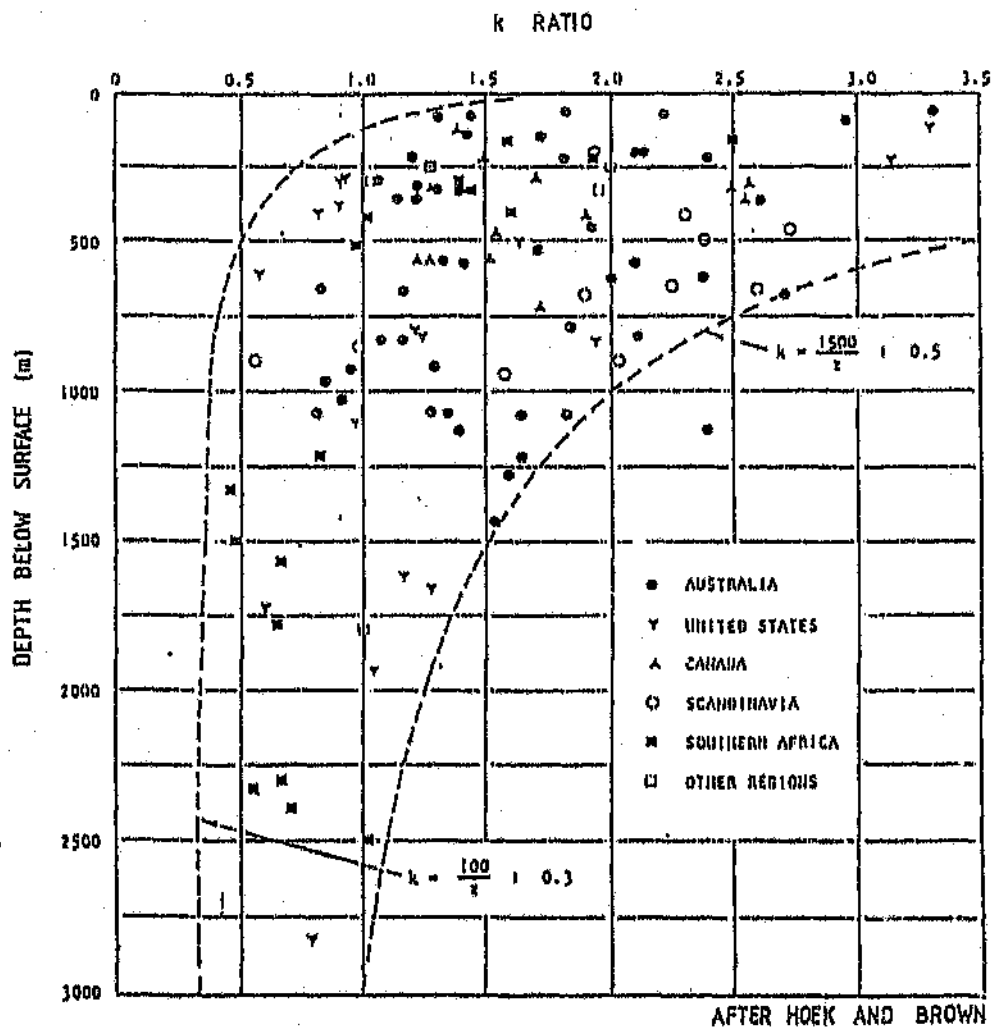
Directions : Two components of horizontal stress, and a vertical component, define a virgin stress state. For purposes of modelling, the vertical component can reasonably be assumed to have acted perpendicular to surface, although in moderately dipping rock mass it could have been inclined a few degrees away from the down dip direction. Normally any variations that might result from this would be such that they can be ignored. It is also assumed that one component of horizontal stress acts parallel to strike and that the second component acts parallel to the dip direction. These too are reasonable assumptions in that they are consistent with data obtained by direct measurement at a number of hard rock mines (HOEK AND BROWN, 1980).

Magnitudes : The magnitude of the vertical component is

assumed to equal the weight of the overlying rock mass to any point of interest below surface. The magnitudes of the horizontal virgin stress can vary considerably, more especially near surface where residual stress (that locked into the rock mass from greater depths than which is now manifest as a result of surface weathering) or tectonic stress (that caused by regional rock mass movement) can result in magnitudes greater than the vertical component. The two horizontal components can also be unequal.

The horizontal virgin stress components are also found to be dependant on the depth below surface. Their rate of increase with depth is usually specified by a constant k (BUDAVARI, 1983a). k is a ratio which is obtained by dividing the average horizontal virgin stress into the vertical component of virgin stress. It is considerably more difficult to determine the value of k than the magnitude of the vertical stress component acting at a point. It has to be determined by direct in situ measurements. Figure 3.3 (AFTER HOEK AND BROWN, 1980) details k ratios for a wide variety of hard rock mines from around the world, including deep level South African gold mines.

From 1 km upwards, with decreasing depth, the value of k increases rapidly to an approximate maximum of 1.5 (BUDAVARI, 1983a). High horizontal stresses increase the frictional forces on the planes of joints in the rock mass overlying underground excavations. Higher horizontal



$k \text{ ratio} = \frac{\text{average virgin horizontal stress}}{\text{vertical component of virgin stress}}$

$z = \text{vertical depth}$

FIGURE 3.3 VARIATION OF K-RATIO WITH INCREASING DEPTH

stresses would, therefore, promote stability over stable mined spans. However, as no in situ stress measurements have been taken in the regions and depths of interest, a k value of 1 is assumed for modelling purposes, which is a reasonable and valid assumption for the worst case method adopted.

3.1.5 Surface Considerations

In the following sections, the sources, magnitudes and effects of, and limit criteria for possible types of surface movement in the area of interest are discussed. These form the basis for the relevant analyses and conclusions of Sections 4 and 5. However, the destabilising effects of joint zones associated with dykes and faults, which may result in large scale rock mass movements as described in Section 3.1.2, are ignored as they, at this stage, cannot be predicted.

Two main sources of potentially damaging surface movements are identified for the type of rock mass described in Section 3.1.1 : elastic deformation over the created mining spans; and progressive failure to surface. In the following sections these are considered separately and in terms of the consequences of South and Main reef mining on the types and magnitudes of surface movement.

3.1.5.1 Elastic Movement

Behaviour : In section 3.1.2 of Appendix A it was concluded that a rock mass of the type previously

described would deflect in an elastic manner over subcritical spans. Smooth and continuous surface subsidence profiles would form in such cases (SUBSIDENCE ENGINEER'S HANDBOOK, NCB). An idealised example is detailed in Figure 3.4.

Criteria : No readily available data exists for the setting of limit surface movements, usually quoted as strains, for such behaviour in the Witwatersrand basin. Because of this, the criteria utilised for analysis were drawn from the literature of coal mining. This approach is considered valid in that similar surface movements would have similar effects on surface structure, irrespective of either the source of these movements or the characteristics of the deflecting rock mass. The National Coal Board's criteria of maximum surface movements which, when exceeded, may result in structural damage (SUBSIDENCE ENGINEER'S HANDBOOK, NCB) and summarised in Table 3.2, are well established and generally accepted. Accordingly, these were used.

TABLE 3.2 MAXIMUM ALLOWABLE SURFACE MOVEMENTS

MOVEMENT	LIMIT CRITERIA	COMMENTS
Horizontal strain	0,5 mm/m	Compression or tension
Tilt	2,5 mm/m	

Conclusions : The subcritical mined spans which determine

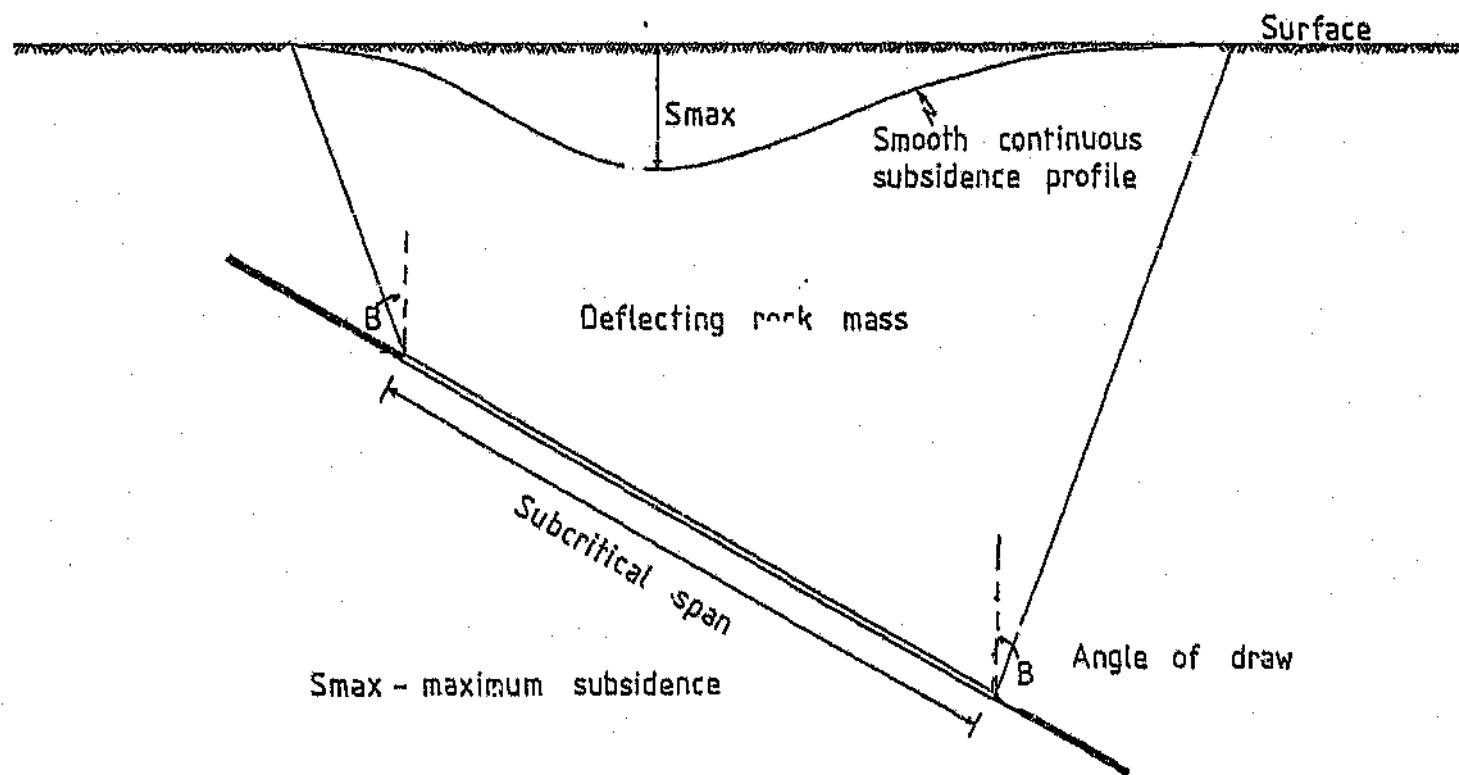


FIGURE 3.4

IDEALISED EXAMPLE OF ELASTIC MOVEMENT OVER SUB-CRITICAL NINE SPAN

the likely maximum magnitudes of elastic surface movement are those created, or to be created in the South reef only. The reason is that the dominant South reef pillars/remnants are formed from the subvertical dykes and peripheral reef pillars left on the dykes and faults. These dykes are projected to the Main reef horizon. That is, the pillars are superimposed. In addition, as the result of more scattered and patchy values (PRETORIUS, 1972), the Main reef is not as extensively mined in the top portions of the Central Witwatersrand mines as the South reef. As long as the Main reef mined spans are equal or smaller than the South reef mined spans at subcritical spans, the middling between South and Main reef excavations will be stable and as explained in Section 3.1.5.3 South reef spans need to be considered only (BLACK, 1960).

STASIKOWSKI (1987) showed that for the rock mass previously described, subcritical South reef mined spans at the depth range of interest (to a depth of 240 m), would result in (elastic) surface movements at least one order of magnitude less than the maxima stated in Table 3.2. As such, they were not considered further in any detail. However, supercritical South reef spans could give rise to inelastic surface movements, for the reasons described in the following sections.

3.1.5.2 Inelastic movements - South Reef

Behaviour : The failure process is described in Section 3.1.3 of Appendix A. For the uniform rock mass under review, progressive failure of rock slabs and blocks would in most cases result in bulking (the effect caused by the creation of voids between blocks, thereby resulting in a volumetric expansion of the failed mass compared with the intact mass; see Section 1.1). Progressive failure could therefore either extend to some point within the overlying strata or to surface, depending on the average magnitude of bulking, the void into which caving occurred and the reef depth. Should failure extend to surface a stepped subsidence profile would result (SUBSIDENCE ENGINEER'S HANDBOOK, NCB).

However, the margins of the failing rock mass would not cave vertically : the peripheral failure profile would tend to extend over the mined out area. For the uniform type of rock mass under review, the failure profile would probably approximate to a persistent line defined by an angle of break (Section 2.1.1(vi)). WHITTAKER (1989) shows that in competent ground this line approximates 70° from the horizontal. Underground observations in collapsed stopes tend to confirm that the angle of break lies towards the worked out area and attains a magnitude of 70° from the horizontal.

The principal effect of an angle of break would be to

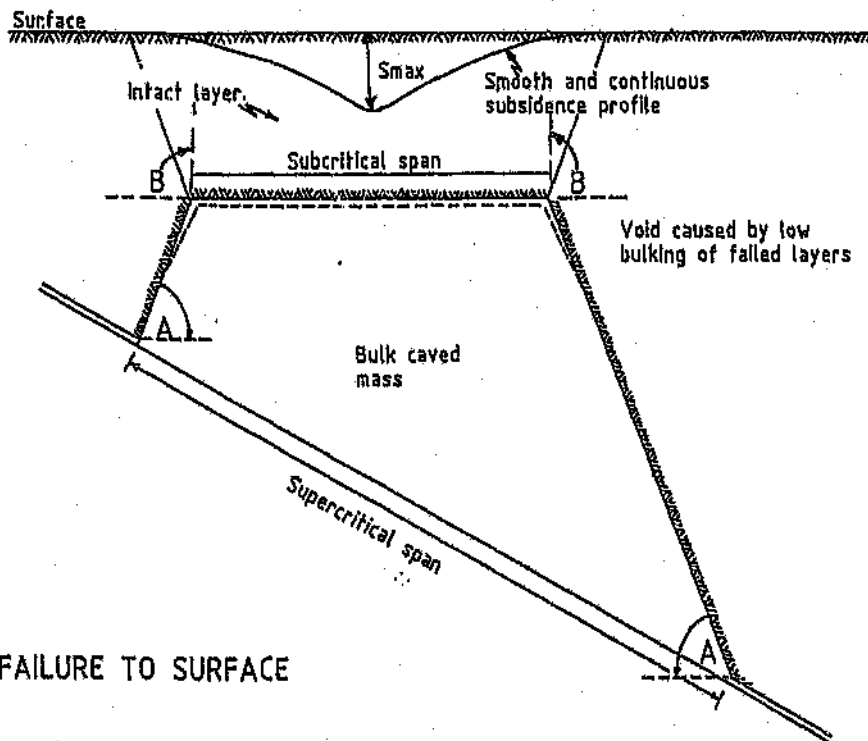
progressively reduce the free span of the otherwise failing layer as the height of caving increased. Should this span reduce to subcritical dimensions, then shear failure would stop and the intact layer would remain as a stable arch. Although a void, caused by inadequate bulking, could still exist below the stable layer, elastic deformation only would occur on surface.

It is in such circumstances the magnitude of a supercritical mined span plays an important role in determining the likely maximum height of caving and likely surface effect. An idealised example of partial caving from the South reef is presented as Figure 3.5A. Figure 3.5B is an idealised example of failure to surface.

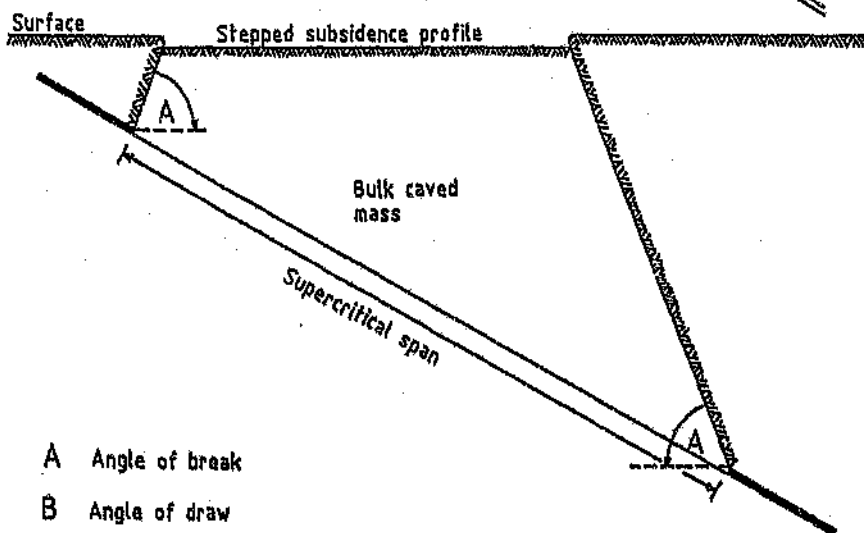
In the case of partial caving, the stability of the remaining intact layer largely depends on its structural characteristics. As described in Section 3.1.1, it would be massive to widely jointed and would act as a single and elastic but flawed layer (Section 4.1.1.1). However, underground observations indicate that if its width is less than about 15 m, then its continuity probably breaks down.

In such cases caving could therefore be reasonably assumed to extend as far as the bulking rock mass allowed. Should caving extend to the surface weathered zone and water table, then these layers, which would act as a deadweight, could reasonably be expected to fail as a vertical plug

A BULK ELASTIC MOVEMENT



B FAILURE TO SURFACE



A Angle of break

B Angle of draw

FIGURE 3.5 : PARTIAL AND TOTAL FAILURE TO SURFACE SUPERCRITICAL MINE SPANS : SOUTH REEF

with no bulking. In such circumstances inelastic, rather than elastic, surface subsidence would occur.

The preceding discussions reveal four possible caved states that could exist in the area of interest and over supercritical south reef mined spans :

- * Condition 1 - caving to surface, resulting in surface subsidence, when the theoretical height of caving exceeds the mined depth less the thickness of the surface weathered zone and water table (12 m, see Section 3.1);
- * Condition 2 - caving to some point between the base of the weathered zone and 15 m below the weathered zone, which could result in inelastic surface movement (15 m being the minimum width of an elastic but flawed layer of quartzites);
- * Condition 3 - partial caving to some point equal to or below 27 m below surface (15 m + 12 m), at which height a stable intact layer remains, resulting in elastic surface movement only; and
- * Condition 4 - caving to some point below the first stable intact layer for the

deflecting rock mass, resulting in elastic surface movement only.

In addition, rock mass failure could occur along the joint zones associated with the subvertical dykes and faults, which is not considered here.

Section 4 will quantify the possible caved states defined above.

3.1.5.3 Inelastic Movements - Main Reef

Behaviour:

The physical characteristics of the middling between the South and Main reef workings were described in Section 3.1.1 as similar to the rock mass overlying the South reef. As such, the previously defined failure process, bulking characteristics and minimum intact thickness for a stable layer (15 m) equally applies here.

Therefore, the same cave angles and theoretical heights of caving for the same stoping widths apply.

Three possible caved states can exist in the middling, depending on the mined span :

- * Condition 1 - caving to the South reef;

- * Condition 2 - partial caving to a stable

layer; and

- * Condition 3 - elastic deflection only over subcritical Main reef mined spans.

Conditions 2 and 3 would give rise to elastic movement only at the South reef horizon and would not induce any noticable surface movements. As such, they are not considered in further detail. However, condition 1 could result in four possible scenarios :

- *1A - additional surface movement if the new height of caving exceeds $h - 12$ m (weathered zone) for the South reef condition $W_{max} < W$; (W_{max} being the limit or critical span, W : a supercritical span in this case and h the depth below surface);

- *1B - new surface movement caused by an increase in the height of caving such that it newly exceeds $h - 12$ m for the South reef condition $W_{max} < W$;

- *1C - no inelastic surface effect if the new maximum height of caving does not exceed $h - 12$ m for the South reef condition $W_{max} < W$; and

*1D - no additional inelastic surface effect for the South reef criterion $W_{max} > W$ (W being a subcritical span).

In addition rock mass failure could occur along the joint zones associated with the subvertical dykes and faults. This source of large scale instability was, however, not considered further here.

A number of complicating factors also exist in that the following are not known :

- * whether further bulking of the failed rock mass overlying the South reef would occur if caving extended from the Main reef;
- * whether the failed slabs would be sufficiently large to bridge any failed Main reef mining spans and thereby prevent additional upward caving movement.

If mining of the Main reef took place first Main reef caving to the South reef would result in the full extension of caving according to the combined South and Main reef mined heights and depth below surface. Extensive South reef extraction would not have been possible had the footwall subsided as a result of Main reef mining to supercritical spans. However, from scrutiny of plans South reef mining took place first.

3.2 Bushveld Igneous Complex Mines

It was found reasonable to concentrate on the UG2 horizon of the Bushveld Igneous Complex as that zone has a weaker hangingwall sequence compared to the Merensky reef horizon. The worst case situation is therefore addressed.

3.2.1 Lithologies and stratigraphy

Details of the stratigraphy of the UG2 are based on geology sections for boreholes drilled in the Marikana area, (COERTZE 1971).

Figure 3.6 details the geology sections for three boreholes as well as an average succession based on the information of the same boreholes. The lithological descriptors and stratigraphic divisions detailed thereon are those referred to in the text.

The sequence appears to be typical for this area of the Bushveld Igneous Complex (BIC) in that the stratigraphy is persistent, and consistent with that in mines in the area.

However, variations occur, in the thickness and structure of the pyroxenites, which has an impact on support considerations.

3.2.1.1 Norite/Anorthosite Hangingwall Series

The norite/anorthosite series include all lithological divisions from the FW7 norites to the HW2 anorthosites (Figure 3.6). The series is massive and continuous.

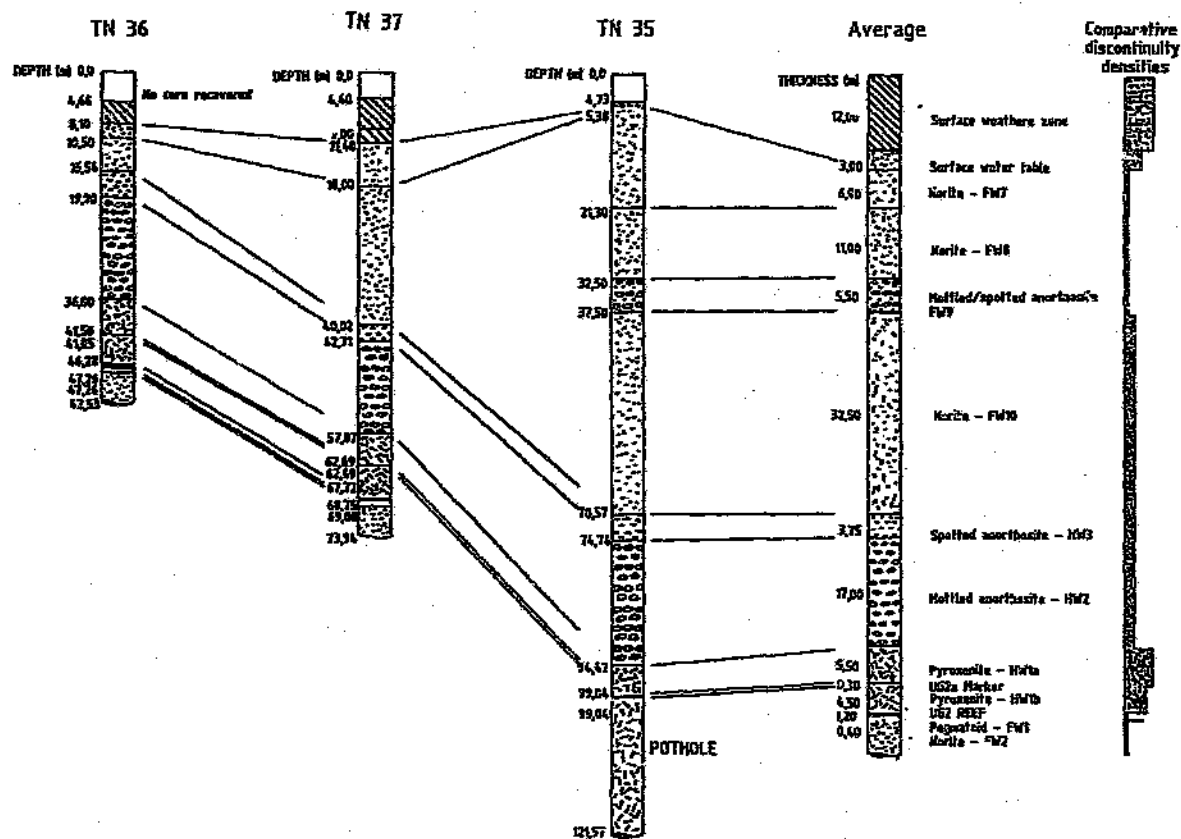


FIGURE 3.6 GEOLOGICAL SECTIONS: BIC FOR THE UG2 REEF (AFTER VILJOEN)

The bottom contact of the norite/anorthosites with the pyroxenites is sharp, distinct and irregularly weathered to a depth of at least 70 m below surface.

From observations the contact is marked and weak in tension at this depth range.

3.2.1.2 Hangingwall Pyroxenite Sequence

The pyroxenite series is summarised on Figure 3.7 (WALRAVEN, 1986, VILJOEN, 1986).

The HW1a portion is, on average, 5,5 m thick and generally well jointed. The thickness of the UG2A marker typically varies between about 0,2 m and 0,5 m, with an average of about 0,4 m. Rockfalls extend usually to this marker, which is extremely weak in tension.

The HW1b pyroxenite sequence is, on average, 4,5 m thick and generally less jointed than the HW1a portion.

3.2.1.3 UG2 Reef

For purposes of this report, an average dip of 14 degrees and a maximum stoping width of 1,5 m were assumed.

In an unweathered state, the top contact of the reef is most often distinct and cohesive. To depths of about 70 m below surface it is irregularly weathered, clay filled and acts as a discrete parting plane. Below depths of about 70 m it can be expected to be clean, tight and cohesive

AVERAGE UG2 REEF INTERSECTION, WESTERN BIC

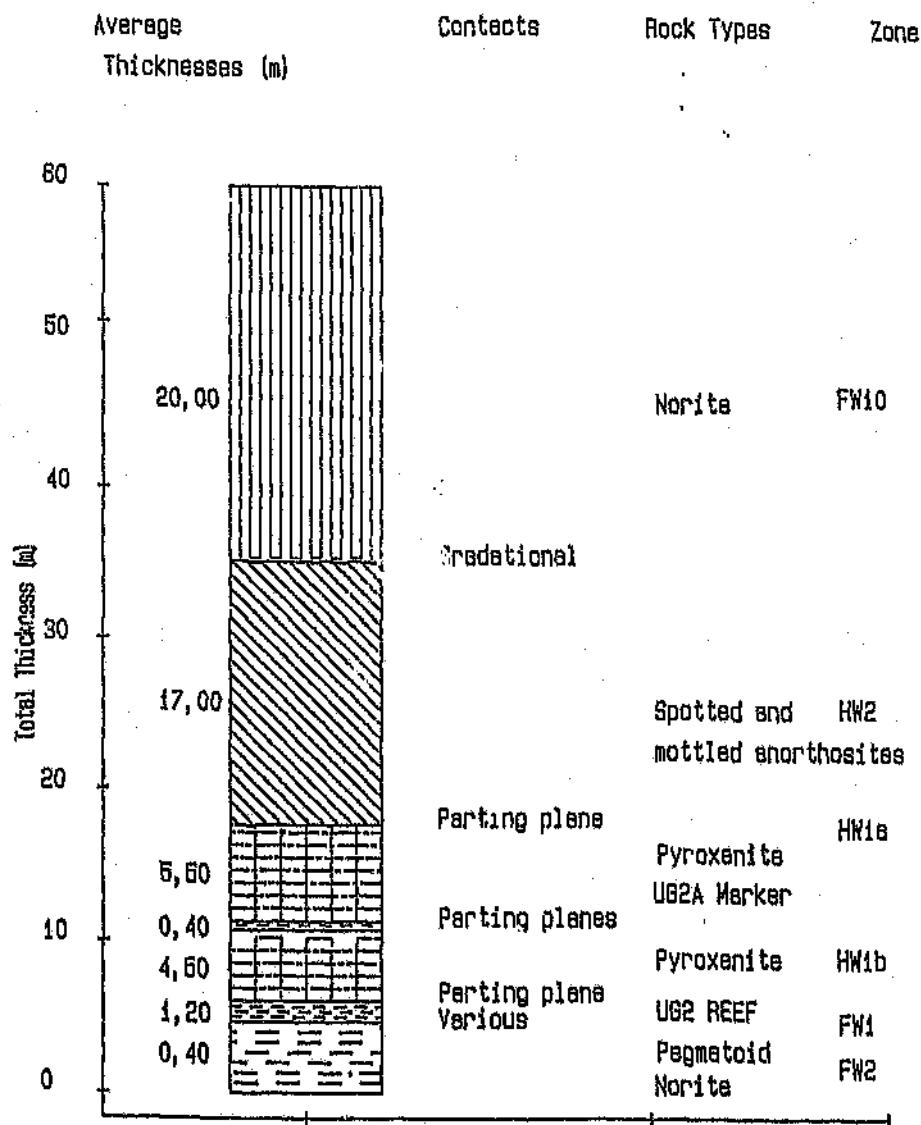


FIGURE 3.7 : SECTION TROUGH HANGINGWALL SEQUENCE (AFTER COERTZE)

(LEEB-DU TOIT, 1986).

3.2.1.4 Footwall sequence

In the logged boreholes, and in all the current underground reef exposures, the immediate footwall is a FW1 pegmatoid. The pegmatoid can be up to about 0,5 m thick with an average of about 0,4 m. In an unweathered state the reef-pegmatoid contact is distinct and cohesive.

The contact between the FW2 and the FW1 pegmatoid is usually sharp, weak and acts as a discrete parting plane.

3.2.2 Surface Weathered Zone

Figure 3.8 summarises the average weathering profiles for the western section of the BIC as determined from borehole information and underground observations. Weathering and moisture content can rapidly reduce the strength of competent rock (STACEY, 1986).

The boundaries between weathered, water bearing and fresh rocks are progressive and vary according to local joint densities as well as surface topography (for example, depressions where weathering can be expected to be locally more deeply seated). However, for the worst case analysis method adopted, the indicated limits of weathering are accepted as average and typical for the area.

3.2.2.1 Influence of Weathering on Hangingwall Stability

The thickness of unweathered norites/anorthosites above

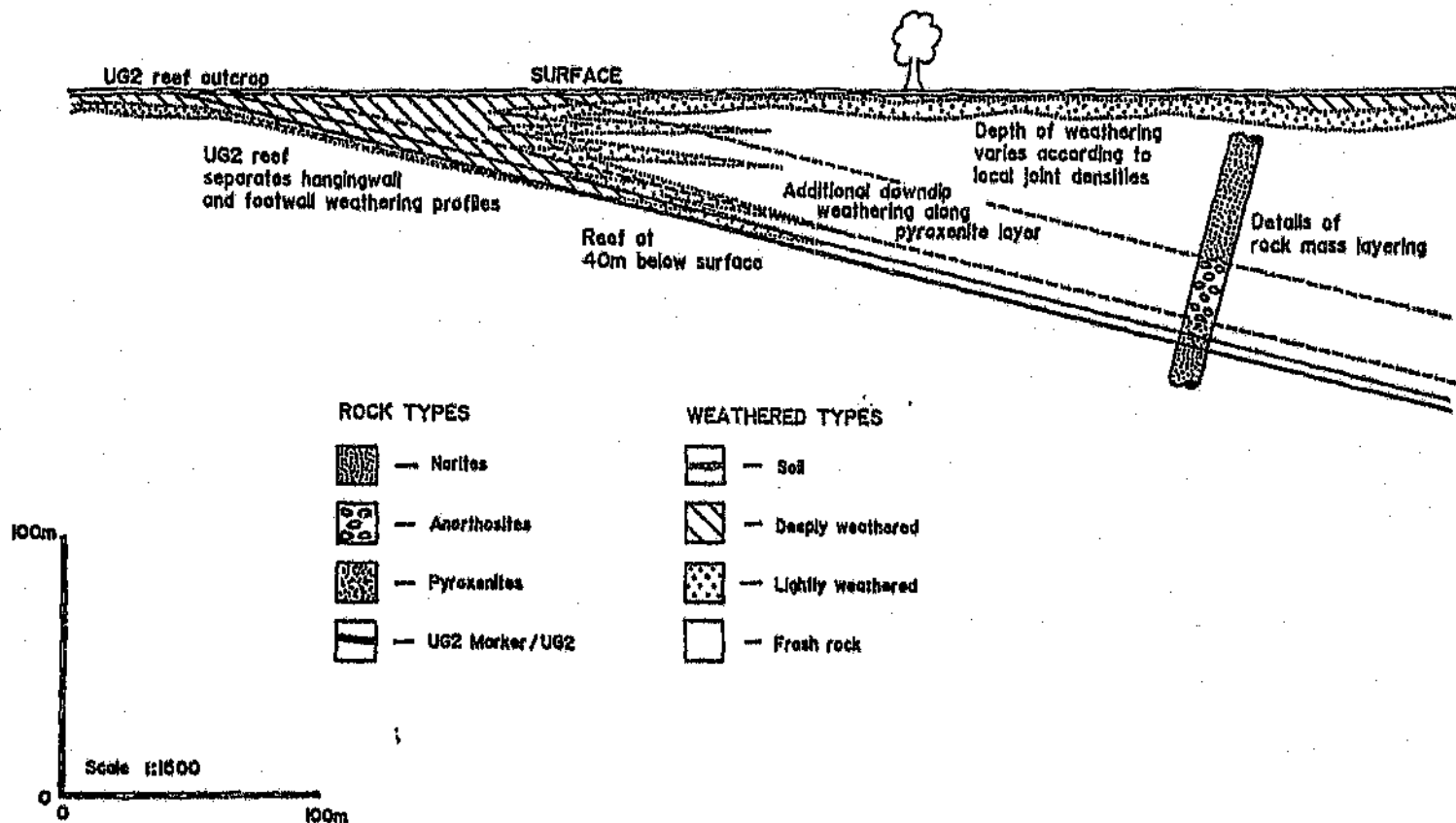


FIGURE 3.8 WEATHERING PROFILE OF SURFACE WEATHERED ZONE

shallow UG2 reef stopes is an important design consideration - it dictates safe mining spans.

Where the norites/anorthosites outcrops, and in areas unaffected by geological disturbances, the surface weathered zone extends to an maximum of about 12 m to 15 m below surface.

Within this zone the strata vary from surface soil, to deeply weathered, small blocky and loose water bearing layer (subsoil), and a medium blocky, leached and loose water bearing layer at the base. This layer has no inherent strength and acts as a deadweight on the underlying strata.

Further downdip weathering in the pyroxenites has been observed. In most cases, this additional weathering is well developed to a depth of about 35 m below surface. Thereafter it progressively recedes until it is expressed as a thin zone of weathered joint planes at a maximum depth of about 50 m below surface.

The weathering profiles in the pyroxenites vary considerably. This can result in deceptive hangingwall conditions in the stopes. For example, the immediate cut hangingwall can appear fresh and competent from depths of about 30 m below surface, but it is overlain by extensively weathered pyroxenites.

The extensively weathered nature of the pyroxenites is attributed to their generally well jointed nature resulting in extensive and deep weathering to a depth of about 30 m below surface. Thereafter weathering mostly occurs along the joint planes in a thinning layer to a maximum depth of about 65 m below surface.

The UG2A marker in the pyroxenites (Figure 3.7) has the effect of creating a distinct parting plane in the pyroxenites.

3.2.2.2 UG2 Reef

The behaviour of pillars in shallow excavations can depend on their structural stability, rather than the strength of intact blocks. As the former can depend on the weathering characteristics of the reef, a knowledge of the weathering profiles becomes a prerequisite for optimum pillar design.

From observations the oxidised zone typically extends to about 20 m below surface, although it can extend to as much as 30 m below surface.

In this zone the reef is typically altered to a weak and friable mass which progressively strengthens down dip.

The weathering depends on local joint densities in the hangingwall pyroxenite sequence and progressively decreases down dip to a maximum depth of about 50 m below surface.

The principal effect of this could be a reduction of the intact strength of the reef, thereby influencing minimum safe pillar dimensions. The magnitude of this effect is discussed in Section 3.2.5.3.

3.2.2.3 Immediate Footwall

The footing stability of pillars and internal stope support will largely rely on the weathering profiles in the immediate footwall. As such, the definition of the type and depth of weathering is an important consideration when determining the associated mining risks in the shallow surface excavations.

The footwall pegmatoid is deeply weathered to a weak and unstable mass to a depth of about 30 m below surface. It has a sharp bottom contact represented by a discrete parting plane.

From about 30 m below surface the depth and severity of weathering progressively reduces to a maximum depth of about 70 m below surface. In this zone the reef will most often cleanly part along the bottom contact.

However, from 50 to 60 m below surface weathering can extend either along the bottom contact or along the first parting plane below this. This will dictate the point at which the footwall will most often part.

3.2.3 The Effects of Geological Structures

Figure 3.9 is an idealised summary of the effects of three principal outcropping structures (faults, dykes and shear zones) on shallow weathering profiles. Where these are either expressed on surface or in the surface weathered zone they act as channels for preferential groundwater movement and hence weathering. This is usually restricted to joint zones associated with the margins of the structures. Severe weathering extends to much greater depths than average, due to the presence of a (now weathered) shear zone. The obvious indicators of this are the bleached and small blocky appearance of the rock.

The depths to which weathering can extend vary according to joint frequencies and the mineralogy of a joint zone. No generalised depth can, therefore, be determined - although in general this appears to be at a reef elevation of about 70 m below surface.

In the hangingwall norite/anorthosite series, or in the footwall norites, faults and shear zones usually dip at between 70 and 80 degrees. However, in the pyroxenites these are generally expressed as a flat dipping (20 to 40 degrees) zone. If this is combined with groundwater movement, frequent hangingwall collapses have been observed.

3.2.4 Jointing

This section is important because at the depths of mining

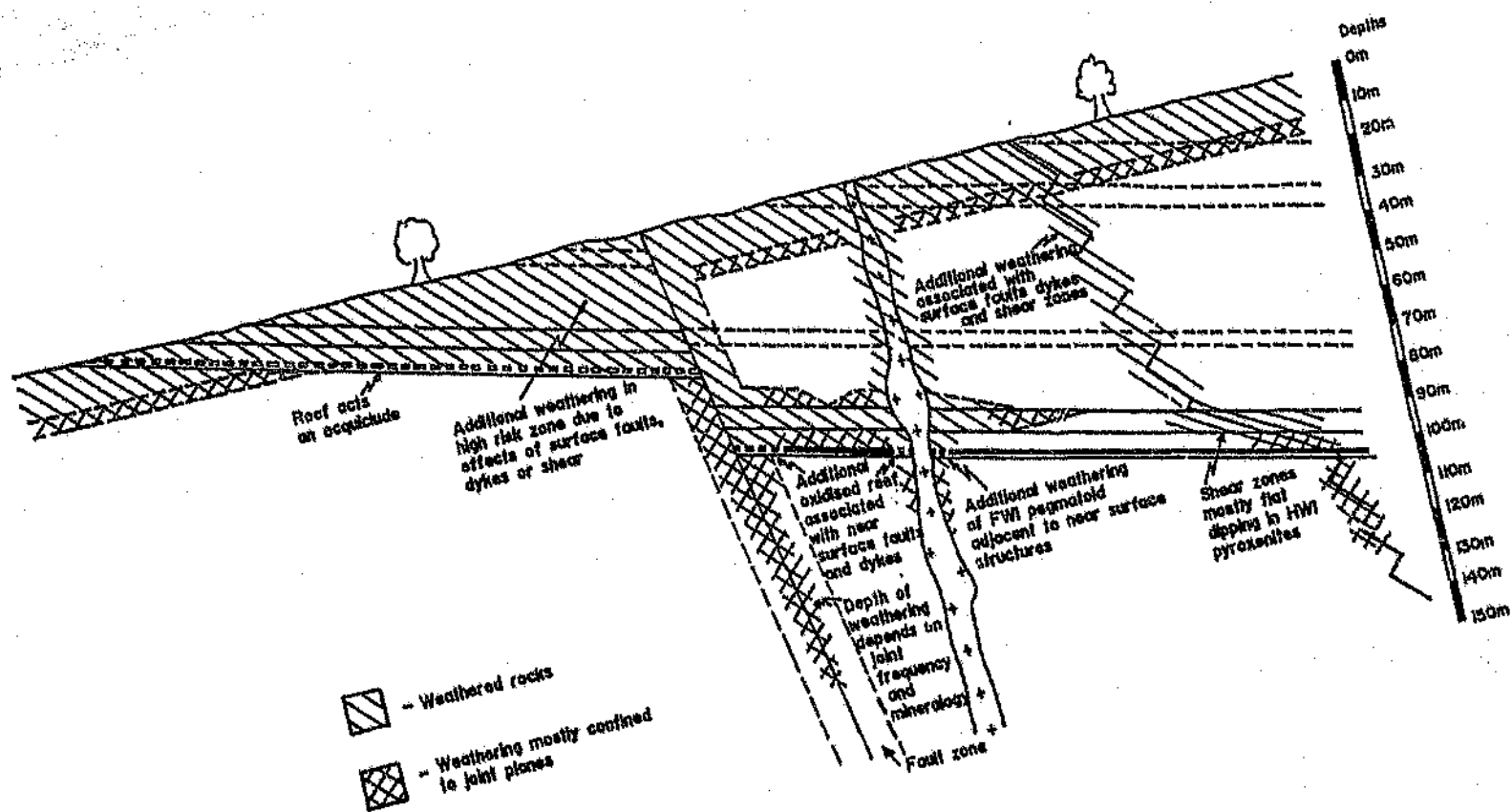


FIGURE 3.2
EFFECTS OF GEOLOGICAL STRUCTURES ON WEATHERING PROFILE

under consideration, the structural characteristics of the rock mass will effect its performance over the created mining spans.

From borehole information and underground observations it appears that few joints fall below the critical angle of 50 degrees (STACEY, 1986).

It also appears that no obviously regular or persistent joint patterns exist and they rarely extend further than a few metres in any direction. As such, they probably represent local and transversely random structures indicative of cooling features rather than any tectonic or regional jointing trends. These observations are consistent with others made elsewhere in the BIC. The only exceptions occur next to faults, potholes and igneous intrusions such as dykes. In these cases regular jointing patterns can be readily observed in the limited zones associated with the various structures.

The observed joints were continuous across the mined areas. It is therefore reasonable to conclude that in situ the patterns and length of individual joints are continuous and extensive.

Three joint sets were identified in the HW1b section which are detailed in Table 3.3.

TABLE 3.3 JOINT SETS - HW1b PYROXENITES

JOINT SET	AVERAGE DIP (DEGREES)	AVERAGE DIP DIRECTION (TRUE NORTH THROUGH EAST)
J1	74	000 degrees
J2	80	070 degrees
J3	50	165 degrees

The joint frequency was about 2/m.

Figure 3.10 is an isometric drawing of the interaction of the three defined joints sets for the hangingwall. It can be concluded from this that possibly large blocks and wedges will exist in the immediate hangingwall which are capable of falling or sliding out under the influence of gravity.

3.2.5 Material Properties

3.2.5.1 Norite/Anorthosite Hangingwall Series

Intact specimens of the principal rock types (norites and anorthosites) of the unweathered norite/anorthosite series are typically homogeneous and in most cases isotropic. As such, little difference in their material properties can be expected over large areas.

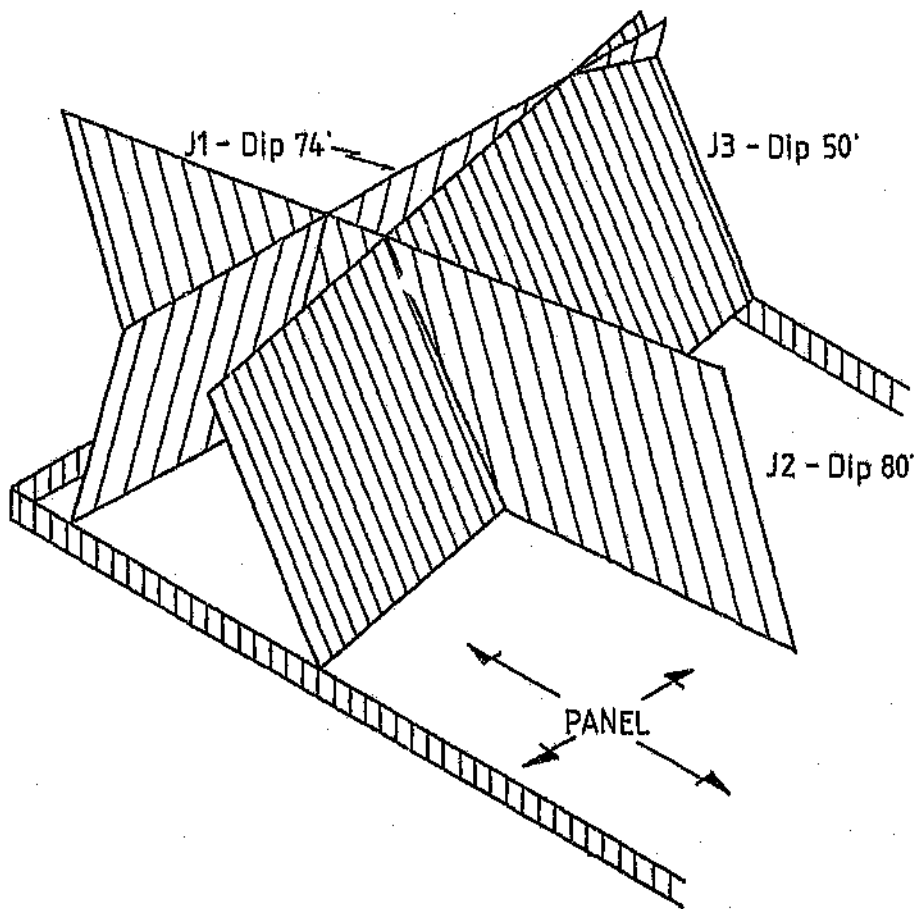


FIGURE 3.10 ISOMETRIC DRAWING OF THE INTERACTION BETWEEN THREE JOINTS

TABLE 3.4 ROCK PROPERTIES - HANGINGWALL
NORITE-ANORTHOSITE SERIES

ROCK TYPE	UCS (MPa)	UTB (MPa)	Co (MPa)	E (GPa)	v	d kg/m ³	ϕ
Norite	230	15	45	85	0,22	2850	47
Spotted Anorthosite	220	14	45	85	0,22	2800	45
Mottled Anorthosite	200	13	45	90	0,20	2750	41

MPa = Mega Pascals

GPa = Giga Pascals

UCS = Uniaxial compressive strength

E = Young's Modulus

UTB = Brazilian strength

v = Poisson's ratio

Co = Cohesion

d = Density

ϕ = Angle of internal friction

3.2.5.2 Hangingwall Pyroxenite Sequence

The material properties of the pyroxenite sequence are not essential for this investigation as their bulk behaviour will be controlled by the inherent flaws rather than by the properties of intact blocks.

However, for purposes of computer modelling, some of the constants detailed in Tables 3.4 and 3.5 were used.

3.2.5.3 UG2 Reef

The matrix of the reef may be weathered to a depth of about 50 m. This could affect the strength of the reef pillars and STACEY (1986) recommends a strength reduction factor of about 35 %. As such, a knowledge of the intact strength of the reef to such depths is an important consideration - the design of pillar dimensions and analyses of their stability depend on the information.

TABLE 3.5 ROCK PROPERTIES - HW1 PYROXENITES

ROCK TYPE	UCS (MPa)	UTB (MPa)	Co	E (GPa)	v	d kg/m ³	ϕ°
Pyroxenite	140	12	35	100	0,24	3200	45

The CSIR Geomechanics Laboratory conducted tests on UG2 reef which indicate a homogeneous and isotropic rock type. It also confirms an earlier conclusion : the UG2 reef is massive and structurally uniform. Table 3.6 details the averaged values for all test data for the UG2 reef.

TABLE 3.6 ROCK PROPERTIES - UG2 REEF

Sample Depth	UCS (MPa)	TCS (MPa) Confining stress			E (GPa)	v	d kg/m ³	Co	ϕ°
		5 MPa	10 MPa	15 MPa					
55 m	124,5	152,5	189,3	216,9	101,8	0,39	3790	25,4	46,
75 m	117,3	156,8	191,8	220,1	103,8	0,34	3870	22,7	48,
ave	120,9	154,6	190,5	218,5	102,8	0,36	3830	24,1	47,

3.2.5.4 Footwall Sequence

The material constants for the footwall pegmatoid are unknown. This is not vital information as in the weathered state it is known to be very weak. It would also be extremely difficult to obtain adequate samples for testing. In an unweathered state evidence from the western side of the BIC indicates that it is sufficiently strong to afford a competent footwall to reef pillars to the depth of 240 m +.

3.2.6 Conclusions

In the Central Witwatersrand the weathered surface zone is a reasonably uniform, horizontal layer of about 12 m thick, acting as a deadweight on a uniform rock mass. The oxidised and weathered outcrops of the reefs have all been mined before the turn of the century and weathering of the outcrop areas is, therefore, not a consideration. Weaknesses in the rock mass overlying the reefs are confined to the jointed margins of faults and dykes. Design criteria would only have to consider sub and supercritical span, with stabilising or bracket pillars on faults and dykes, the design of which would depend on the strength of the pillar material and load. As the hangingwall and footwall consists of competent, strong quartzites, they need not to be considered for factors affecting the stability of the pillars, such as foundation failure.

In the Bushveld Igneous Complex, at the other hand, the weathering along the outcrop extends downdip to a far greater extent and influences the stability of the hangingwall to depths up to 50 m. The weathering of dyke and fault planes extends even deeper and reaches depths of 70 m. The jointing in the immediate hangingwall pyroxenites is shallow dipping and intense. In addition, the UG2 marker in the pyroxenites is very weak, affording no cohesion. Pillar support for the protection of the surface has to be designed to cater for the deeply weathered nature of the reef, hanging- and footwalls.

Safe mining spans depend on the competent norite/anorthosite hangingwall and the design of support for the pyroxenite hangingwall has to be independent from the norite/anorthosite series. It should, however, have a high support resistance (ANON, AN INDUSTRY GUIDE, 1988).

The next section uses the findings of this section to arrive at failure criteria and design parameters for the shallow mines in the Central Witwatersrand and Bushveld Igneous Complex.

4. BEHAVIOUR, CRITERIA AND MODELS

This section deals with the implications of the results of the geotechnical investigations presented in section 3. The behavioural characteristics of the premining/intact rock mass are discussed from which suitable design criteria and methods for analysis of the relevant areas of interest are established. These form the basis for the analyses, discussions and conclusions which concern factors affecting the protection of the surface over shallow mining areas in the Central Witwatersrand and BIC regions.

4.1 Central Witwatersrand

4.1.1 Rock Mass Overlying the South Reef

Behaviour : The intact rock mass (that which existed prior to any mining) overlying the South Reef and the surface is considered as two separate units : the surface weathered zone and water table; and an underlying, unweathered mass.

Weathered Layers : The surface weathered zone was previously described as having little or no intrinsic bridging strength and could reasonably be expected to have acted as a deadweight on any underlying layers.

The combined weight of 12 m of overburden gives rise to stress levels of about 0,3 MPa. This value is used for

purposes of analysis.

Unweathered Layers : The unweathered and intact portion was previously described as uniform, and randomly and widely jointed with discontinuous joints. As such, it is modelled as an elastic medium with a reduced modulus. In this context, the principal effect of the inherent discontinuities would have been to reduce the bulk modulus & rigidity to about 70 % that of intact rock (JAEGER AND 1979). That is, to about 50 GPa. For the intact rock mass, failure is therefore considered to be a function of its bulk elastic properties, the stress state and the created mining spans.

4.1.1.1 Mode of Failure

The overlying rock mass extends to the top contact of the South Reef. As such, the determination of its condition over either the previously mined or future planned mining spans primarily relies on whether the mined dimensions between stability and bracket pillars are in a subcritical or supercritical state. For example, should the existing mined spans be supercritical, then it could reasonably be concluded that failure of the type described in section 2.1.2 occurred. VAN NIEKERK (1989), by drilling from surface into collapsed workings at several sites, found that the hangingwall was severely unravelled near the stope, resulting in cavities to form in the hangingwall. Where these cavities extended to surface, "bottlenecks" were formed. The margins of these "bottlenecks" formed,

on average, angles of 70°. Where these cavities did not extend to surface, gradual diminishing of open joints were observed towards the surface layer. The increase of open jointing above cavities with depth was also observed by CAMERON-CLARKE (1990). Reports on caving in underground workings at Crown Mines in the archives of the Johannesburg Inspectorate (IMJ 153/50 of 24 April 1970) also refer to "bottlenecking" where the caved areas in the workings are larger than the reported surface effects. From the descriptions of strata behaviour in Section 3.1.5.2 and Section 3.1.3 of Appendix A and the reported cases described above and personal observations the theoretical post caving profiles are summarised on Figures 4.1 and 4.2. Since the jointing is not continuous, it is unlikely that this could have an appreciable effect on the caving profiles.

4.1.1.2 Criteria and Methods

The onset of induced shear failure can be approximated by the Mohr-Coulomb failure criterion. This relates shear stress acting along a theoretical plane to the forces resisting sliding along the plane.

$$t = C_o + \sigma_n \cdot \tan \phi \quad - (4.1)$$

where t = shear stress

C_o = cohesion

σ_n = normal stress acting across the shear plane

ϕ = internal friction angle

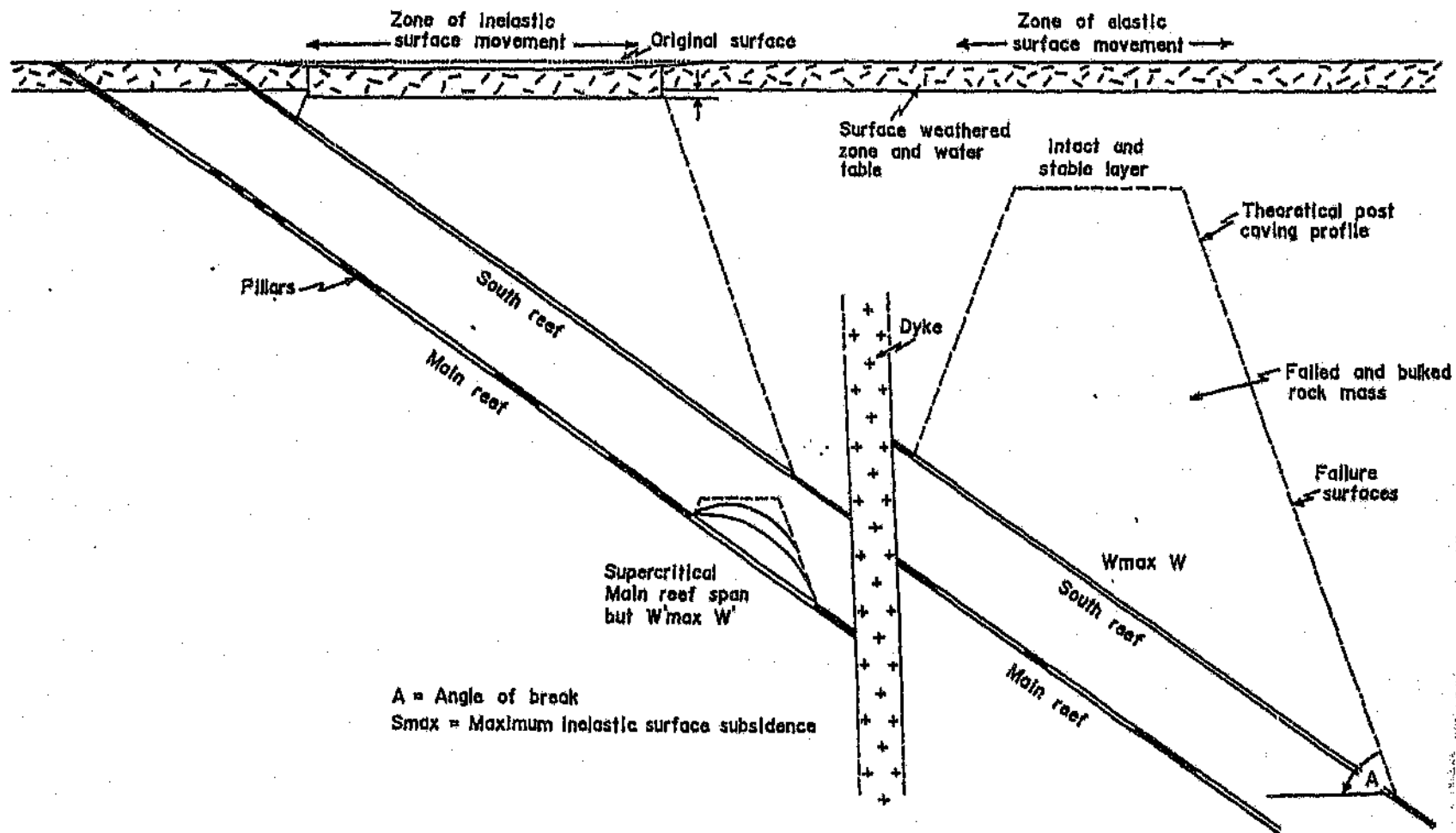


FIGURE 4.1

IDEALISED SUMMARY OF CURRENT STATE OF ROCK MASS ABOVE SOUTH REEF :
DIP ORIENTATED SECTION

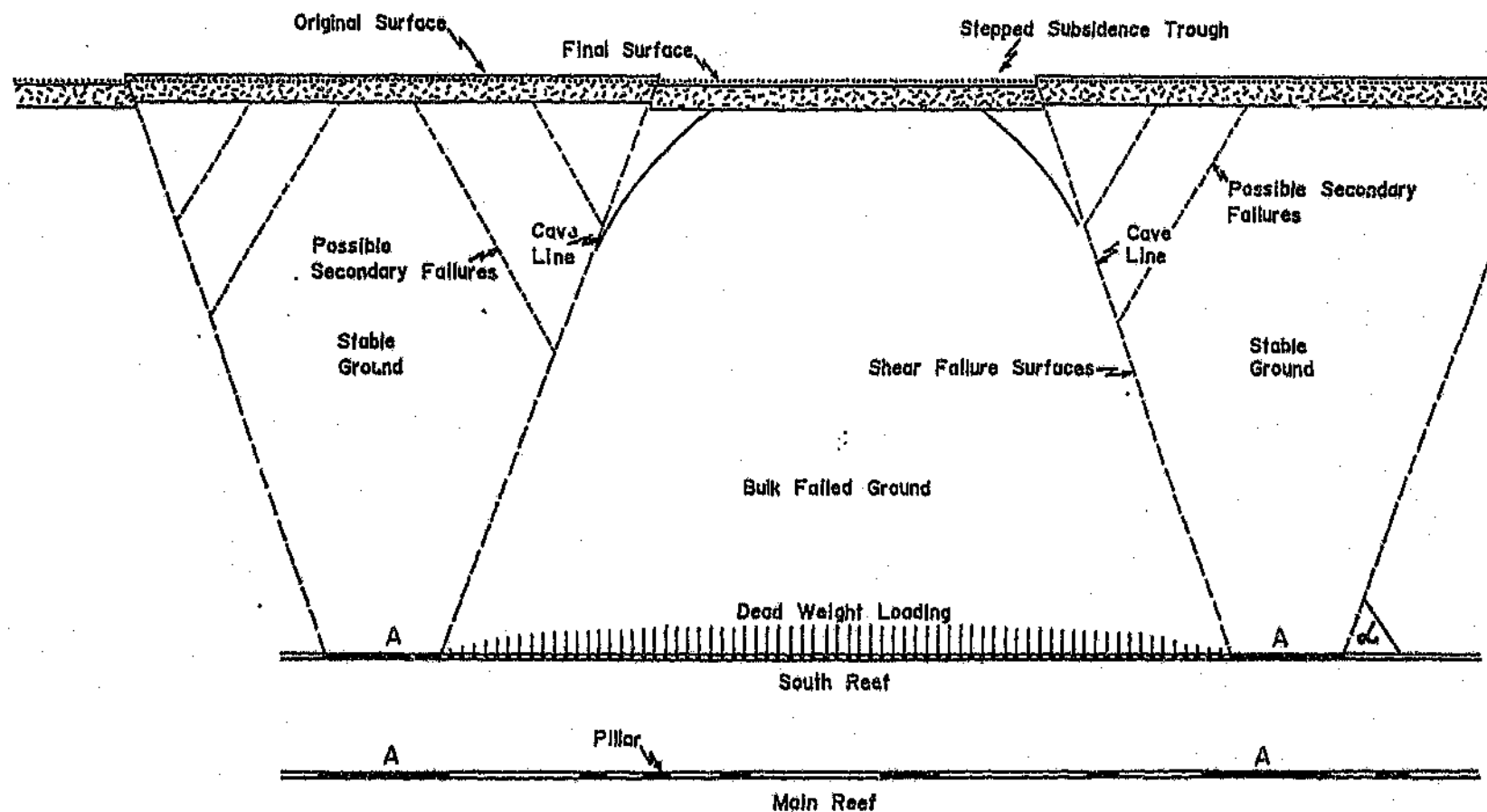


FIGURE 4.2

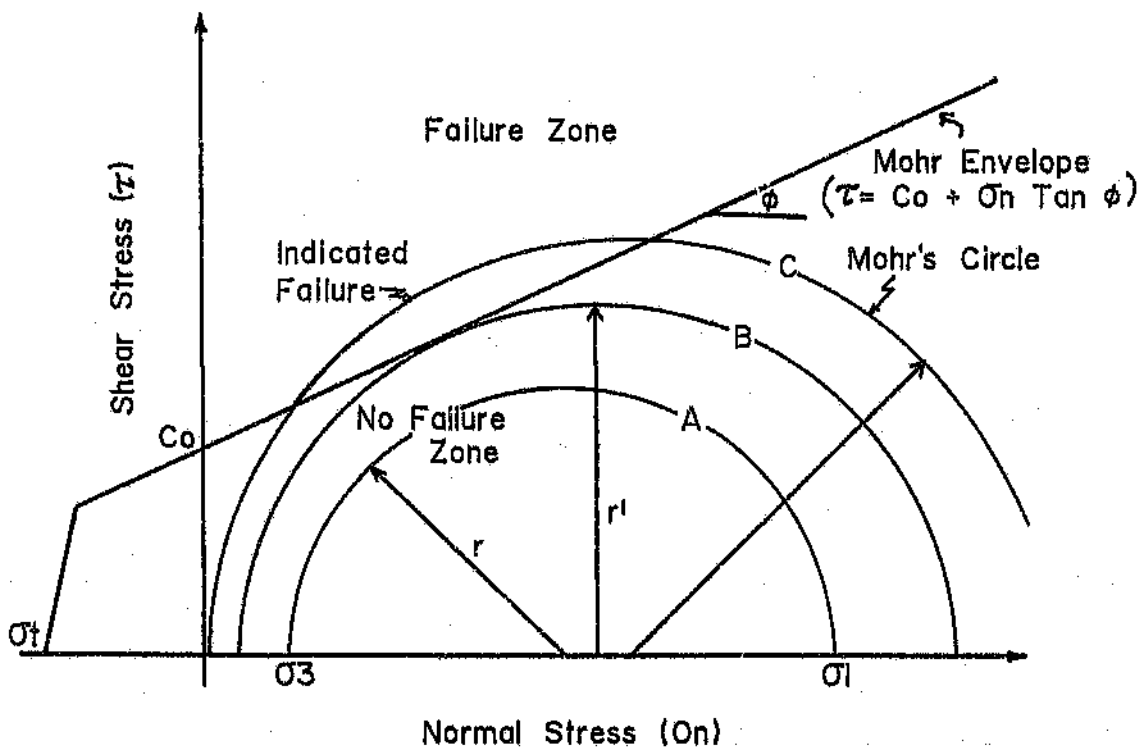
IDEALISED SUMMARY OF CURRENT STATE OF ROCK MASS ABOVE SOUTH REEF :
STRIKE ORIENTATED SECTION

This criterion can be represented as a line of critical stress state that separates a failure region above the line from a no-failure region below the line. This line, known as a Mohr's envelope, is unique for each material type. Figure 4.3 illustrates a typical example.

If the major and minor principal stresses are known for any point within the rock mass, then these can be plotted on the (Mohr's envelope) graph as a Mohr circle.

If a Mohr circle is fully enclosed in the no-failure region, as defined by the characteristic Mohr envelope, then stability is indicated. However, if it cuts the envelope and extends into the failure region then stress related failure is indicated. If an envelope acts as a tangent to a Mohr circle then the stress condition is at the critical stress state (that is, it is on the extreme limit of stability).

The failure index method, a feature of BESOL computer programs (CROUCH 1988) utilises a similar method. The computed field stress state (the state of stress existing in the ground as a result of adjacent mining activity) for a point is considered as a Mohr circle, compared with the critical stress state for a fixed minor principal stress, and then similarly compared with a fixed major principal stress. The ratio (r'/r) of the radii of circles described by the critical stress state (r'), and the true



- A - Stable Stress State
- B - Critical Stress State
- C - Unstable Stress State
- σ_1 - Major Principal Stress
- σ_3 - Minor Principal Stress
- C_o - Cohesion
- σ_t - Tensile Strength
- ϕ - Internal Friction Angle

$$\text{Failure Index} = \frac{r'}{r}$$

FIGURE 4.3 FAILURE INDEX USED IN NUMERICAL MODELLING

field stress state (r), is the failure index or strength : stress ratio for that point (CROUCH, 1976). An index of $F < 1$ indicates induced shear failure at that point, as detailed in Figure 4.3.

If all the computed values for every point within an area of interest are contoured, then failure indices for the modelled excavations are derived.

It should be noted that the Mohr-Coulomb failure criterion defines only a threshold beyond which shear fracturing is active. The model used does not follow the reduction in load-carrying capacity of the rock by reducing cohesion as a function of plastic strain.

4.1.2 South Reef

Behaviour : The South reef was previously described as massive to widely jointed with cohesive gradational contacts. Pillars and remnants may therefore be considered as unfailed and relatively intact units rather than blocks that could unravel under the influence of gravity or imposed loads.

As long as such pillars and/or remnants remain sufficiently wide to withstand imposed loads and deformations, the integrity of the entire overburden strata would be maintained during and after the mining process.

There is a high risk of sudden collapse of hangingwall if the additional loading caused by mining of pillars and remnants is to drive the remaining pillars to failure. This may result in large scale surface movement.

4.1.2.1 Criteria and Methods

Strength : The maximum stress criterion (JAEGER AND COOK, 1979) was used to analyse South reef pillar/remnant behaviour under imposed loads. This states that when an applied normal load approximates or exceeds the strength of the material, failure in compression occurs. In the case of pillars and remnants failure generally starts as corner and sidewall spalling as the stresses are higher at the corners (Figure 4.4). Failure progresses towards the centre and finally towards total failure.

The onset of compressive failure in normally loaded laboratory rock specimens usually starts at about 70 % of the rock's ultimate strength (JAEGER AND COOK, 1979), fracturing becomes severe when the applied loads approximate to about 90 % of its ultimate strength.

Therefore, for purposes of analysis, values equal to 70 % of the assumed intact and unconfined strengths are used as safe (and conservative) limit criteria for pillar edge stresses. For the South reef this value equals about 155 MPa.

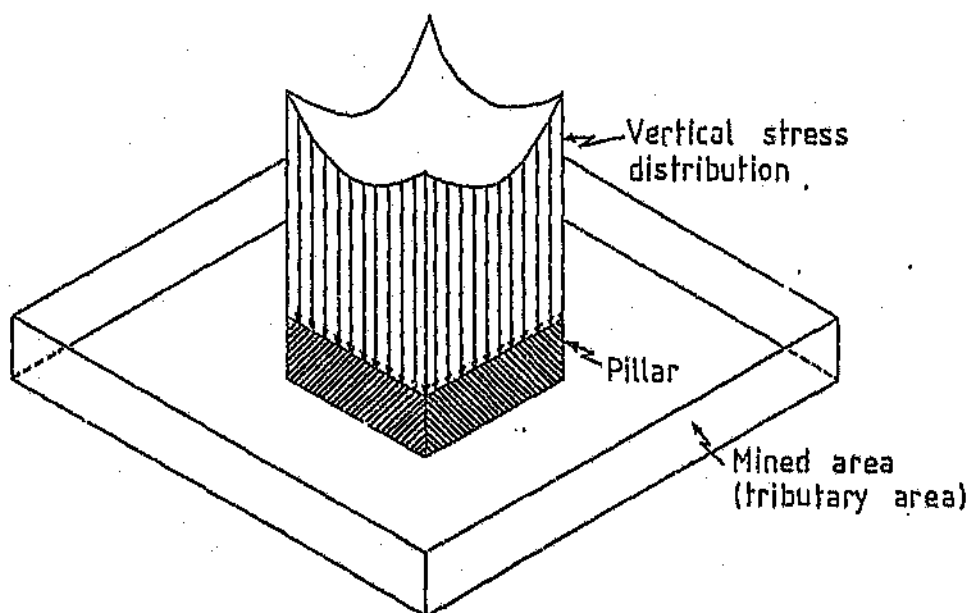


FIGURE 4.4 IDEALISED PILLAR STRESS DISTRIBUTION

However, the strength of individual pillars/remnants varies according to their bulk properties, rather than the laboratory determined values for small, intact and prepared specimens. The former are generally accepted to be 20 % to 30 % less than the latter (BIENIAWSKI, 1968), due to the influences of, for example, microfractures and other discontinuities such as joints. The critical stress level at which pillar corner and sidewall failure starts in the South reef is therefore assumed to equal 125 MPa.

The effects of weathering around isolated pillars, noted in Section 3.1.1 are ignored when setting the preceding strength criterion. The observed subaerial weathering is a limited peripheral feature which occurs along open fractures rather than through the rock fabric. As such, it would have little direct bearing on short- or long-term pillar/remnant strength.

Deformations : with regard to rock mass deformations, the preceding conditions concerning the effects of bulk properties on pillar and remnant strengths equally apply here. As such, the Young's modulus for the South reef pillars/remnants was reduced to 70 % of the assumed intact value, i.e. to about 50 GPa.

Elastic deformation of the hangingwall strata was modelled using a boundary element computer program, namely BESOL, CROUCH 1986. In two-dimensional modelling, pillars are assumed to be "continuous strips" of unmined reef. To

account for the effects of three-dimensional pillars on strata deformations, the pillar stiffness was reduced by a factor of e , which is the extraction ratio along the strip pillars, along their third dimension, as given by the formulae 4.2 and 4.3.

$$K_n = \frac{E_i}{S_m} \cdot e \quad - (4.2)$$

and
$$K_s = \frac{E_i}{2(1+\nu)} \cdot \frac{e}{S_m} \quad - (4.3)$$

Where K_n = normal bulk stiffness (GPa/m)
 E_i = in situ Young's modulus (GPa)
 S_m = stoping width (m)
 e = extraction ratio along the strip pillars
 K_s = bulk shear stiffness (GPa/m)
 ν = Poisson's ratio

4.1.3 Inter-reef parting

The inter-reef parting was previously described as a typical sequence of massive to widely jointed and competent Witwatersrand quartzites with minor grits. As such, its intact behaviour was modelled in the same manner as the rock mass overlying the South reef, with the exception of the deadweight effect of the weathered zone. The same criteria and modelling techniques were therefore applied.

4.1.4 Main Reef

The Main reef was previously described as similar in all respects to the South reef. As such, the behaviour, instability characteristics, strength and stiffness criteria of pillars and remnants were considered the same.

4.1.5 Criteria and Equations : Strata overlying the South Reef

Empirical Approach : The criteria and equations detailed in the following sections were specifically derived for purposes of this investigation. They describe the possible caved states defined above and were used for purposes of the analyses presented.

Two principal parameters define the likely caved state of a uniform rock mass over supercritical South Reef spans : the actual mined span (W) and limit span (Wmax) (SCHUMANN, 1988). Wmax defines the maximum safe span for mining which allows a stable intact limit cave angles to some point below 27 m below surface. The 27 m is made up of a 12 m weathered zone and a 15 m elastic but flawed layer, which is the minimum thickness (see section 3.1.5.2). The 15 m layer is represented by "t" in formula 4.5.

GALVIN (1983) quantified the effective span of a dolerite sill bridging over a goaf. In order to produce a span S_{eff} at the base of the dolerite sill, a critical minimum lateral dimension of the opening at the mining horizon is required, that is a panel width W_c , which must satisfy the following expression :

$$W_c = S_{eff} + 2 \left[t_p \tan (A - 90) \right] \quad - (4.4)$$

where t_p is the parting thickness between the base of the dolerite sill and the seam horizon, and $(A-90)$ is the

angle of break (Figure 4.5).

Geometrically, the caved state over supercritical spans of the South reef can be compared with the goaf under a dolerite sill (Figure 4.6). Accordingly, equation 4.4 was modified and yielded :

$$W_{\max} = S_f + 2 \left[\frac{h - (t+12)}{\tan A} \right] \quad - (4.5)$$

where S_f = safe span for an intact layer of thickness t (m)
 h = South reef depth below surface (m)
 A = caving angle (70 degrees)
 t = minimum intact layer (25 m)

When W is less or equal to $W_{\max}$ it would have little influence on inelastic rock mass behaviour. Two principal conditions can, therefore, arise :

$$A: \quad \text{If } W_{\max} < W \quad - (4.6)$$

then the height of the caved zone, h_c , becomes

$$h_c = \frac{S_g}{BF-1} \cdot RF \quad - (4.7)$$

where S_g = the South reef stopping height
 RF = the recompaction factor defined as the compression of failed rock layers caused by successive blocks loading previously failed blocks, in % and
 BF = the bulking factor in %.

From correlation between surface depressions reported

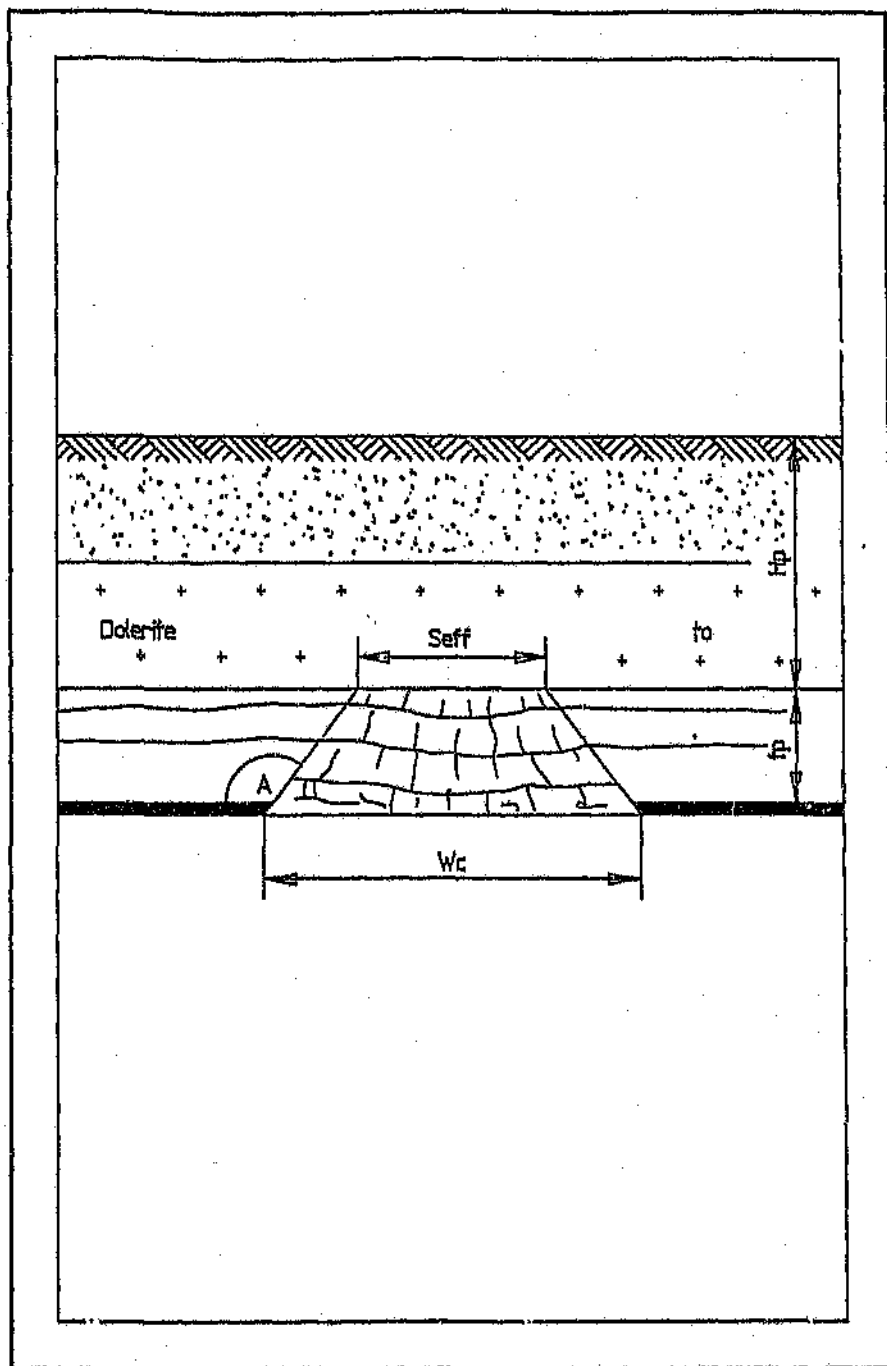


FIGURE 4.5 EFFECTIVE SPAN (AFTER GALVIN)

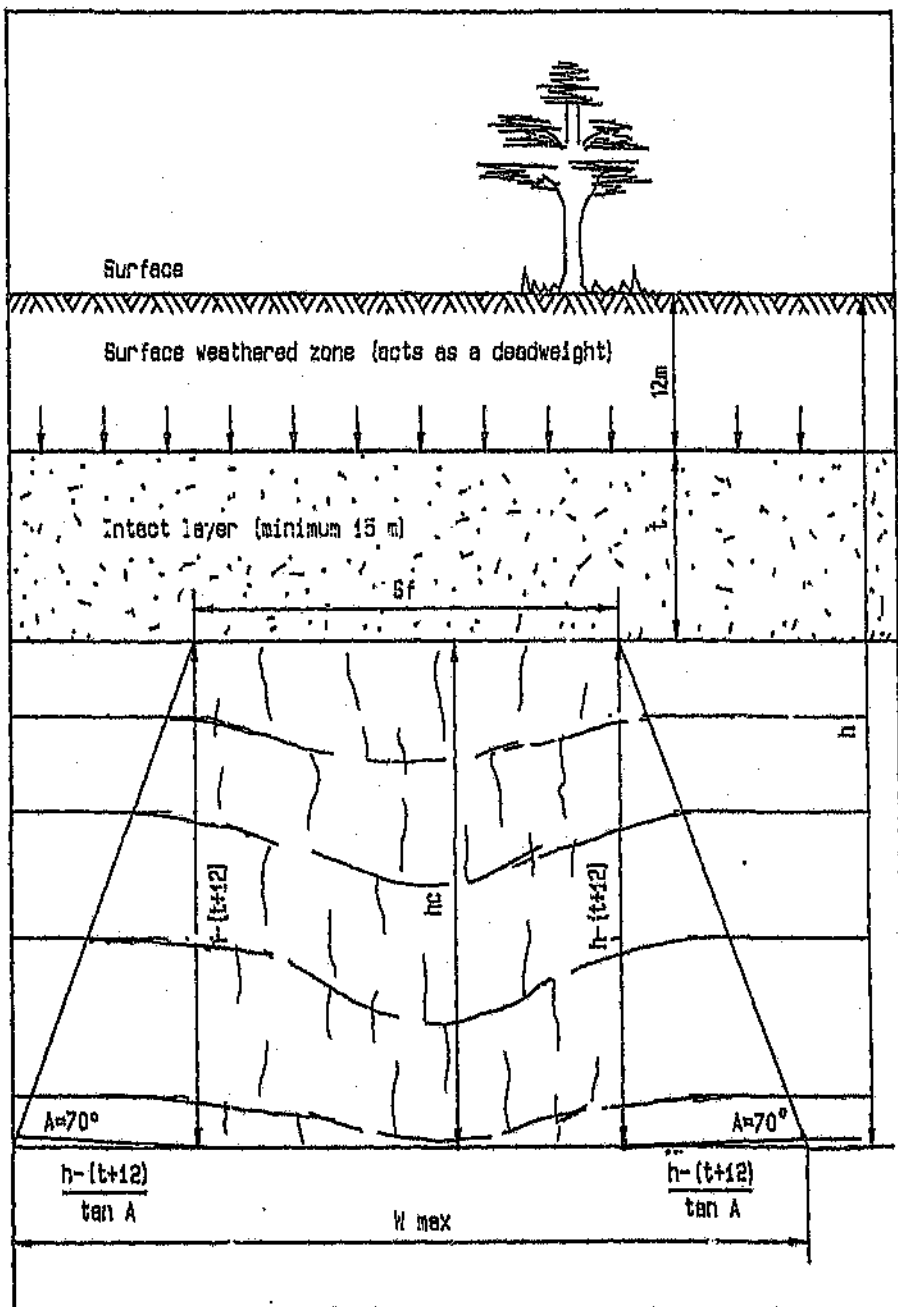


FIGURE 4.6 SAFE SPAN CAVED STRATA

between 1903 - 1927 in the Government Mining Engineer's Annual Reports (section 2.1.3.2) and stoping heights, it is unlikely that the recompaction factor exceeds 5 % (RF = 1.05).

$$\text{If } h_c > h - 12 \quad - (4.8)$$

(h - 12 being the mining depth minus the weathered zone)

then surface subsidence will occur, according to condition 1 in Section 3.1.5.2. The magnitude of the subsidence can be defined as :

$$S_{\max} = h_c - \left[\frac{(h - 12)}{RF} \right] \cdot (BF - 1) \quad - (4.9)$$

where $S_{\max}$ = maximum surface subsidence.

B : When $W_{\max} > W$, the maximum height of caving, h_c , is defined by the position of the first intact layer and that is :

$$h_c = (W - S_f) \tan A \quad - (4.10)$$

Note that if $h_c > h_0$ then equation 4.7 applies.

Figure 4.7 summarises equation 4.7 as a series of graphs detailing possible heights of caving for a range of

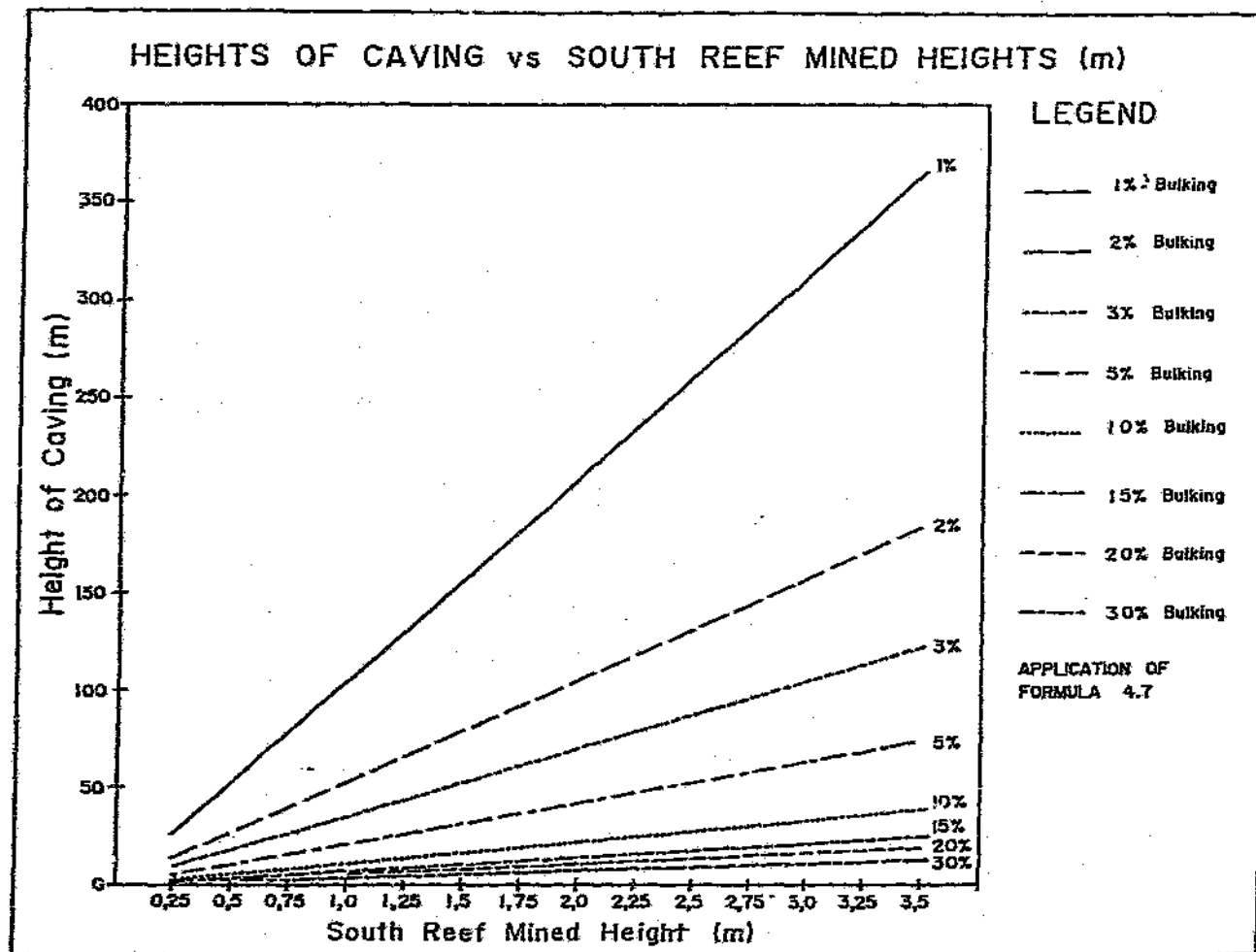


FIGURE 4.7 HEIGHTS OF CAVING VERSUS SOUTH REEF MINED HEIGHTS

bulking factors and South reef mined heights. The graphs indicate that the height of caving decreases with an increase in the percentage bulking. It is reasonable to assume that the bulking factor of quartzites lies between 5 % and 10 % (VAN NIEKERK, 1989). The graph of 10 % indicates that at a stoping width of 1,5 m supercritical spans at a depth range to about 25 m will cave to surface.

Numerical Modelling Approach : In common with empirical methods, computer based analytical methods rely on comparing in-situ strength of a pillar system to the calculated applied stress state. However, computer based methods have the distinct advantage of allowing rapid and independent analyses of any number of influencing variables. As such, their use is preferred.

Intact thicknesses over the mined areas were further analysed using RESOL. The failure index criterion as explained in Section 4.1.1.2 was used as the criterion in determining the critical mining spans. The constants used for modelling studies are given in Sections 4.1...2, 4.1.1.2 and 4.1.5.

A wide range of depth-span ratios were simulated. This was achieved by modelling span increasing at increments of 5 m between 20 m and 70 m for increasing depth at increments of 30 m, between 30m to 240 m.

The failure indices at critical mining spans were then

plotted on a graph, which details the computed critical mining spans for a depth range of 15 m to 240 m (Figure 4.8). The figure bears out underground observations of collapsed overlying strata in South reef workings at the depth range and spans indicated. For instance, reclamation mining at about 100 m depth in a South reef stope, where the critical span was widened to over 40 m, resulted in massive hangingwall collapse (Chief Inspector of Mines, Heidelberg, internal report on stope collapse at Nigel Gold Mines, 1988).

4.1.6 Criteria and Equations : Strata Overlying the Main reef

For the reasons already described, the equations and criteria defined in Section 4.1.5 for the South reef equally apply here. The following notation is adopted : h' is middling thickness, S_f is the critical span, t' is the thickness of the intact layer and S_m is the stoping width.

The relevant equations are then :

$$W_{max} = S_f' + 2 \left[\frac{h' - t'}{\tan A} \right] \quad - (4.11)$$

$$hc'' = \frac{S_m}{(BF - 1)} \cdot RF \quad - (4.12)$$

The total height of caving hc' can be defined by:

$$hc'' = \frac{S_m}{BF - 1} + \frac{S_s}{1} \cdot RF \quad - (4.13)$$

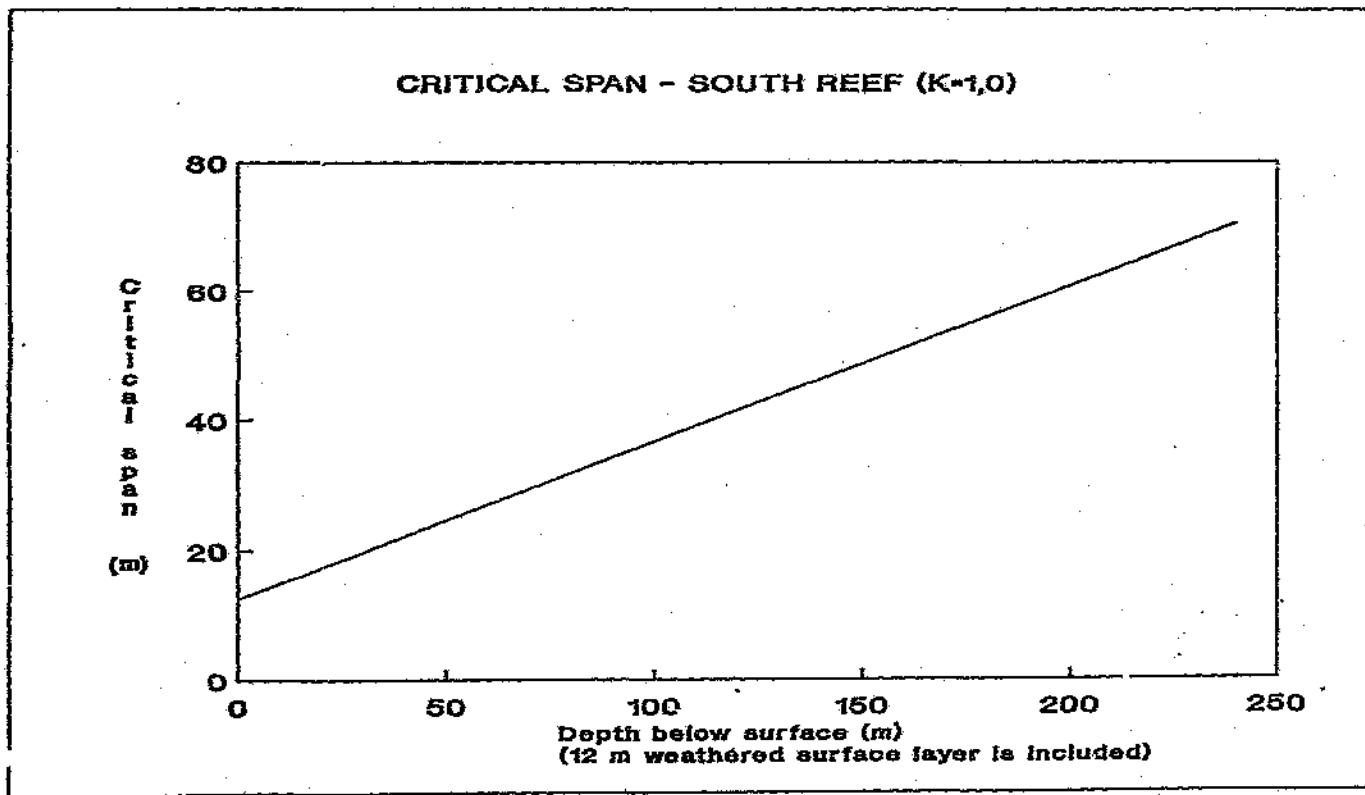


FIGURE 4.8 CRITICAL MINE SPANS VERSUS DEPTHS : SOUTH REEF

Also note that Equation 4.9 changes to:

$$S_{max} = (BF - 1) \left(\frac{hc'' - h'}{RF} \right) \quad - (4.14)$$

that is, $BF = 0$ for the failed rock mass overlying the South reef.

Equation 4.12 does not change as this is independent of Main reef mined spans for the reasons mentioned in Condition 2 as described in Section 3.1.5.3.

The same formulae and FLSOL program as described in the preceding section were used to determine critical spans at a depth range of 15 m to 240 m below surface. The graph depicted on Figure 4.9 details the critical mining spans for Main reef workings. This figure indicates that there is a strengthening effect with increasing depth of the 25 m thick middling between the South and Main reef workings. This could be attributed to the effect of the increase in horizontal stress, thereby increasing clamping forces.

Figure 4.10 summarises formula 4.12 as a series of graphs detailing possible heights of caving for a range of bulking factors and Main reef mined heights. When the same bulking factors are considered as with the South reef (5 % - 10 %) the graphs show that increasing stoping widths from 1,5 m to 2,75 m caving to the South reef workings will occur at supercritical spans.

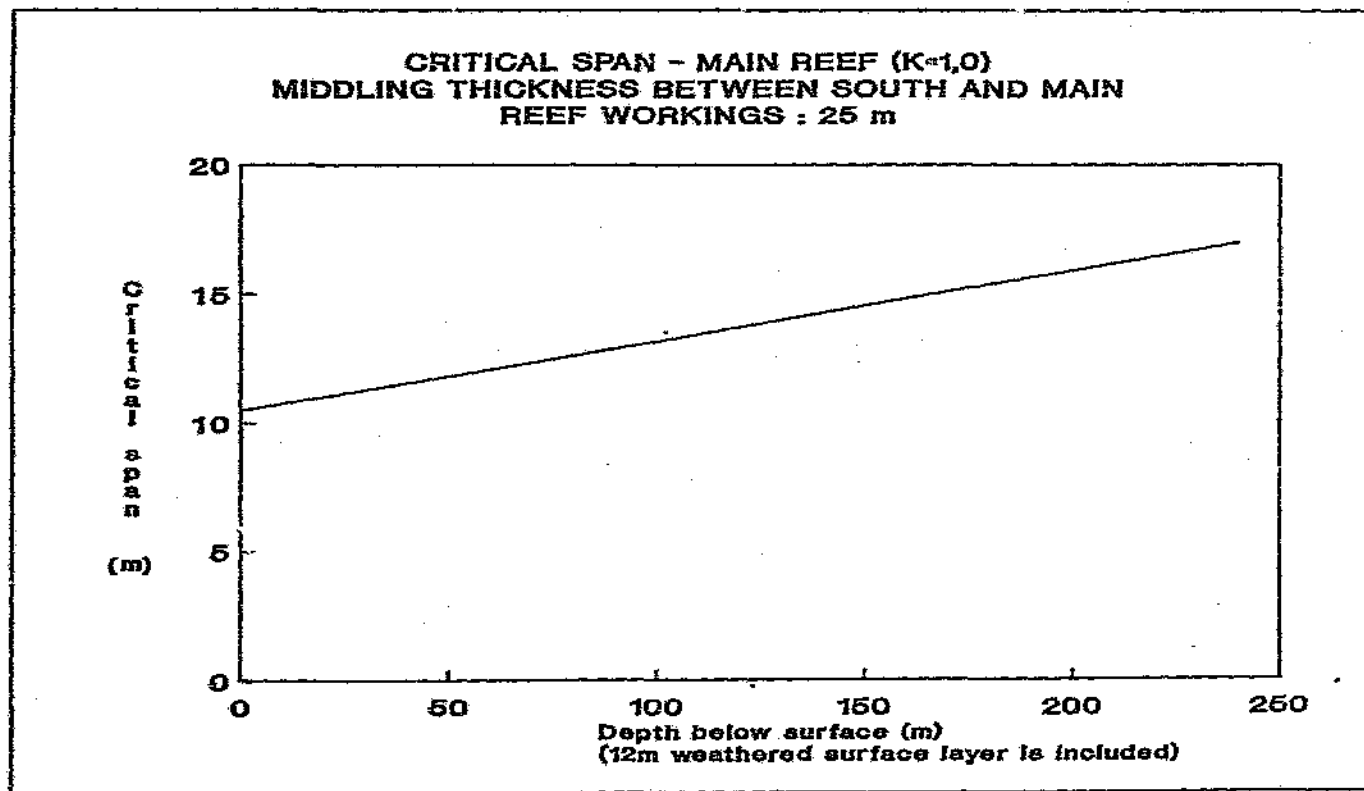


FIGURE 4.9 **CRITICAL MINE SPANS VERSUS DEPTHS : MAIN REEF**

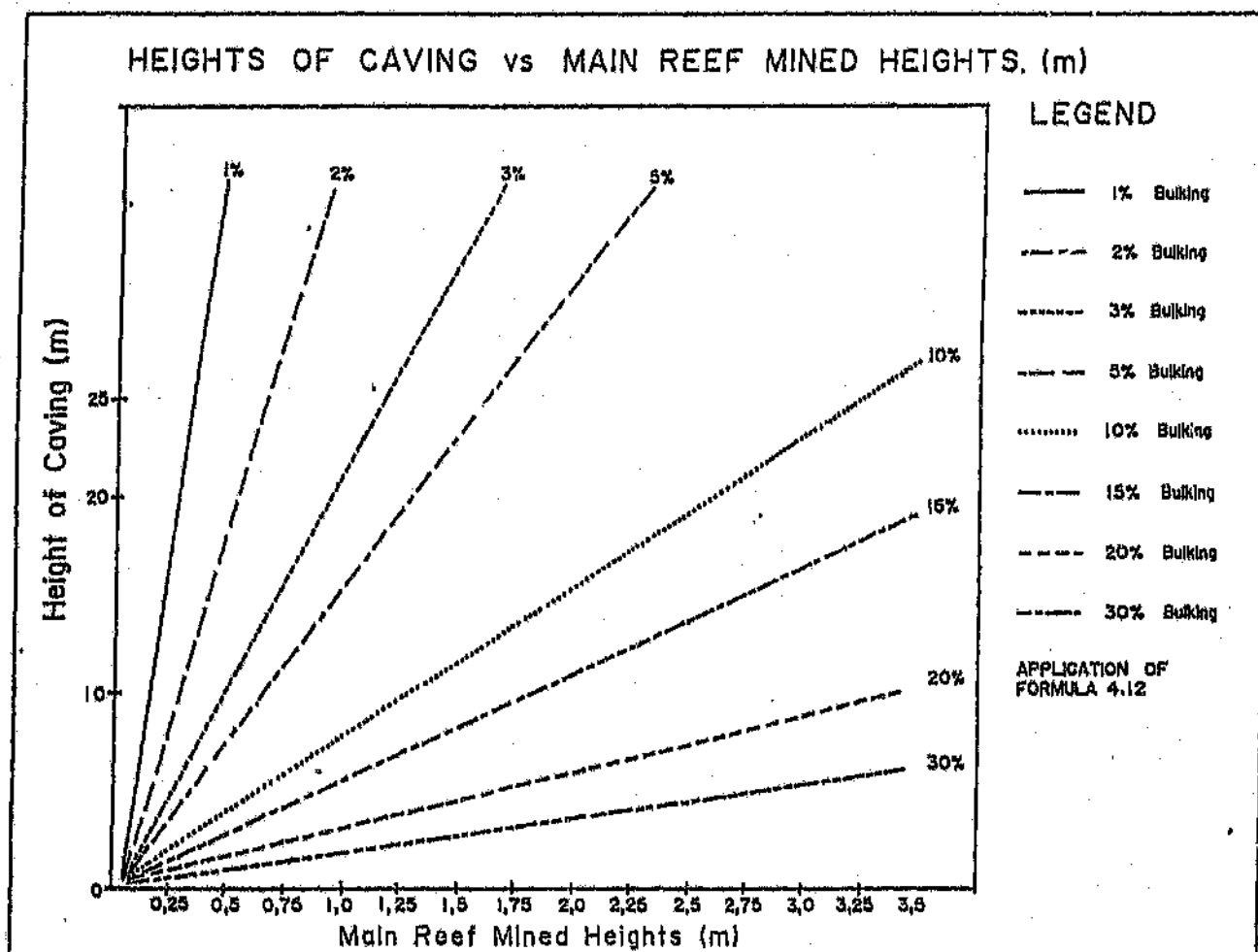


FIGURE 4.10 HEIGHTS OF CAVING vs MAIN REEF MINED HEIGHTS

4.1.7 Pillar Design Criteria and Remnant Mining

The reef pillars left in situ have 5 m side lengths and are approximately square (Section 3.1.2). Underground investigations revealed no deterioration or scaling of these pillars. These pillars can be accepted to be suitable for surface protection as pillars with a width : height ratio of 5 or more normally do not shed load, OZBAY, 1987. As the stopping width, on average, is 1 m, these pillars are suitable for surface protection purposes.

Scrutiny of mine plans has shown that in the extensively mined stopes, the original mining has stopped against or near to the reef intersections of the joint zones associated with the dykes. Total extraction of these remnant reef pillars peripheral to the dykes would incur an extreme risk of adverse surface movements. The principal reasons for this are the potential for subsidence and rock movement along dykes and faults and the possibility of induced shear failure of the undermined hangingwall. In either case large scale inelastic surface movements would occur (CAMERON-CLARKE, 1990).

Partial pillar stripping would carry less risk of adverse surface movements than total extraction of pillars and remnants. However, the associated risks would remain high due to the influences of unknowns such as the characteristics of the joint zones associated with the dykes.

The abovementioned rock movement is not limited to depth and may occur over a considerable period of time (CAMERON-CLARKE, 1990).

4.2 Bushveld Igneous Complex : Zones, Rock Mass

Behaviour and Design Criteria : The approach for the BIC is somewhat different to that for the Witwatersrand, although it also deals with the implications of the geotechnical analysis presented in Section 3. However, the rock mass is first zoned according to the prevailing ground conditions. The general behavioural characteristics of the rock mass are then determined from which the design criteria for the defined zones are set. An idealised representation of the structural types for the rock mass is given on Figure 4.11.

4.2.1 Geological Zones

4.2.1.1 Norite/Anorthosite Hangingwall Series

The norite/anorthosite hangingwall series can be conveniently considered as two separate units : the surface weathered layers; and an underlying, unweathered mass.

Weathered Layers : The depth to the base of the main surface weathered zone can be defined as approximating to 15 m for the worst case. Gravity will play the dominant role and the layer can be reasonably expected to act as a deadweight over most mined spans. The stress caused by

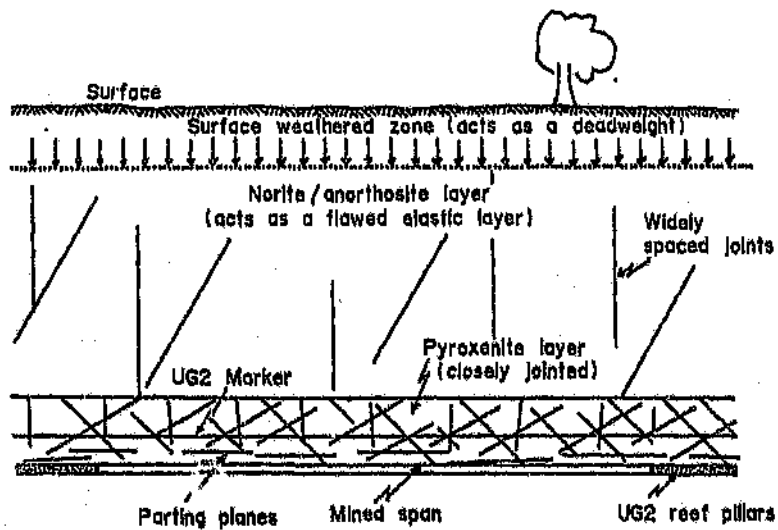


FIGURE: 4.11 IDEALISED REPRESENTATION OF THE STRUCTURAL TYPES FOR THE ROCK MASS OVERLYING THE UG2

this deadweight is taken as 0,3MPa, the means used to analyse its effects on excavation stability.

Unweathered Layers : The unweathered portion of the hangingwall norite/anorthosite series can be described as widely jointed with discontinuous and mostly subvertical joints. The stability of the norite/anorthosite layer depends on the properties of the inherent joints: the interlocking blocks are bound by joints and are subjected to the effects of gravity (Sections 3.1.2 and 3.1.3 of Appendix A). The width of the mining spans also influences the stability of this layer (Figure 4.12) and the magnitude of the horizontal stress, an increase of which would result in larger frictional forces on the joint planes (Section 3.1.4).

At thicknesses of unweathered norite/anorthosite of 15 m and more (the equivalent of a reef depth of 40 m below surface) the stability depends on the bulk properties of the layer and applied stress state. Joints, which are widely spaced and subvertical, reduces the modulus of rigidity of the layer to about 50 % of intact rock (BRADY AND BROWN, 1985), that is, to about 40GPa for the norite/anorthosite layer. It would be capable of bridging/increasing spans as its thickness increases with depth.

4.2.1.2 Hangingwall Pyroxenite Sequence

The hangingwall pyroxenite sequence is particularly prone to collapses, as stated in Sections 3.2.1.2 and 3.2.2.1.

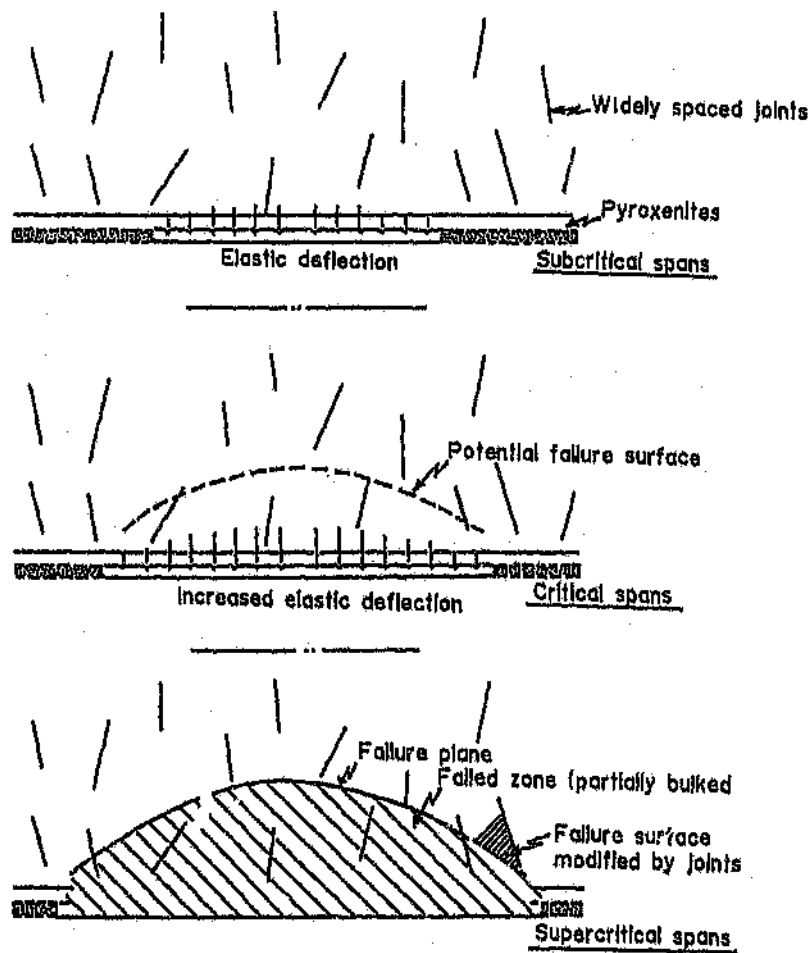


FIGURE 4.12 IDEALISED SUBCRITICAL TO SUPERCRITICAL MINE SPANS : BIC

Should a collapse occur then this would rapidly develop as weathered layers; that associated with the unweathered but jointed layers; and that related to the parting planes in the immediate hangingwall. These differentiations are important as the rapidly changing and deceptive hangingwall conditions can impact significantly on stope support requirements.

The behaviour of the weathered layers would be very similar to that of the norite/anorthosite hangingwall weathered layers and it is reasonable to conclude that over most mined spans they will act as a deadweight on any underlying intact layers or installed support, and would be prone to unravelling should a key block failure occur.

In contrast, an unweathered sequence would act as a series of interlocking blocks. Its stability would, therefore, also depend on the frictional resistance to sliding, partly afforded by lateral clamping forces along planes inclined at angles greater than about 50 degrees to the horizontal (STACEY, 1986).

It can be concluded that the in situ behavioural characteristics of the hangingwall pyroxenite sequence are :

- * the hangingwall layer acts independently of the overlying and intact norite/anorthosite series;
- * to depths of about 70 m below surface, the

hangingwall pyroxenite sequence acts as a single deadweight unit on the installed internal stope support; and

- * the hangingwall pyroxenite layer plays no direct role in determining safe panel spans.

The above mentioned characteristics must be qualified: From observations there is a marked increase in both the strength and stability of the hangingwall pyroxenite sequence in a westerly direction on the western side of the BIC. The pyroxenite could, therefore, form part of the stable hangingwall.

4.2.1.3 UG2 Reef

In the oxidized zone the reef is deeply weathered to a weak and friable mass which largely precludes the cutting of pillars. As such, underground mining in the oxidized zone would be extremely difficult and result in low extraction ratios. As described in Section 3.2.2.2, the oxidized zone varies along strike and extends between 20 m to 30 m below surface. As such, mining to the base of the oxidized zone would best be carried out on a selective basis.

As stated in Section 3.2.2.2 the weathered zone extends to a depth of about 50 m below surface. As the reef in this zone is characterised by deeply weathered and randomly orientated planes, pillar stability depends mainly on

their bulk strength characteristics rather than the strength of intact blocks.

The weathering profile in this area could cause the weakening of the top contact of the pillars and of the pillars themselves which, in turn, could result in hangingwall collapses around the pillars by allowing relaxation of the rockmass and an increased probability of hangingwall failures through loss of frictional resistance across joint planes.

4.2.1.4 Footwall Sequence

As stated in Section 3.2.2.3 the inherent weakness of the deeply weathered pegmatoid could be a potential source of footing instability for any pillars and/or internal stope support, which could allow relaxation of the hangingwall sequence, thereby increasing the probability of local failures or collapses. Such problems can be expected to be severe to a depth of about 40 m below surface.

4.2.2 Models

To reef depths of about 200 m below surface, either tributary area theory or computer based analytical design methods, such as BESOL type programs, can be used to determine pillar stability.

4.2.2.1 Pillar Design Criteria

Several applications for permission to undermine surface objects above the UG2 reefs were the subject of studies on

pillar design (BUDAVARI 1983b, NOBLE, 1989; KOTZE, 1983). It was found that a safety factor of 2 for pillars to protect surface objects, was acceptable. The safety factor is determined by dividing the load or pillar stress into the pillar strength :

$$\text{Safety factor} = \frac{\text{Pillar Strength}}{\text{Pillar Stress}} \quad - (4.15)$$

The strength of a pillar is calculated by using an empirical formula :

$$\text{Strength} = K \frac{W^{0.5}}{H^{0.75}} \quad - (4.16)$$

where K = Cubic strength of UG2
 W = Width of pillar
 H = Height of pillar

The above formula applies to square pillars. WAGNER (1974) suggested the following formula to obtain W in formula 4.16 for rectangular pillars :

$$W_{eff} = \frac{4 A}{C}$$

where A = Cross-sectional area (m²)
 C = Circumference (m)

The load/stress is calculated, using the tributary area theory, as modified by BUDAVARI, 1983 :

$$\text{Load} = \frac{u \times dc \times sc \times H}{W \times L} \quad - (4.17)$$

where : u = unit weight of rock mass
 dc = dip centres of pillar
 sc = strike centres of pillars
 H = depth below surface

W = pillar width
L = pillar length

Numerous observations have proved that rectangular pillars with their long axes at right angles to geological weaknesses and joints prevented major falls of ground.

Square pillars and rectangular pillars parallel to the weaknesses and joint sets are associated with major rock falls, especially in the weathered zone.

A further stipulation was that the width to height ratio of the pillars should be 5 for the protection of the surface. In practice, these pillars are kept to a width of 5 m at stoping widths of 1m. All situations where these criteria were applied, have been investigated and no scaling or deterioration of rectangular pillars of a width of 5 m has been observed. Recent studies (RYDER AND OZBAY, 1990) have also indicated that these pillars do not shed load when the width to height ratio is 5.

4.2.3 Design Considerations

The following can be concluded from the preceding discussions :

- * the determination of safe mining spans primarily depends on maintaining the stability of an interite/anorthosite layer, although this can be dramatically altered by the presence of geological

structures;

- * the stability of the hangingwall pyroxenite sequence, and any other overlying weathered layers, is primarily a concern of internal stope support, they play no direct role in defining safe mining spans, although a marked improvement of pyroxenite hangingwall may result in the pyroxenite to form part of the hangingwall series.
- * Apart from pillar stability, an important pillar design consideration is their ability to prevent an "overrun" of ground in the event of an uncontrolled hangingwall pyroxenite collapse, in particular to a reef depth of about 50 m below surface; and
- * support in those areas affected by the weathered footwall-pegmatoid (to a reef depth of at least 60 m below surface) should be designed to accommodate the effects of its weak nature.

4.2.4 Design Criteria and Methods

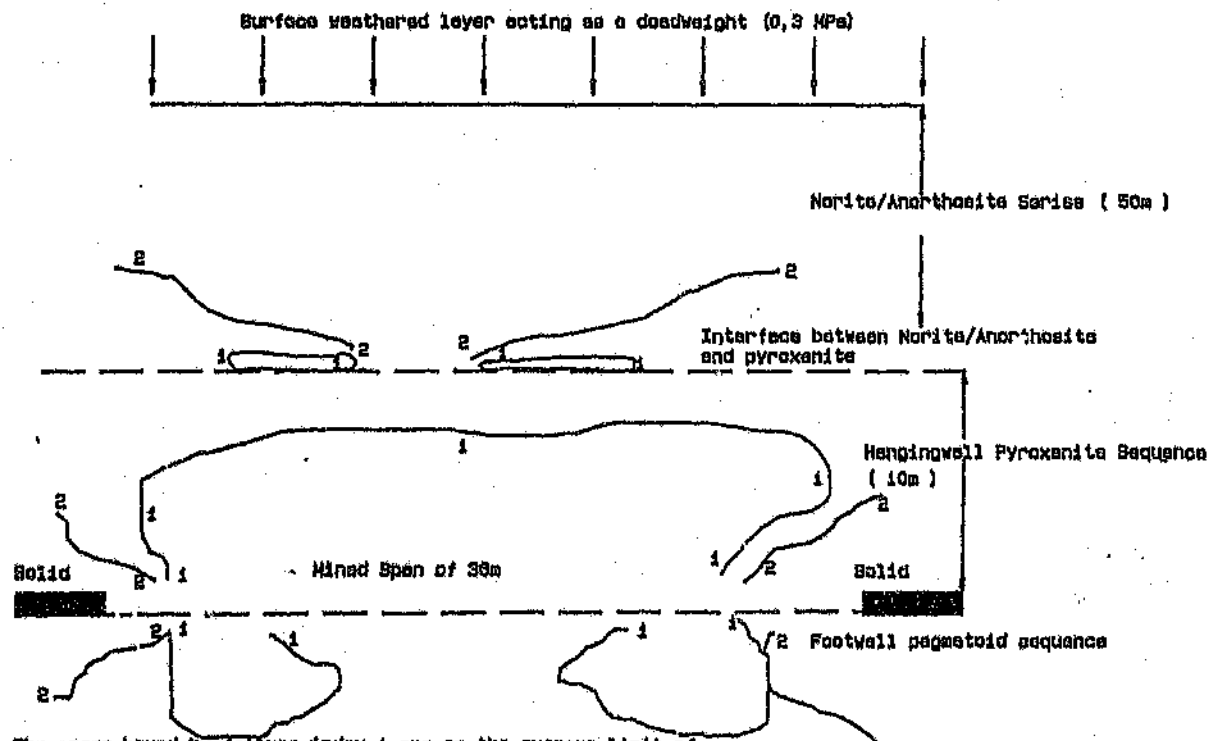
The use of displacement discontinuity type boundary element is valued for modelling the behaviour of the norite/anorthosite layer. The model used for purposes of analysis, was an elastic but flawed layer with the material constants defined in Table 3.4, except for a modulus reduced by about 50 % compared to intact rock ($E =$

40 GPa). The failure index method based on the Mohr-Coulomb failure criterion (equation 4.1) was used to establish the resulting critical mined spans in the same manner as described in Section 4.1.5.

The same criteria and methods were used as detailed in Section 4.1.2.

In all cases the hangingwall pyroxenite sequence was modelled as a separate unit with independent properties. The surface weathered zone was modelled as a line load equal to 0,3 MN/m². The virgin stress state was modelled as $k = 1,0$ for the reason described in Section 3.1.4. A parallel rib pillar system was assumed. An example of a plot is given on Figure 4.13. The figure depicts the plot of a span of 36 m with a norite/anorthosite layer of 50 m. A load of 0,3MPa is imposed on this layer and represents the surface weathered layer. A pyroxenite sequence of 10 m was modelled which already shows a much larger area of critical stress state than in the norite/anorthosite layer. Critical stress states are developing in the norite/anorthosite layer and this mining span was plotted as a critical mining span against a norite/anorthosite thickness of 50 m on Figure 4.14.

The following intact thicknesses were analysed : 5,0 m increments between 5,0 m and 20,0 m; 10,0 m increments between 20,0 m and 50,0 m; and 20,0 m increments between 50,0 m and 150,0 m. The failure index method, which is



The areas bound by failure index 1 are on the extreme limit of stability. At norite/anorthosite thickness of 80m the critical span is 36m. This corresponds with a depth of 75m below surface.

FIGURE 4.13 MODEL OF COMPUTER GENERATED FAILURE INDEX FOR BIC SITUATION

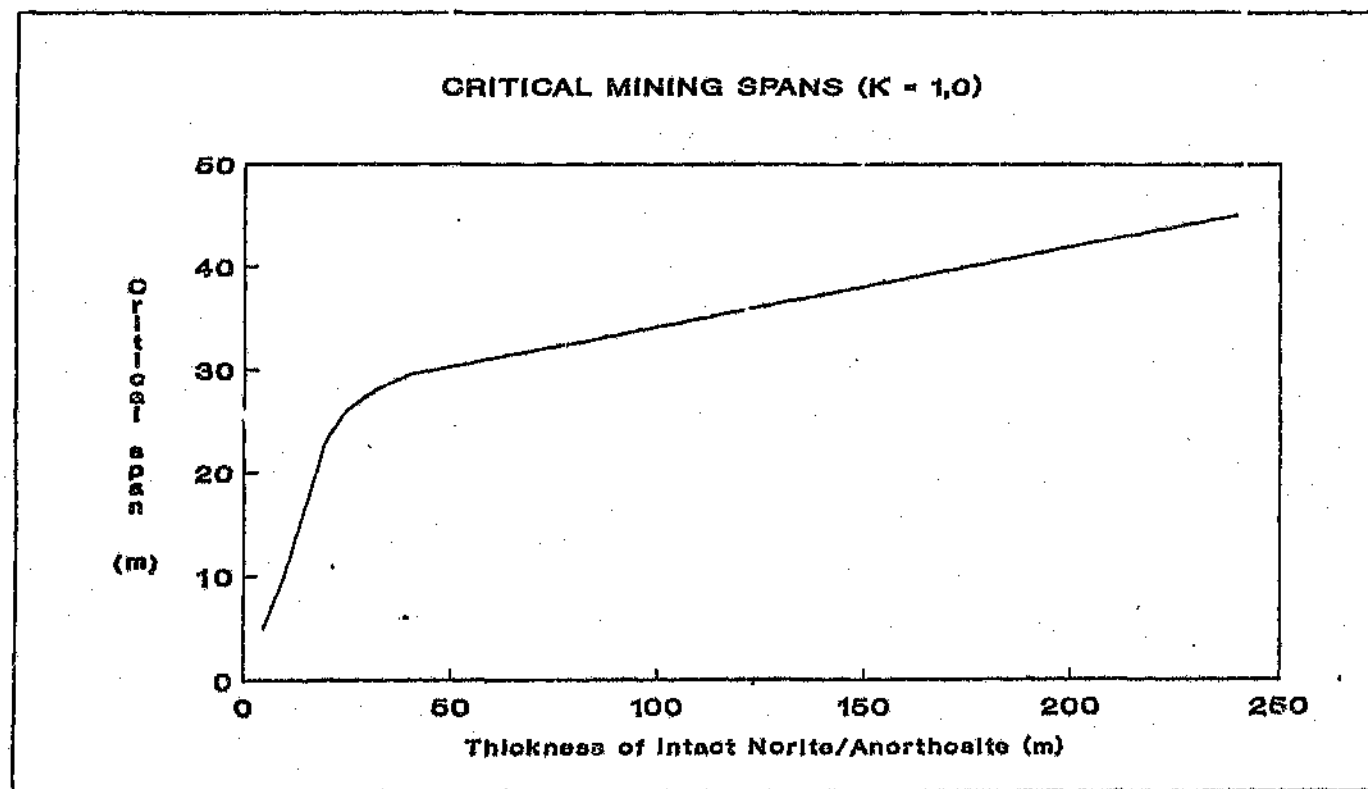


FIGURE 4.14 CRITICAL MINE SPANS VERSUS INTACT THICKNESS OF NORITE/ANORTHOSITE SERIES

based on the Mohr-Coulomb failure criterion (equation 4.1) was used to establish the resulting critical mined span.

The failure indices at critical norite/anorthosite thicknesses were calculated and critical mining spans plotted on a graph, in the same manner as described in Section 4.1.5 and which details the computed critical mining spans for a depth range of 5 m to 240 m (Figure 4.14). This figure indicates a rapid increase in the strength of the norite-anorthosite layer up to a thickness of 50 m, after which the increase in strength is uniform. It must again be emphasised that there is a marked increase in the strength and stability of the pyroxenites on the western side of the BIC. As a consequence, the pyroxenite layer can be incorporated into the norite/anorthosite layer after investigating the hangingwall layer proves its stability.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Central Witwatersrand

5.1.1 Models

As stated in Section 4.1.1 BESOL allows the determination of potential failure zones rather than actual failure zones.

As stated in Section 3.1.2 the hangingwall above the South reef workings have collapsed where spans exceeded the critical span as determined by the BESOL generated critical span curve (Figure 4.8).

Certain other conclusions therefore arose concerning the likely state of the rock mass overlying the South reef:

- * The failed portion of the rock mass can reasonably be expected to have retained no lateral or transverse stiffness; it probably acts as a deadweight on the footwall layer and as a series of loosely interlocking blocks with little or no intrinsic bridging strength.
- * The effect of a cave angle would have resulted in a mass of unfailed rock resting on most of the remaining pillars and remnants. These unfailed masses could include intact shallow layers of the type described on Figure 4.6. If the effect of

the cave angle has not reached surface, the remaining intact layer would be in a critical stress state. Any widening of the original excavation by, for instance mining of pillars or remnants, could result in its destabilisation, which in turn could result in inelastic surface movement (Section 4.1.1.1).

In view of the importance of the preceding conclusions on the mining of the pillars and remnants, the criteria and equations detailed in Section 4.1.5 were used to determine critical free spans for the South reef horizon, as detailed on Figure 4.8.

As mining activities in the Central Rand at the depth range of interest can be classified as reclamation mining, it is unlikely that mining in pristine rock will take place. Recommendations as to mining pristine rock on this horizon are nevertheless made in Section 5.1.3.

5.1.2 Design of Pillars

As far as pillar and remnant stability of the existing pillars is concerned, the models and criteria detailed in Section 4.1.5 were used. Worst case models were used to establish the magnitudes of normal and shear stress acting on the pillars/remnants. A cave angle of 70 degrees was assumed, as well as near surface intact layers according to the critical spans detailed on figure 4.8 and the likely caving characteristics defined by equation 4.7 and

detailed on figure 4.7. For purposes of these models the Main reef was modelled as mined to random spans with randomly sized pillars. These pillars/remnants left at and around (subvertical) dykes were also modelled as being superimposed between reefs.

In all cases the computed worst case results revealed vertical stresses on pillar edges of no more than about 65 MPa (to a maximum depth of 300 m). That is, about half the critical stress level of 125 MPa (see Section 4.1.2.1) for the onset of sidewall failure. Pillar stiffness was also found to be adequate to restrict excessive hangingwall sag when their widths are greater than 10 m. The magnitudes of induced shear stress in the hangingwall on the edges of pillars, were found to be sufficiently small to not warrant further consideration.

5.1.3 Mining spans

Figures 4.8 and 4.9 summarises the results from the model studies carried out for establishing critical spans for a range of depths and middling thickness at depths varying between 27 m and 240 m. Figure 4.10 implies an increase in the stability of the hangingwall strata of the South reef stopes with an increase in depth, while figure 4.9 shows a slight increase in the strength of the 25 m thick middling between the South and Main reef with an increase in depth.

However, an objective analysis of the current state of the middling to the Main reef would be greatly complicated by the wide variety of original mined spans and configurations. As such, no general conclusions could be made other than failure to the South reef horizon would have occurred in some cases. This could have resulted in inelastic surface effects, depending on the caved state of the rock mass overlying the South reef, for the reasons described in Section 3.1.5.3.

5.1.4 Recommendations

5.1.4.1 Mining options, South reef

Two possible South reef mining options are considered:

- * the removal of reef from the margins of the pillar/remnants left around dyke positions; and
- * footwall and/or hangingwall stripping in the previously mined stopes.

(i) Pillar/remnant stoping

It is worth noting in this regard that in the extensively mined stopes, the original mining would have most probably stopped against or near to the reef intersections of the joint zones associated with the dykes. As stated in Section 4.1.7, any mining of these peripheral pillars may cause rock movement along the dykes and faults,

resulting in differential subsidence on dyke/fault contracts.

No pillar/remnant mining or partial pillar stripping is recommended for reasons described in Section 4.1.7.

(ii) Footwall/hangingwall Stripping

As footwall/hangingwall stripping may have an effect on the width to height ratio of pillars it is recommended that footwall/hangingwall stripping is restricted to areas away from pillars.

(iii) Primary Mining

For safety purposes the critical span on the graph shown on figure 4.10 has been decreased by a factor of 10 % to form a safe span (Figure 5.1). The factor of 10 % is based on possible damage by blasting and weathering of the pillar sides, which would have a weakening effect. It is unlikely that the damaged/weathered zone would result in increasing the critical span by more than 10 %.

From the criteria and analyses in the preceding chapters the following conditions are considered to be reasonable :

(a) Mining activities at depths less than 27 m

measured vertically below the ground surface; would cause surface subsidence, as explained in section 4.1.5.

- (b) breast mining - maximum panel widths read off from figure 5.1 with interpanel pillars with a width to height ratio of no less than 5; (Section 4.1.7)
- (c) room and pillar mining - square pillars with a width to height ratio of no less than 5 and regularly spaced at intervals read off Figure 5.1.
- (d) Mining near geological structures: pillars to be left on the contacts of faults and dykes of the same dimensions as mentioned under (a) and (c).
- (e) Reclamation mining of peripheral pillars left at dykes and faults carries an extreme risk of inducing en bloc movement along the dyke and fault planes (Section 4.1.7) and is not recommended.

Mining must not alter the original South reef mined dimensions such that new or additional caving could occur.

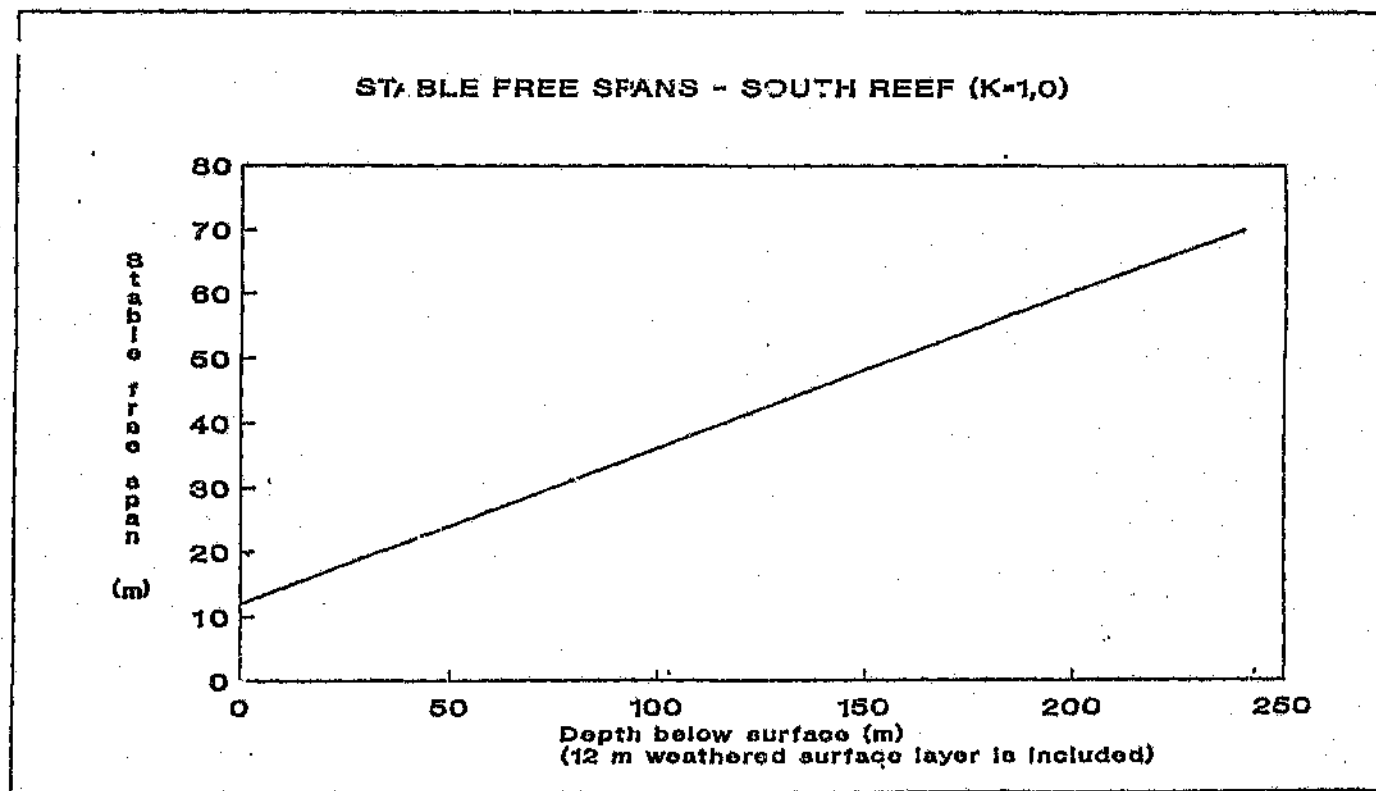


FIGURE 5.1 SAFE MINE SPANS VERSUS DEPTH : SOUTH REEF

(iv) Restricted area

No reasons were found to alter the present definition and calculation of a restricted area. They are :

When the dip is less than 20 degrees, the restricted mining area will be defined by a horizontal distance measured from the side of the surface structure to be protected in all directions of $d/2,7$.

When the dip of the reef is greater than 20 degrees, the extent of the restricted area will be defined as follows in terms of d , the depth to the footwall of the deepest reef being mined beneath the site :

- (a) rise side: a distance of $d/2,7$ measured up and at right angles to the strike of the reef;
- (b) dip side: a distance of 3 m measured down at right angles to the strike of the reef;
- (c) strike sides: a distance of $d/5,7$ measured along the strike of the reef.

5.1.4.2 Mining options, Main reef

The following mining options are considered :

- * the removal of peripheral reef from the margins of the pillars/remnants left around dyke positions;
- * mining of the large scale remnants;
- * footwall and/or hangingwall stripping in the previously mined spans;
- * pillar robbing in the previously mined room and pillar stopes.

(i) Pillar/Remnant Stripping

The comments and conclusions summarised in Section 5.1.4.1 above concerning partial stripping of the remnant reef peripheral to the subvertical dykes in the South reef equally apply here.

(ii) Remnant Mining

The conditions summarised in the preceding section, equally apply here.

(iii) Footwall/hangingwall Stripping

The risks associated with this mining option depend on the current state of the rock mass in the original stopes.

In the case of old stopes that collapsed to the South reef, the comments and conclusions

summarised in Section 5.1.4.1 apply.

In those areas where partial collapse to an intact layer occurred, hangingwall and/or footwall stripping may be possible depending on the thickness of the failed layer and the type of internal support used.

In those areas where the old stopes are stable any amount of hangingwall or footwall stripping could be carried out at low risk.

Hangingwall and/or footwall stripping in partially caved or stable stope represent the lowest risk of all the mining options considered. Stable stopes/panels would be immediately obvious underground. The state of partially caved stopes, and hence the internal support requirements, can only be assessed on an individual basis.

The preceding comments assume that secondary mining, that would create supercritical spans and hence caving to surface, would not take place.

(iv) Pillar robbing

The robbing of any isolated pillar (for example, the approximately square pillars with 5 m side lengths that were left in large areas of the previously mined Main reef) that results in the

creation of critical hangingwall spans is not recommended under any circumstances.

The principal reason for this recommendation is that it would incur extreme risks during and after the mining process. For example :

- * supercritical mined spans would result in uncontrollable and large scale hangingwall failure during the mining process and to the South reef; and
- * it could induce large scale inelastic surface effects.

(v) Primary mining

For safety purposes the critical span of the graph of figure 4.11 has been decreased by a factor of 10 % (figure 5.2) for the same reasons as explained in Section 5.1.4.1(iii).

- (a) no mining is permitted at depths less than 27 m measured vertically below the ground surface to prevent surface subsidence;
- (b) breast mining - maximum panel widths read off from figure 5.2 with interpanel pillars no less than 5.0 m, wide (see Section 4.1.7);

(c) room and pillar mining - square pillars with side lengths of no less than 5,0 m, and regularly spaced at intervals read from Figure 5.2;

(d) mining must be stopped at least 5 m short of the reef position of the joint zones associated with dykes and faults.

Mining must not change the previous Main reef mined dimensions such that new or additional caving could occur.

(vi) Restricted Area

The same criteria as under (iv) of Section 5.1.4.1 are applicable.

5.2 Bushveld Igneous Complex

5.2.1 Models

The critical spans for various thicknesses of the norite/anorthosite series detailed on figure 4.12 has been decreased by a safety margin of 10 % for reasons explained in Section 5.1.4.1(iii) (Figure 5.3). The depth below surface is obtained by adding the weathered zone (15 m) and the pyroxenite sequence to the intact norite/anorthosite series.

The formula: $S_f = 0,0925 T_l + 26 \text{ m}$ - (5.1)

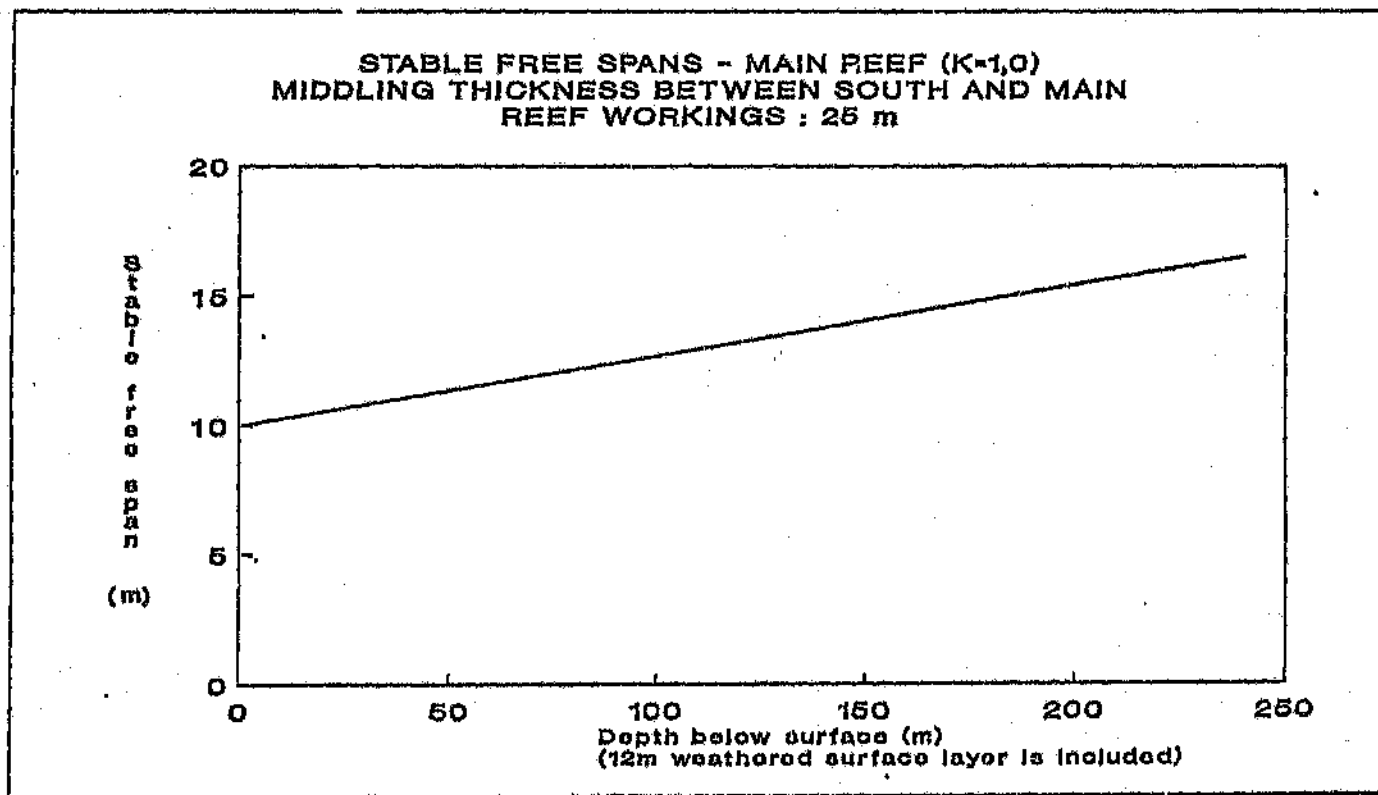


FIGURE 5.2 SAFE MINE SPANS VERSUS DEPTH : MAIN REEF

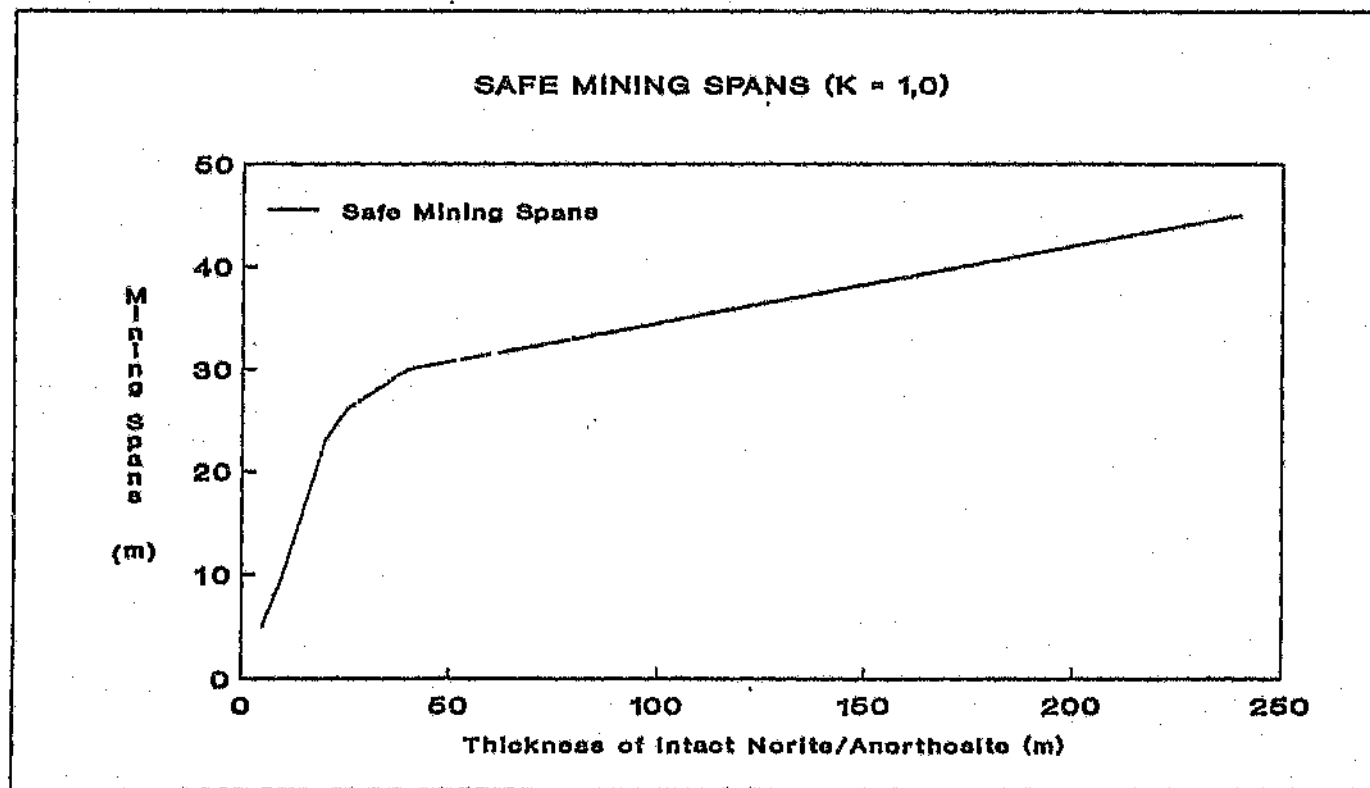


FIGURE 5.3 **SAFE MINE SPANS VERSUS INTACT THICKNESS OF NORITE/ANORTHOSITE SERIES**

may be used for a depth of 120 m and deeper to calculate safe spans, where S_f = Safe span

T_i = intact noxite/anorthosite layer.

5.2.2 Design of pillars

5.2.2.1 Pillar Shapes and Pillar Systems

Panel pillars have to be capable of vertical and lateral support of hangingwall blocks to the first joint plane along which parting could occur. Thereafter stability of the interlocking blocks is primarily a concern of internal stope support, which has to be stiff to achieve the desired stability.

In this region unravelling of the hangingwall is associated with the first joint intersection from the pillar sidewall, and in any direction. Thus, isolated pillars would not be capable of controlling hangingwall runs except over their own surface area.

It is for these reasons that a rib pillar system is preferred to an isolated square/rectangular pillar system. The use of the latter to a reef depth of about 50 m below surface is considered to be an especially high risk option, due principally to the effect of a low stress field.

However, it must be re-emphasised that the potential for a key block failure, which is the precursor to a hangingwall run, depends in part on the magnitude of lateral clamping forces, and in particular below a reef depth of about 50 m below surface.

5.2.2.2 Dimensions

No analytical method is readily available to quantify the optimum limits for pillar design to a reef depth of about 50 m below surface due to the combined complexities of reef horizon weathering and the weak footwall/hangingwall contacts. The setting of design criteria therefore relies on experience from elsewhere. The stability of pillars below a reef depth of about 50 m below surface, according to the strength parameters defined in Section 3.2.5, were analysed and confirmed using displacement discontinuity type computer models.

5.2.2.3 Regional Support

The panel pillar system outlined in Section 5.2.3 is also designed to withstand the weight of all the overlying strata to surface. As such, it will act as both panel and regional support.

This, however, precludes the possible destabilising effects of surface geological structures (they can act as planes along which en bloc movement of the rock mass to surface can occur). In those special cases where such problems could occur, additional pillars may be required.

Alternatively, the plan position of a standard layout may have to be moved to accommodate any problem areas. Problem areas can only be identified on an ongoing basis as the required geological information becomes available.

The recommendation relating to orientation of pillars to geological weaknesses and joint sets should always be considered (section 4.2.1.2).

5.2.3 Recommendations

5.2.3.1 Mining spans

Mining spans may be read off from figure 5.3 or by using formula 5.1 at depths below 120 m. The thickness of the pyroxenites and especially its stability are factors to be considered when determining depths below surface: surface weathered zone, norite/anorthosite series and pyroxenite sequence determine the depth below surface. Pyroxenite sequences can be stable and may then be incorporated into the norite/anorthosite series.

5.2.3.2 Pillars

Surface to 50 m below surface

A rib pillar system is recommended for mining in this zone. However, no optimum pillar dimensions can be recommended by virtue of the deeply weathered nature of the reef and/or footwall pegmatoid. In practice, pillars with a width to height ratio of 5 with 3 m holings not closer than 8 m apart skin to skin, prove to be effective.

50 m to 100 m below surface

Rib pillars for reasons explained in Section 5.2.2.1 with a minimum width to height ratio of 5, with holings no more than 4 m wide and no less than 30 m apart skin to skin (from Figure 5.3).

100 m to 240 m below surface

The same size rib pillars as required for the depth range of 50 m to 100 m is recommended here, and the spans between the pillars may be read off from Figure 5.3. Internal pillars may be required if the hangingwall conditions are adverse.

5.2.3.3 Geological structures

Pillar support must be provided along the contacts of the dykes/faults of the same dimensions as stipulated in Section 5.2.3.2 in the restricted area.

5.2.3.4 Restricted area

The same requirements as the ones detailed under the Central Witwatersrand are recommended here.

APPENDIX A

PRELIMINARY REPORT BY UNDERMINING AND USE OF UNDERMINED
SURFACE WORKING GROUP ENTITLED : UNDERMINING AND THE USE
OF THE SURFACE OF UNDERMINED GROUND

UNDERMINING AND THE USE OF THE SURFACE OF UNDERMINED GROUND

Report by the Working Group on Undermining Guidelines

1 INTRODUCTION

In terms of a letter dated 1983-12-20 the Government Mining Engineer confirmed that the Minister of Mineral and Energy Affairs had approved the appointment of a Committee to investigate undermining and the use of the surface of undermined ground. Representatives of the Department of Mineral and Energy Affairs, the Chamber of Mines, the Johannesburg City Council, and several private parties were appointed to serve on the Committee in terms of Section 2 bis (9)(a) of the Mines and Works Act 1956. In addition, the Minister agreed that other experts may be co-opted to the Committee when necessary.

1.1 Terms of reference of the Committee

The terms of reference of the Committee approved by the Minister for Mineral and Energy Affairs were to investigate undermining, the utilisation of the surface of undermined areas and related matters, and to make recommendations concerning:

- (a) the existing guidelines applicable to the erection of structures on undermined ground and the undermining of structures;
- (b) the desirability of laying down separate guidelines for
 - (i) the Witwatersrand; and
 - (ii) other areas (all minerals except coal);
- (c) whether Regulations 5.3.1 and 5.3.5 of the Mines and Works Act 1956 still fulfil their function in the light of current advanced knowledge;
- (d) whether shallow undermined proclaimed ground on the Witwatersrand, where further mining is unlikely, should be reserved for future mining; and
- (e) safety zones bordering on mining activities which encroach on ground owned by others, with particular reference to the responsibilities of the various parties.

The inaugural meeting of the Committee was held on 1 February 1984. At this meeting it

was decided that a subcommittee, or working group, should be formed to carry out specific tasks relevant to the terms of reference of the Committee.

1.2 Terms of reference of the Working Group

The terms of reference decided upon for the Working Group were as follows:

- i) examine the existing guidelines as follows:
 - present and past experience
 - rock mechanics principles
 - effects of differences in geology and type of orebody
 - different degrees of protection
 - erection of structures on undermined ground
 - undermining of existing structures
- ii) identify weaknesses of the existing guidelines
- iii) formulate a programme of work in order to improve the existing guidelines.

1.3 Composition of the Working Group

The composition of the Working Group was as follows:

Chairman: Dr H Wagner
 Members: Dr F G Hill
 Mr J H Nel
 Dr T R Stacey
 Mr M D Wright
 Mr H J Wilcocks (Secretary)

Over the period of activity of the Working Group, Mr Nel retired and was replaced by Mr J A le Roux. The secretary changed several times, and the concluding incumbent was Mr D Bakker, who also served as an active member of the Group. In addition to the above, several members were coopted onto the Group for specific purposes. These included Mr G J Krige, Professor S Budavari and Mr A Staskowski. Mr J Greef, who served as secretary of the main Committee at one stage, carried out a review of available reports and records of subsidence on the Central Rand, and produced a very useful summary record of the information.

1.4 Acquisition of relevant information

The information required for the execution of the tasks of the Working Group was obtained from the following sources:

- annual reports of the Government Mining Engineer
- archives of the Inspector of Mines, Johannesburg
- published technical papers, a bibliography of which is given in the appendix.
- unpublished technical reports from the archives of the Chamber of Mines, the Johannesburg City Engineer's Department, and several firms of consulting engineers.
- field levelling measurements carried out specifically for the Working Group.
- results of a comprehensive programme of numerical modelling
- personal experience of members of the Working Group. Mr G J Krige was co-opted onto the Working Group specifically for his experience of reclamation mining in old workings on the Central Rand.

1.5 Scope of investigations of the Working Group

The terms of reference of the Committee included all mining excluding coal, and thus included both underground and surface mining. The Working Group limited its activities to underground mining. Owing to the extent of information available for the Central Rand area, and the lack of information available for other areas, most of the work was concentrated on the Central Rand. This was appropriate since most of the pressure for development of undermined ground comes from this area at present. The intention of the Working Group was not to exclude other areas, however, and it was considered that, in principle, the findings would be equally applicable to other mining of similar geometry. Therefore, in principle, this report of the Working Group is applicable to all geographical areas in which underground mining of tabular ore-bodies, excluding coal, is taking place.

2 BACKGROUND TO THE INVESTIGATION

In this Chapter some of the relevant background to the existing conditions and restrictions will be given. These include the legal provisions, and the guidelines, which will be dealt with further in Chapter 5. A clear distinction must be made between the two situations:

- i) undermining of existing surface structures.
- ii) development of surface structures on previously undermined level.

They are completely different, though related, situations, and as such must be dealt with separately. It will be seen that the legislation makes provision for the restrictions to be relaxed at

the discretion of the Government Mining Engineer, or in some cases, the Inspector of Mines. The guidelines are the bases on which this discretionary power is exercised.

In the early days of mining on the Central Witwatersrand, mining operations presented no significant problem to the surface right holder, who was careful to build well clear of dangerous excavations along the outcrops. However, as mining progressed to deeper levels, the outcrops remained as large cavities which had to be fenced off to prevent inadvertent access. They also were "useful" as dumping sites for refuse. By 1920 mining was taking place well to the south, and the filled-in outcrops to adjacent shallowly undermined areas could be acquired cheaply, initially by way of Industrial Stand Grants and surface rights applications, and ultimately by deproclamation.

4.1.1. Controlling the erection of buildings on undermined ground

The State, by legislation, insisted that restraints should be placed on buildings erected on undermined ground. In the case of deproclaimed land, conditions and restrictions are imposed in terms of Mines and Works Regulation 5.3.5:

"Buildings in vicinity of workings

On land other than land proclaimed or deemed to be proclaimed under the mining laws for the mining of precious or base materials, no buildings, roads, railways or any structure whatever shall be erected or constructed over or within a horizontal distance of 100 metres from workings except with the written permission of the Government Mining Engineer and then only on such conditions and subject to such restrictions as he may prescribe".

In the case of proclaimed land the surface is put under the control of the State. This is done in terms of the Mining Rights Act, No. 20 of 1987. The effect of the proclamation of land under the mining laws and the granting of a mining title is that the owner's rights are suspended and, although he retains dominium, he himself, like any other person, requires the permission of the State to occupy or use the surface. Any permission in terms of this Act is also subject to restrictions and conditions laid down by the Government Mining Engineer.

To begin with it was considered that only light structures built of corrugated iron could safely be permitted and this line of thought prevailed for many years. When a more substantial building constructed on a reinforced concrete mat straddling the Main and Main Reef Leader outcrops showed no evidence of damage due to ground movement, the official attitude was changed and brick buildings on shallow undermining became more frequent. The concession was, and is still, given under strict conditions.

2.2 Legislation controlling the undermining of surface structures

South African Common Law determines that, in the case of a conflict between the surface right holder and the mineral right holder, the use of surface rights must be subordinated to mineral exploitation. The mineral right holder must, however, provide subjacent support for the soil of the landowner, and lateral support for the soil of the adjacent landowner, so as to avoid damage to the surface. It seems clear that in the case of a threatening interference with the landowners right to subjacent and lateral support, the landowner will be entitled to an interdict to restrain the mineral right holder from interfering with the right. In the case of actual damage suffered by the landowner he will be entitled to claim damage from the mineral right holder.

Mines and Works Regulations 5.3.1, 5.3.2, 5.3.3 and 5.3.4 make provision for the mining under or near surface structures:

Regulation 5.3.1: No owner or manager shall carry on any mining operations under or within a horizontal distance of 100 metres from buildings, roads, railways, or any structure whatever, or under or within a horizontal distance of 100 metres from any surface which it may be necessary to protect, without first having given notice in writing to the Inspector of Mines of his intention so to do and obtain his permission therefor.

Regulation 5.3.2: Whenever, in the opinion of the Inspector of Mines, it may be necessary to protect the surface of a mine or of any ground adjoining such mine, or to protect buildings, roads, railways or any structure whatever situated thereon, the Inspector may, by notice in writing, prohibit the owner or manager from mining in any portion of such mine except under such restrictions and subject to such conditions as the Inspector may, with the approval of the Government Mining Engineer, determine.

Regulation 5.3.3: Where mining operations have already taken place, and where, in the opinion of the Inspector of Mines, it is necessary to protect the surface of a mine, or of any ground adjoining such mine, or any structure or object on or near such surface, safety pillars or other adequate means of support shall be provided of such extent and in such position as the Inspector of Mines, with the approval of the Government Mining Engineer, by notice in writing to the owner or manager of the mine may direct.

Regulation 5.3.4: No such safety pillars or other supports or any portion thereof shall be removed except with the permission in writing of the Government Mining Engineer, and then only to such extent and under such conditions as he may prescribe.

From the wording of these regulations it is clear that when mining takes place under or in

the vicinity of surface objects requiring protection, the State, in the form of the Government Mining Engineer, becomes involved. This involvement derives from the State's duty to protect life, limb and property.

2.3 Guidelines controlling the erection of buildings on undermined ground

During the period 1903 to 1927 numerous subsidences and other surface effects were reported in the annual reports of the Government Mining Engineer. These cases were all in relation to the mining activities in the Central Rand area where mining was taking place from the outcrops to a depth of around 250 m below surface. Unfortunately there was no sustained, systematic monitoring of surface settlement during this period.

After 1927 several cases of surface effects due to mining were reported to the Inspector of Mines. These were notably in the Bushveld Igneous Complex when mining was taking place at shallow depth, and in the Central Rand area many years after mining had ceased. More recently there have been several publications dealing with subsidences in the Central Rand and Bushveld Complex areas.

In the period 1903 to 1927, 58 case studies were obtained from the GME annual reports. These reports only mention the effects on surface of mining in the depth range up to 240 m. By 1927 mining activities had progressed to well below 240 m, and after 1927 there was virtually no mention in the GME's annual reports of surface disturbances due to mining. Apparently the phenomena of visible subsidences and fractures had decreased to such an extent that they no longer merited recording and comment. 80% of reported subsidences prior to 1927 occurred for mining depths shallower than 240 m. The 240 m depth contour, beyond which restrictions on mining and surface development are not normally imposed, was thus probably based on the observed reduction both in frequency of occurrences and in surface effects beyond this point.

The standard building restrictions imposed by the Government Mining Engineer limit the permissible heights of proposed buildings in accordance with the depth of mining below the site. The restrictions are progressively relaxed on a sliding scale and, where the mining depth exceeds 240 m, they are totally lifted unless mining circumstances are unusual. The restrictions are summarised in the table below.

Depth of Reef (m)	No. of Storeys	Height of Walls (m)
0 - 90	Nil	-
90 - 120	One, with one basement	5,0
120 - 150	Two, with one basement	8,5
150 - 180	Three, with one basement	12,0
180 - 210	Four, with one basement	15,5
210 - 240	Five, with one basement	19,0

In the above table, the depth of reef is the depth below surface to the hangingwall of the shallowest economic reef.

Single storey buildings for limited purposes may be permitted for depths to reef between 60 m and 90 m where the original stoping width was less than 1,25% of the depth, but where future mining will be restricted. Where the depth to reef exceeds 240 m, no building restrictions are normally imposed except where excessive stoping widths exist, or when the Inspector of Mines is of the opinion that very severe shocks or tremors may seriously damage the buildings to be erected.

Owing to the development of new construction techniques and the improved knowledge of the stability of undermined ground, consideration is given to increasing the allocated heights of buildings between depths to reef of 90 m and 240 m in cases where the stability of the ground has been satisfactorily proved. Each such case is dealt with on its merits, however.

Normally a shock warning clause is inserted in the conditions to ensure that the owner of the stand or land is aware that his property is, or may be, undermined, and that he must accept liability for damage to his property.

The basis for the above restrictions is the observed subsidence behaviour over the shallow gold mine workings which will be outlined in Chapter 4.

2.3.1 Application of the present guidelines for the erection of buildings on undermined ground

The guidelines emphatically state that "each case has to be considered on its merit". In the present situation in which there is increasing pressure on the available space for development within the central business district of Johannesburg, the Government Mining Engineer tends to give favourable consideration to applications for the

relaxation of the standard building restrictions. His concern is primarily with safety and consequently applications must be well motivated from a technical point of view, and supported, where necessary, with detailed proposals as to the method of stabilising the undermined ground.

The available information indicates that the immediate outcrop area is always suspect, and careful measures have to be taken to stabilise the undermined ground in this area, and to adapt the design and construction of the structure to minimise the potential damage should any movements occur. Specific attention must be paid to situations in which the dip of the reefs is near vertical, particularly when the footwall is in shale which is softer and weathers more rapidly than the quartzite. In such cases footwall and hangingwall surfaces may break away and fall into the workings below. In the case of shallow dips ($< 20^\circ$) where several reefs have been mined, outcrop stability problems are also likely to occur.

It appears that the undermined area outside the immediate outcrop area could be used more intensively than is the case at present.

Other important factors which must be taken into account in any application are :

- the presence of major dykes and faults on the site
- the time elapsed after cessation of mining
- ore reserves locked up in pillars which might be mined at some later date.

2.4 Guidelines controlling the undermining of existing surface structures

Since collieries are specifically excluded from the terms of reference of the Undermining Committee, the following is limited to the guidelines applicable to gold and other metal-liferous mines. Structures placed on coal mining will only be mentioned where they are relevant.

In the early part of the century the notion of $d/2,7$, where d is the depth of mining, to determine the horizontal distance from the surface object to the restricted mining area was already in use. It appears to have been based on investigations in 1907 into gold mine subsidences, when it was found that the angle of fracture (draw) never exceeded 70 degrees. The circular of 1946 refers to this angle: "... although it might be said that the majority of subsidences of the surface in this country, due to undermining, have a negative angle of draw, there are instances where subsidences have had a positive angle of draw. It is consequently necessary to protect against such a contingency and the formula of $d/2,7$ which gives a positive angle of draw of 20 degrees from the vertical has been used

to good effect and has so far proved satisfactory*.

Up until 1927 the Government Mining Engineer's records show that the great majority of cases of surface subsidence occurred for mining depths shallower than 240 m. An article in the Journal of the Chemical, Metallurgical and Mining Society of South Africa of March 1907 stated that "... one may be justified in concluding that the effects of caving at a depth of 1000 feet will never reach the surface".

From the above it may be assumed that the lack of restrictions below the 240 m depth contour was based on actual observations. This statement must be qualified by the proviso that no restrictions are applied beyond the 30 m depth contour if the combined stoping widths do not exceed 1,25% of the vertical depth. If the combined stoping widths exceed this figure, support requirements are specified even when the depth of mining exceeds 240 m. In this regard, the records show that instructions to leave pillars or to waste pack in restricted areas were given as far back as 1906. At that time strength tests had been carried out on quartzite material and used to calculate the required size of pillars. It was also recognised that waste packing afforded similar support compared with pillars.

From the records and literature of the time, it appears that the pillar and support density specified was based on calculations, practical experience and knowledge of local conditions.

The above is the background to the existing guidelines which are as follows:

The underground area affected by the prohibition to mine near or under surface structures etc is called the restricted mining area. In determining the restricted area, the procedure followed by the Government Mining Engineer's office is to provide protection along the rise, dip and strike, and where the dip of the reef is less than 20 degrees, it is usual to define this area as "within a horizontal distance of $d/2,7$ ", where d is the vertical depth to the footwall surface of the workings of the deepest reef beneath the natural surface of the ground, and the horizontal distance is measured from the sides of the objects to be protected. This is illustrated in Figure 1.

When the dip of the reef is greater than 20 degrees, the restricted area is shown in Figure 2 and defined as follows:

- i) up dip or rise side - a distance of $d/2,7$ measured up dip, at right angles to the strike of the reef.
- ii) strike side - a horizontal distance of $d/5,7$.

- iii) dip side - no protection is required, but a nominal distance of 3 metres is usually specified.

The area so restricted is limited according to the depth of the reef, and normally a restricted area is only applicable to depths less than 240 metres.

Objects to be protected are usually divided into two main categories:

- a) those that belong to the mining company and are undermined by the owner.
- b) those that do not belong to the mining company.

When dealing with the former, the Government Mining Engineer is mainly concerned with the protection of life and limb, whereas in b) he is concerned with protection of property as well. The category b) objects are subdivided as follows:

- i) objects requiring very rigid support to prevent any surface settlements. Examples are schools and hospitals.
- ii) objects requiring support such that controlled surface settlements may occur. Examples are roads and railways.
- iii) objects which may be undermined by normal mining methods without endangering persons.

A typical example of restrictions imposed on mining below a public road is as follows:

- no mining is permitted in the restricted area down to a vertical depth of 30 metres.
- normal mining operations are permitted in the restricted area at depths greater than 30 metres provided that the combined stoping widths do not exceed 38 cm for every 30 m of vertical depth.
- where the combined stoping widths exceed this stipulated value, the measures of support summarised in the table below are required on each of the reefs stoped. In this table the solid support and systematically packed waste rock support are alternatives.

Vertical Depth Range (m)	Solid Pillar Support (%)	Waste Rock Pack Support (%)
30 - 90	15	40
90 - 150	12	30
150 - 200	10	20

As further qualifications on this support, the pillars shall not be less than 3,5 m square and their spacing shall be equidistant. In the case of waste rock packing, the packs shall be 8 m x 8 m, spaced equidistantly and carefully built of selected stone. They shall have a suitable batter and shall be properly toed into the footwall.

Consideration would be given to limiting stoping widths, and to the existence of, or requirement for, the superimposition of pillars on the different reefs. The Inspector of Mines would have to be satisfied that the normal method of support of the overburden cover is such that no danger would result from a sudden and violent collapse.

The restrictions given above appear for the first time in a circular from the Government Mining Engineer dated 30 October 1946. This circular refers to previous circulars, but it appears that 30 October 1946 was the first time that restrictions were formally and uniformly applied in South Africa.

3 EFFECTS OF UNDERGROUND MINING ON THE SURFACE

In this Chapter, a general overview of strata movement caused by underground mining will be given and the basic concepts of subsidence and its associated terminology will be introduced. This is considered to be necessary to ensure a logical and unambiguous understanding of the remainder of the report. A very brief review of the methods of control of subsidence in several other countries is also given.

3.1 The effects of underground mining on hangingwall strata

In this section a qualitative description is given of the deformation mechanisms which are believed to occur in the hangingwall strata as a result of mining.

3.1.1 Qualitative description of strata behaviour

When an underground opening is excavated or enlarged, the surrounding rock mass is affected in various ways. The nature and magnitude of these effects depend on :

- the quality of the rock mass
- the geological conditions
- the prevailing state of stress in situ
- the dimensions of the opening
- the depth below surface
- the dip of the reef or seam
- the type and extent of solid or artificial support provided.

In order to give a qualitative description of mining induced effects relevant to the development of surface subsidence, it is appropriate to consider an opening with a rectangular cross-section.

3.1.2 Underground openings with small roof spans

As a result of the excavation the pre-mining stresses in the rock mass are redistributed. Experience, model studies and analysis indicate that this stress redistribution can cause increased compressive stresses to be induced in the sidewalls of the excavation, and tensile stresses to be induced in the roof. In addition, high shear stresses are present in the immediate hangingwall rock above the edges of the opening. The consequences of these stress changes depend on the quality of the rock mass. In massive competent rock at shallow and moderate depths, the effects of excavation are negligible. In competent, but well-bedded rock, the induced vertical tensile stress may cause the beds to separate, resulting in a loosened zone and a redistribution of stresses. Outside this zone a generally stable, self-supporting arch is formed where the prevailing stresses are compressive.

In a poor quality rock mass, in which the rock material strength may be low, and the rock jointed and laminated, the effects of both tensile and shear stresses on the roof can be detrimental. The result may be that the rock beneath the "arch" may loosen and, if no support is provided, collapse into the opening. This will particularly be the case if key block action is destroyed. This type of behaviour is likely to stabilise naturally as the opening fills with collapsed material. With regard to the surface, subsidence is unlikely to occur unless the collapsed material is removed, which

would allow progressive failure to develop.

It may be concluded therefore that, except in highly weathered and weak rock when the excavation is close to the surface, the effects of a small excavation will be localised and will not induce any measurable surface displacements.

3.1.3 Underground openings with moderate and large spans

The conditions for horizontal seams or reefs will be considered first. As the span increases, the depth to span ratio decreases, and both the magnitudes of stress and extent of the potentially loosened zones increase. The quality of the rock mass has an overriding influence on the response of the hangingwall strata to these induced changes.

In massive, competent rock masses, the immediate hangingwall in the stope moves downwards and the footwall moves upwards. These displacements are due mainly to the elastic response of the rock mass. At shallow depths the upward movement of the footwall is small in comparison with the downward displacement of the hangingwall. Owing to the massive, competent nature of the rock mass, almost all the vertical displacement of the immediate hangingwall is transmitted to the upper strata. In this case, therefore, subsidence is caused mainly by elastic deflection of the overburden.

Over shallow workings in relatively massive strata, the induced tensile stresses may cause the formation of rupture planes or zones leading up from the edge of the workings to the surface. This may delineate a massive block with the potential to move down into the workings between the rupture zones, resulting in visible cracks at the surface near to the subsidence trough margins. This phenomenon is particularly prevalent when the total extraction width is high. In well-bedded rock the capability for bed separation to occur will increase the potential for subsidence to occur.

When the quality of the rock mass is poor, with an increase in span the potential for caving of the hangingwall increases. The weaker rock does not have the capability to withstand the compressive stresses necessary to promote arching. The caving process is accompanied by bulking of the displaced rock, although in stratified rock this bulking may be rather limited. The resulting void eventually becomes filled with caved material, thus arresting further caving. The main roof deflects under its own weight, causing consolidation of the bulked rock, and this deflection of the upper strata results in the lowering of the ground surface. This kind of response to underground excavation is typical when coal is being extracted by the longwall

method of mining.

An important type of rock mass response, which is different from those discussed above, occurs when a competent rock mass contains near vertical geological planes of weakness which divide the hangingwall into blocks. During the early stages of excavation, the blocks are in equilibrium under the action of the induced stresses. With an increase in the span, the effective normal stress acting across these planes and generating the shear resistance on the block boundaries is reduced. When the shearing resistance is exceeded, rigid body motion of the block occurs under the influence of gravity, and block subsidence results. At relatively shallow depths of mining the vertical boundaries of the block may reach up to the surface. In this case the layer of decomposed or weathered surface rock or soil is also affected by the block displacement. In addition to natural joints, block displacement is also due to some major structural features such as dykes or faults, which provide planes of weakness whose shear strength is exceeded at some critical stage of mining.

The above discussion refers to horizontal deposits, and is applicable when the dip of the reef or seam is less than 20 degrees. If the dip is steeper than this, the mechanisms acting on the strata change, and somewhat different effects are brought about. The main cause of the departure from the conditions existing around horizontal workings is that gravity no longer acts in a direction normal to the span of the workings. In addition, owing to the fact that the weathering of the rock decreases with depth, an inclined excavation will influence the hangingwall strata differently at different depths. The presence and size of a crown pillar left at the outcrop is very significant. If no crown pillar is present, the wedge of soil and rock in the hangingwall acts as a cantilever, and local widening of the outcrop can occur. Even if a crown pillar is present, collapses of the weathered, and perhaps soft, decomposed hangingwall rock may occur immediately below and adjacent to the crown pillar, leading to possible substantial surface displacements.

At depths where the rock masses are more competent, more effective arching can develop. As a result of the inclination of the excavation, the shape of the theoretical tensile stress zone is distorted. In addition, the magnitude of the down-dip component of displacement of the hangingwall relative to the footwall (ride) is comparable with the displacement component normal to the stope (closure). The consequences are that all mining induced effects superimposed on the hangingwall strata are asymmetric. Thus the strata disturbance can be substantially different on the up-dip side of the workings from that on the down-dip side.

As for the horizontal excavations, mining induced effects of inclined stopes in massive

competent rock masses will be very limited. Unless the hangingwall strata contain significant geological planes of weakness, or the total stoping width is very large, the rock mass around the inclined stope is expected to behave in a quasi-elastic manner. Consequently, the observed surface subsidence will be the result of elastic deformation of the hangingwall strata. Owing to the stope inclination, the surface effects will be asymmetric and will not follow the well-known distributions associated with the extraction of horizontal deposits.

In less competent rock masses, the development of rupture surfaces will be similar to that described above for horizontal excavations. The dip of the rupture surfaces, and the extent and location of the visible effects on surface will be influenced by the dip of the stope. If the failure of the hangingwall is only partial, the upper strata layers are affected indirectly by their deflection. Again, the excavation inclination influences the relative magnitudes and occurrences of surface expression. An important aspect, in regard to steeply dipping stopes, is the collapsed material may slide down the stopes thus reducing the potential for bulking and natural stabilisation of the collapse.

Block subsidence can occur equally in inclined stoping situations. As a result of the increased length over which shearing must take place on major weakness planes as the depth of the mining increases, for inclined deposits, the surface step formed will tend to decrease in magnitude the deeper the stoping.

3.2 Definitions of subsidence related terms

Much of the terminology in the field of subsidence originates from the coal mining industry. The principles are, however, applicable to tabular mining in general.

Observations of ground movement induced by underground mining indicate that two different types of surface deformations occur. The first case is the continuous distribution of ground movements resulting in the formation of regular depressions or troughs. In the second case, underground mining brings about fractures in the ground leading to discontinuous deformation of the surface. Continuous subsidence is more amenable to prediction. Discontinuous subsidence is more common in shallow mining situations.

Both continuous and discontinuous subsidence have been experienced over shallow gold, platinum and chrome mining. Typical mechanisms of subsidence experienced in these operations are shown in Figure 3, and are described as follows:

- i) continuous subsidence resulting from regular closure of the underground workings and competent behaviour of the hangingwall strata.
- ii) discontinuous subsidence resulting from the cantilevering of the wedge of hanging-wall defined by a shallowly dipping stope and the ground surface. This behaviour is commonly restricted to an area adjacent to the stope outcrop (within about 30 m of it), and may result in the formation of a step or steps in the surface profile with open cracks.
- iii) discontinuous subsidence resulting from block movement in which the subsided block of ground is defined by major fault and/or dyke contact planes, the stope and the ground surface. Open cracks may be observed at the contact. In some cases more than one major contact plane may define the block of ground. This form of subsidence may occur over a very wide range of mining depths and is not restricted to the outcrop area. Very significant differential subsidence can occur.
- iv) discontinuous subsidence resulting from the ravelling or washing away of fill from a stope outcrop area. This type of subsidence is commonly called a sinkhole, but should not be confused with the true sinkholes which form in dolomite rock formations. Sinkholes are localised occurrences restricted to the immediate stope outcrop area. They may appear as open holes, and ventilation air is commonly noticed indicating connection with mine workings at greater depth.

3.2.1 Deformation of the surface

The effects of ground movement on the surface may be described by the following components:

Vertical displacement at a point or subsidence. The vertical displacements of surface points form a subsidence trough which frequently extends, in plan view, beyond the edges of the mined out area in all directions.

Horizontal displacement of points on the surface accompanies subsidence.

The above displacement components are absolute movements. Differential movements of the surface also occur. This affects the slope of the subsidence profile. Surface strains result from the differential ground displacements, and both lengthening and shortening of the surface occur. Curvature of the subsidence profile occurs.

The subsidence profile is a curve depicting subsidence on a section drawn across the subsidence trough. A section drawn parallel to the direction of advance of an underground excavation results in a longitudinal subsidence profile, while a section at right angles to this gives a transverse subsidence profile.

Most of the present knowledge on subsidence movements is based on observations made during the mining of tabular deposits, mainly coal seams, in which the resulting surface deformations are often continuous. In the following, most of the basic terms and definitions relate to this type of surface deformation.

3.2.2 Terms associated with subsidence profiles

Reference should be made to Figure 4 when reading the following descriptions.

Angle of draw is the angle between the vertical to the edge of the workings and the point at the surface where subsidence diminishes to zero. Therefore, it defines the limit of subsidence with respect to a particular underground production excavation and is sometimes called the limit angle, α in Figure 4. In some countries the angle of draw or limit angle is defined as the angle of inclination, from the horizontal, of the line connecting the edge of the workings and the edge of the subsidence area (cf. in Figure 4). This angle is constant for horizontal stratification. In the case of inclined deposits, the angle of draw is no longer constant, but depends on the dip angle of the seam. It is smallest at the rise edge (the up-dip side) of the workings and increases towards the dip edge.

The **angle of break** is the angle of inclination of the line connecting the edge of the workings and the point of maximum lengthening of the surface. This is angle β in Figure 2.

Maximum possible subsidence or full subsidence is the maximum possible vertical displacement of a point on the surface caused by working a critical area. Mining of the critical area produced full subsidence at only one surface point. Areas that produce full subsidence at more points are super-critical. Areas that produce no full subsidence are sub-critical. In Figure 4 the subsidence, horizontal displacement and horizontal and sub-critical areas of extraction.

The **transition point** is the point of transition between concave and convex curvature of a subsidence profile. It coincides with the half-subsidence point, where subsidence has half the amplitude of that of the maximum in the profile.

3.2.3 Differential movement components

The slope or tilt of any part of a subsidence profile is calculated as the difference in vertical displacement between two points close together divided by their distance apart, and usually expressed in parts per thousand, for example mm/m. In mathematical terms it is the derivative of the subsidence curve with respect to the horizontal variable. The slope is sometimes expressed as an angle.

Differential subsidence is the difference in vertical displacement between two points usually close together.

Horizontal strain is defined as the change in length per unit original length of ground. It is calculated as the difference in horizontal displacement between two points close together divided by their original distance apart, and is the average horizontal strain between the two points. In mathematical terms horizontal strain is the derivative of the horizontal displacement with respect to the horizontal variable. It may be tensile (positive) or compressive (negative). In subsidence engineering it is expressed in units of mm/m.

The curvature, in a vertical plane can be expressed by the difference in slope between two points. Mathematically it is the derivative of the slope or the second derivative of the subsidence curve with respect to the horizontal variable. Curvature has units of 1/m. The curvature of the surface is often expressed by its reciprocal, the radius of curvature.

3.2.4 Relationship between ground movement components

With respect to extensive horizontal tabular workings subsidence is proportional to the thickness of extraction; that is, the full subsidence S_{max} is a function of the subsidence factor, a , and the thickness of extraction, m . It is given by the linear expression:

$$S_{max} = a.m.$$

The subsidence factor is the ratio of full subsidence to thickness of extraction. It is dependent on the mining method as well as on the type of underground support, packing or filling used, the type of hangingwall strata, and the depth of mining. The value of the subsidence factor ranges from 0,1 to 0,9. For bord and pillar workings

It is extremely low, while for total extraction panels it tends to be high.

By analogy with the expression for full subsidence, the greatest possible horizontal displacement may be referred to as the full displacement and denoted by u_{max} . For horizontal coal mine workings referring to Figure 4, an empirical relationship between u_{max} and S_{max} has been found as :

$$u_{max} = 0,4 S_{max}$$

Experience has shown that the maximum slope T_{max} , the horizontal tensile strain E_t , and the horizontal compressive strain E_c over a super-critical, parallel-sided panel can be expressed as follows:

$$T_{max} = 2,75 S_{max}/H$$

$$E_t = 0,65 S_{max}/H$$

$$E_{max} = 0,65 S_{max}/H$$

where the symbol H represents the depth of workings below surface.

The distributions of the ground movement components and the relative positions of the appropriate maximum values are depicted in Figure 4. It can be seen from Figure 4 that the curvature is proportional to the horizontal strain.

3.2.5 Damage caused by components of ground movement

The type of damage caused by the individual components of ground movement are summarised briefly below. Damage, damage criteria and acceptable levels of damage are dealt with in more detail in Chapter 5.

Vertical subsidence rarely causes direct damage if all points on a structure move by the same amount. Problems may arise, however, when water courses or ground-water are involved, and there is the possibility of flooding in low-lying areas.

Differential subsidence can cause severe distress to, and even failure of, structures of all types. The effects will be worst when the differential movements are localised, for example on a fault plane, or occur across a very short base length.

The slope of subsidence troughs may change the gradient of roads, railways, machinery in factories, gas and water mains, sewerage and storm water drains etc, and may therefore be the cause of adverse functioning of these structures and

services. It can also induce tilting of buildings which may result in instability. Typical measured slopes from the coal mining industry range from 2 to 20 mm/m.

Curvature induces two types of structural damage; distortion of the structure, owing to shear strain, and flexural bending of structures such as long load-bearing walls. Concave curvature, for example, induces tension at the bottom and compression at the top of a building. Common values of the radius of curvature from the coal mining industry are between 1 and 20 km.

Horizontal displacement, if uniform, seldom causes damage to surface structures.

Tensile and compressive strains cause the majority of the damage recorded in coal mining areas. Their main effects are the generation of tensile or compressive fractures in the structure, and the squeezing or buckling of structural elements. The maximum strains in single subsidence troughs over coal longwall workings are of the order of 1 to 10 mm/m. The degree of damage is dependent on the nature of the structure (the materials, shape, age and design). The main factors are the intensity of the strain and the size of the structure to which the strain is applied.

3.3 Subsidence and its control in other countries

A review of legislation and other literature on subsidence control in several countries was carried out by the Working Group of the Undermining Committee. In all cases considered subsidence was associated with the extraction of coal seams of uniform thickness. It is appreciated that the rock types found in the hangingwall strata of the gold reefs on the Witwatersrand and the platinum and chrome reefs of the Bushveld Complex are different from those of the coal measures. However, the nature of the basic problem, and the approach adopted to control subsidence are similar. It is considered that this limited information will be of interest as background to the consideration of the South African situation.

3.3.1 United Kingdom

Subsidence problems prevalent in Britain are those resulting from the undermining of structures already present on the surface. These problems are often countered by planning the mining extraction so as to achieve strains on surface which are acceptable to the structures. One way in which this has been achieved was in the use of longwall partial extraction systems. In this method intervening pillars are left behind between the panels, their width being approximately equal to a quarter of the depth of the working. Another system used successfully is that of stepped faces. With this method, two adjacent faces are worked in the same seam separated by a

specific lag. The strains induced by the two panels are designed to counteract each other, the principle being to balance out the compressive and tensile strains from two or more faces.

The National Coal Board has presented a classification of subsidence damage which has been developed on the basis of observations. Only the strain is used as an indication of damage, and damage is usually proportional to the length of the structure.

The owner of structures damaged by subsidence is reimbursed by the National Coal Board provided that it can be proved that the damage was caused by subsidence. Every effort is made to prevent the occurrence of mining subsidence related damage in the first place.

3.3.2 Australia

Methods used to predict subsidence are based on those developed by the National Coal Board in the United Kingdom. It has been observed that the subsidence displacements measured in the New South Wales Coalfields are significantly lower than those predicted by the direct application of the British National Coal Board technique. Partial extraction systems are increasingly used to strike a balance between mining and urban development.

In New South Wales the Mine Subsidence Board was established in the 1920's to administer the Mine Compensation Act. The Act confers on the Board the power to recommend proclamation of coal bearing parts of the State, where significant surface developments are likely to occur, as mine subsidence districts. Within these districts the Board has the power to approve, with or without conditions, or reject, development applications. The Board also deals with subsidence damage compensation.

3.3.3 West Germany

In West Germany there is no single method accepted for subsidence prediction. A number of mathematical methods and graphical methods (the influence function method) have been developed for different mines coal regions to suit their particular subsidence phenomena. The influence function method is the oldest and most widely used technique, however. Since 1925 the influence function of the vertical component of movement has been ascertained many times from subsidence measurements over both small and large workings.

The General Mining Law of Germany states: "For all damage done to landed property or its appurtenances by the underground or opencast operation of a mine, the owner of the mine is obliged to render full compensation, regardless of whether the mine operation took place beneath the damaged property or not, of whether the mine owner is to blame for the damage or not, and of whether the damage could have been foreseen or not.", and "No special compensation is due to mortgagees of land or buildings or to rent creditors." According to this, so long as there is a priority public interest in a mining activity, the landowner must put up with the mining operation permitted by the mines authority and the inevitable damage. For him it is a matter of "suffer and charge". A preventive injunction which could otherwise be obtained against damage to property, is reserved to the State in respect of public utilities installations in the security of which there is an indispensable public interest. For its part, the mining industry must accept that areas of influence at the surface will be built on and that mining damage will consequently occur.

Nowadays the basic principle used in German subsidence engineering is that prevention is better than cure. To this end measures are utilised which relate to :

- the conduct of mining operations, such that the structure to be protected is either exposed to a less damaging type of deformation or is stressed only to an acceptable degree of movement or deformation.
- In new constructions, the taking of precautions against mining damage, either by stiffening foundations to withstand the forces induced by the ground deformation, or by enabling structures to avoid these forces through the provision of expansion and slip joints.
- regional planning to select, for large new structures, locations that will be subject to a minimum of future mining influences.

3.3.4 United States of America

The method of subsidence prediction which most closely matched the observed subsidence in the Western United States was found to be the Donets profile function from the Soviet Union. The Donets method uses a subsidence factor of 0.6 obtained empirically from the Donets coalfields, and was found to be more applicable than the National Coal Board method which has a subsidence factor of 0.9. A study in the Western United States found that the maximum subsidence was of the order of 67% of the extraction height, and the angle of draw was 25 degrees. The study site was over a single mine, working at a depth of 450 m and using a longwall extraction

measured.

3.3.5 Eastern European observations

Information regarding details of subsidence studies carried out in Eastern European countries is largely unavailable. However, the regulations pertaining to subsidence damage and allowable limits of various subsidence parameters are freely available. The categories of protection for Poland and the Soviet Union are similar to those for Britain, but are less stringent in their application. The Soviet categories are dependent on the coalfield to which they are applied, and vary accordingly. For example, in the Donets coalfield it is generally suggested that most structures will be safe if the following magnitudes of ground deformation are not exceeded:

Tilt : 4 mm/m
Curvature : $0,2 \times 10^{-3}/m$
Strain: 2 mm/m

For the Kraganda coalfield, corresponding values of 6 mm/m, $0,3 \times 10^{-3}/m$ and 4 mm/m are suggested for the same degree of protection. When compared with the British values it would appear that the Eastern Bloc countries are prepared to tolerate greater subsidence damage effects. It is not clear whether the size of structures is sufficiently taken into account, whether the structures are inherently more tolerant than their British counterparts, or whether the classifications refer to certain types of structures. It is also possible that the definitions of the levels of damage (appreciable, slight or negligible) are different in the different countries.

3.3.6 Comparison of information from different countries

It is immediately clear from the literature studied that there is no common solution for the prediction of subsidence. In every undermined region considered, the mechanics of subsidence, though similar, have been treated differently. Further, no method that is successful in one region can be applied with the same degree of accuracy in another region. The reason most commonly given to explain this is that the geological conditions vary to such an extent as to invalidate methods derived elsewhere. The original work on empirical subsidence studies carried out in Britain culminated in an effective subsidence prediction method. Many countries which experienced subsidence related problems began their subsidence work by trying to apply the British method. When these proved to be unsuccessful, the formulation of subsidence prediction methods indigenous to that region began.

Most of the interest and impetus to solve the subsidence prediction problem was initiated as a result of the introduction of total extraction mining methods on a large scale. The volume of ground displacement which was caused by the application of these methods necessitated some form of prediction of the subsidence and its damaging effects.

The methods used to control subsidence and related damage to structures in overseas countries fall into two categories:

- i) structural precautions against subsidence damage, ie the implementation of special structural design and construction techniques.
- ii) the use of appropriate mining methods and extraction geometries designed to reduce or prevent subsidence, or to minimise the damaging effects of subsidence.

Such methods have been developed individually in the countries concerned to suit their particular subsidence characteristics.

The mining methods vary from partial extraction systems to the use of stepped faces or harmonic extraction for control of the surface strain. Where subsidence of any sort is unacceptable, bord and pillar mining, stowing or the use of substantial pillars beneath structures to be protected are implemented.

4 SURFACE EFFECTS OF MINING IN SOUTH AFRICA

This Chapter will include a summary of mining factors of potential influence, a review of recorded relevant cases of subsidences in South Africa, a description of a programme of theoretical analyses of subsidence due to shallow mining, and discussion on the potential for prediction of subsidence in South African hard rock mining situations.

4.1 Mining factors of potential influence

There are numerous factors which have had observable, or have potential influence on the ground overlying shallow hard rock mine workings.

Dip of reefs - this has a number of effects. Closure of stopes is more likely for flatter dips and therefore it is more likely that surface movements will occur over shallow dipping stopes. If such movements are to occur, however, they are more likely to occur soon after mining. In contrast, steeply dipping stopes are more likely to remain open and thus present

a restricted, but longer term hazard. If local collapse from the hangingwall occurs, the collapsed material is likely to ravel down steeply dipping stopes. In stopes dipping at angles shallower than approximately 35 degrees, the collapsed rock will not ravel, but is likely to bulk, ultimately, providing support between hangingwall and footwall. Such stopes are therefore likely to be self stabilising.

Stoping widths - the greater the stoping width, the greater the potential magnitude of closure, and hence the greater the potential movements of the surface. An increase in the stoping width has an adverse effect on the stability of pillars, and on the effectiveness of artificial support. Differential stoping widths may be associated with potential movement differentials.

Extent of mining - the greater the areal extent of mining without effective solid pillar support, the greater the potential for subsidence of the surface. Systematic pillar support is not common in areas of shallow undermining. If large areas have been mined, it is likely that closure will have taken place soon after mining was completed, and that any subsidence which may occur is likely to be uniform. Whether this has occurred or not, the greater the area of mining, the less likely it is that differential subsidence will occur. The potential danger area in this regard is close to the mining abutment.

Number of reefs mined - as for the stope widths above, the greater the number of reefs mined, the greater the potential for larger closures, and hence the greater the potential for surface movements.

Separation of reef - the closer that reefs are together, the more likely it is that they will interact, and hence the greater the potential for surface movements. The greater the separation between, the greater the motivation for considering the stopes independently of one another.

Competence of rocks - weak hangingwall or footwall rocks may allow punching of pillars which renders the solid support ineffective. Weak hangingwall rock will allow easier collapse of hanging between supports, with consequent greater potential surface effects. Weak strata in general will allow easier caving of the strata. This has the advantage that it is more likely to have occurred soon after mining has been completed. In a multi-reef situation, weak strata will result in greater collapse potential.

Support - solid pillar support is undoubtedly the most effective support for preventing subsidence of the surface, provided that the spans between pillars are not excessive. The only types of installed support which can be considered to provide some control on the surface behaviour are slime or sand filling and waste pack support, provided that their

existence can be proved, and their permanence assured. These supports will not prevent subsidence, but will reduce subsidence, reduce hangingwall collapse and promote even subsidence. Their effectiveness will depend on the area which they cover, and the spacing between adjacent areas of such support will determine the potential for local collapse of the hanging.

Time elapsed since mining - the results of surface levelling have shown that the rate of mining-induced surface movement reduces with time after mining has stopped. Most records have shown that the rate of these movements reduces rapidly, and effectively ceases within 20 years of completion of mining. The records also show that reactivation of mining, for example as in reclamation mining when solid pillars are removed, also reactivates movement of the surface. In partial extraction systems, collapses of pillars can occur many years after cessation of mining, leading to subsidence of the surface.

4.2 Subsidence observations in South Africa

The recorded subsidences over the gold mines of the Central Rand area apparently led to the development of the existing guidelines as outlined in Chapter 2. The Government Mining Engineer's Annual Reports for the period 1903 to 1927 contain 58 cases of subsidence. During this period no rules had been laid down concerning protection of the surface. After 1927 there was virtually no mention in the GME's Annual Reports of surface disturbances due to mining. Specific cases are recorded in the archives of the Inspector of Mines and in several publications. The several relevant publications are included in the Appendix.

Not all of the reports, records and publications indicate the amount of subsidence, but the following summary observations can be made from these sources:

- i) Subsidences occurred concurrently with mining or shortly after mining had ceased. Renewed mining activity reactivates subsidence movements.
- ii) Early subsidences can be broadly classified as those which occurred at, or initiated from, the outcrop, and those which did not extend to the outcrop. The former extended to a maximum depth of mining of 180 m, and the ratio of subsidence to total stopping width was 0,27. Stopping widths varied from 1,2 m to 4,5 m. Subsidence magnitudes not involving the outcrop varied from 9,8 to 11,4% of the stopping width.
- iii) No subsidences were recorded where the dip of the stopes was greater than 70 degrees.

- iv) Reports on whether hangingwall to footwall closure has been attained after cessation of mining operations for a specified period are inconclusive.
- v) 80% of reported subsidences prior to 1927 occurred for mining depths shallower than 240 m. The 240 m depth contour, beyond which restrictions on mining and surface development are not normally imposed, was thus probably based on the observed reduction both in frequency of occurrences and in surface effects beyond this point.
- vi) Many of the subsidences were of the block subsidence type associated with the presence of faults and/or dykes or other major features. Subsidence in the Bushveld Complex appears to be mainly of the block type.
- vii) Subsequent to 1927, three cases of surface effects were recorded which generated public interest at the time:
 - a subsidence at Nourse Mine took place some 35 years after cessation of mining operations.
 - a subsidence at Haak's Garage, situated over the defunct Ferreira Mine occurred in 1952. Mining operations in this area were performed before the turn of the century.
 - a subsidence at the site of the Johannesburg Council Brewery in Von Wandlgh Street occurred in 1963.

Features common to these cases were the presence of faults and/or dykes, and artificial barriers in the outcrop which were subject to corrosion and unable to contain the slope fill with the passage of time.

- viii) Later reports from the archives of the Inspector of Mines (Johannesburg Office) indicate that the walls of outcropping stopes often break away and plunge down into the old workings. The sub-vertical stopes are particularly suspect, especially if the footwall is of shale, which weathers more easily and is much weaker than the hangingwall quartzites. Problems regarding the stability of the surface near the outcrop of the reefs are more common when the dip of the reefs is small and several reefs have been mined.
- vi) Common subsidence occurrences are those which occur at the outcrops of previously filled stopes due to the ravelling or washing away of the fill. Water is the main culprit.

In summary, the following can be interpreted from the case records:

- a) Of 58 cases of subsidence recorded between 1903 and 1927 (ie mainly during the active mining period), 33 involved movement on dykes and/or faults. The magnitude of subsidence was measured in many of the cases, and showed a variation from 0,4% to 76% of the stoping width. In most of the cases, the subsidence was a small fraction of the stoping width. The distribution of magnitudes is shown in Figure 7. In those other cases (total 10) where dykes/faults were not involved, the measured values were from 0,4% to 38% of the stoping width. 6 of the cases were less than 10%.
- b) Of 23 relevant cases of subsidence recorded between 1935 and 1981 (mining activities probably not in shallow areas), 21 were located on, or close to the outcrops, and the remaining two involved dykes. Many of the outcrop events resulted from the local ingress of water.
- c) With one exception (Nourse Mine), no subsidence occurred where the dip of the reefs was greater than 70 degrees.
- d) In the early reports, numerous references are made to the fact that surface movements occurred gradually. With the exception of Nourse Mine, it is believed that the same applies to the later reports. The data from surface levelling in many shallowly undermined areas support the early observation that surface movements are gradual.
- e) To the best of the recorded knowledge, there has been no loss of life as a result of any subsidence since mining started on the Central Rand.
- f) In the Rustenburg area several subsidences have occurred which have been associated with major geological features (faults, dykes, major joints). This type of behaviour appears to be typical for that area. A bord and pillar system has generally been used, with a very high percentage extraction. Overloading of the pillars and their consequent collapse, associated with the major geological features, has been the probable reason for the surface subsidence. In one case a hospital built on undermined land was damaged when the subsidence occurred. A similar type of large failure occurred on the eastern outcrop of the Bushveld Complex, and it therefore, appears that undermined land in this environment may be susceptible to this type of behaviour if the solid support in the mines is inadequate. There is merit,

therefore, in dealing separately with the gold mining and the platinum/chrome mining areas.

4.3 Theoretical analyses of subsidence effects

A series of theoretical mining simulation stress analyses was carried out as part of the Working Group's investigations. The aim of these analyses was to examine the trends in surface and strata behaviour for different stoping widths, dips and in-stope support. They were continuum analyses, and therefore did not take into account any discontinuities such as dykes or faults. The behaviour of the models was purely elastic. Only key aspects from the results of these analyses are mentioned here:

- a) the maximum horizontal strains are induced when mining takes place at shallow depths and at small reef dips. These values decrease as the depth of mining increases.
- b) the most obvious causes of further strata movement were found to be additional mining in the area of concern and the failure of support in the stopes.
- c) maximum horizontal strains developed during the mining process are about 37,5 mm/m. However, the change in horizontal strain as a result of a small mining step is very small.
- d) maximum tilts developed during the mining process are about 8 mm/m. This is a small value, and the change as a result of a small mining step is very small.
- e) regions of maximum tilt and horizontal strain are associated with the crown pillar, if one is present, and with the down dip abutment of the stope. These effects are less for steeper dips. When mining is taking place at depths greater than 200 m, the effects on surface are very small.

These analyses were aimed at identifying trends, and it is important to note that points b) and e) agree with the observations of case histories of subsidence.

Three dimensional numerical modelling of three subsidence case studies was carried out using the mining simulation analysis method used routinely for the planning of stoping layouts at depth in gold mines. The purpose of this work was to evaluate the potential of the method for the prediction of subsidence. It was found that there was very little

correspondence, even qualitative, between the predicted behaviour and the observed behaviour. This may have been due to inadequate knowledge of or definition of the underground mining sequence, unsatisfactory data on the surface damage and rock mass properties, inadequate representation of the deformation behaviour of the hangingwall rock mass within the numerical model or a combination of all of these. Based on this work it is concluded that the available numerical methods are not suitable for the prediction of subsidence over shallow mine workings.

4.4 Discussion on the prediction of surface subsidence

There have been many methods developed for subsidence prediction. These include mathematical solutions based on the theory of elasticity, empirical methods based on the observation of cases of surface subsidence, numerical methods which have been developed in recent years, and combinations of these methods. Empirical and semi-empirical methods of subsidence prediction have found wide usage in the coal mining industry, where the subsidence due to longwall mining tends to be very regular. Such methods rely on the uniformity of the strata in which mining is taking place, and are applicable to horizontal or shallowly dipping deposits. They require a substantial body of quantitative historical monitoring data which can be used as the basis for developing the empirical predictive method. From the above it is clear that such techniques will not be generally applicable to the shallow hard rock mining in South Africa for the following reasons:

- there is considerable variability in the strata
- there are numerous reefs which might have been mined separately or together, each with different properties
- mining methods varied considerably, and in most cases involved partial extraction
- the strata are intersected by numerous continuous dykes and faults.

There are no adequate methods available for routinely predicting the potential subsidence over partial extraction mining. Most of the mining that has been carried out at shallow depth on the Central Rand and in the Bushveld Complex area has been of a partial extraction nature. In some cases the solid pillar support has been regularly spaced, but in most cases, particularly in the older workings, pillar support layouts were not planned. The implication of this is that the magnitude of subsidence in the area of interest is not predictable.

From the above observations and theoretical work, the following findings can be summarised.

- If surface movements occur at all, they will occur gradually and not suddenly. This

observation applies to movements associated both with and without the effects of dykes/faults. From a safety point of view, therefore, no catastrophic collapse of a structure will occur. Particular caution must be exercised in areas supported by pillars.

- total subsidences are generally a small fraction of the stoping width. These total values include those movements which occur during the mining activity. Observations and surface levelling have shown that most surface movement occurs during mining, and ceases shortly after mining has been completed. The residual potential for surface subsidence will therefore be a very small fraction of the stoping width.
- potential surface tilt and horizontal strain magnitudes which could result from underground collapse or failure of supports, after mining has been completed, are generally very small.
- recent records of subsidences indicate that most cases involved the outcrop area. These subsidences were generally very localised, and many were associated with the ingress of water. The stability of all unremedied outcrop areas must therefore be regarded as suspect.
- most of the significant subsidences have been associated with dykes/faults. Significant dyke and fault contacts must therefore be given special consideration.
- the theoretical analyses have indicated that mining of narrow tabular reef deposits at depths greater than 200 m has only a small effect on surface. This value correlates reasonably well with the 240 m value in the existing guidelines, which was based on observations of occurrences during active mining operations. The shallower depth is considered to be more appropriate in situations in which mining has been completed.

It may be concluded that there are no suitable subsidence prediction methods available for the reclamation prediction of magnitudes of subsidence in the areas being covered by the Undermining Committee. However, from the observations and theoretical analyses, the risks can be quantified as follows:

- i) differential subsidence, not absolute subsidence, is the subject of the recorded case histories.
- ii) the outcrop and adjacent areas are always areas of suspect stability.

- iii) major faults, joints and dyke contacts are locations with a high risk of differential subsidence potential.
- iv) undermined areas not traversed by major faults, joints or dyke contacts have a low risk of developing any surface subsidence effects.
- v) since recorded subsidences exhibited slow rates of movement, the risk of catastrophic movements is low.

5 CONSIDERATIONS LEADING TO THE RECOMMENDATIONS OF NEW GUIDELINES

The undermining guidelines and guidelines for the erection of buildings on undermined ground were both established many years ago. Since then, changes have taken place which have an effect on the applicability of the existing guidelines, amongst which are:

- more time has elapsed since the cessation of mining in many areas.
- much experience has been gained in an understanding of the behaviour of shallowly undermined ground on the Central Witwatersrand.
- more sophisticated design and construction techniques have been developed, providing greater deformation capabilities in structures.
- quantitative data on the surface behaviour over shallow undermining have become available.

In this Chapter, the applicability of the existing guidelines is reviewed, dealing with information on situations in which the guidelines have proved effective, and others in which they have not been satisfactory. Acceptable damage criteria applicable in subsidence areas will then be reviewed, along with the deformation capabilities of structures. Finally, conclusions will be drawn regarding the requirement for new guidelines.

5.1 Review of the applicability of the existing guidelines

Reported subsidences after 1927 were mostly concentrated on or in the immediate vicinity of the outcrop. Other subsidences were due to differential block movement along a dyke, and to a sinkhole formation caused by leaking water columns. No cases on the Witwatersrand were found where subsidences had occurred in areas under which restricted mining was taking place. Possible exceptions to this are:

- subsidence which affected the M2 motorway, Main Reef Road and the main railway

lines at the Johannesburg/Germiston boundary. In this area reclamation mining was taking place under restricted mining conditions defined by the guidelines. No work was being carried out on the shallowest reef (South Reef) due to lack of access. Movement took place on a dyke contact.

- subsidence beneath the Geldenhuis Interchange. The depth of the mining is approximately 400 m which is well in excess of the 240 m limit and movement is taking place on a dyke contact. Reclamation mining may have had some influence, but subsidence took place prior to the commencement of the reclamation mining.

In the Rustenburg area, an area undermined with a stoping width of 1,0 m at a depth of 150 m, and supported by solid pillars, subsided. It appears that a remnant between two stopes was mined out, resulting suddenly in a bigger span which caused the pillars to be overloaded and fail. The maximum subsidence was in the range of 0,17 m to 0,23 m. A hospital on the affected surface showed cracks in its walls.

The restrictions specified for mining in this area were:

- "Between vertical depth of 90 m and 150 m 12% of the stoped areas shall be left intact in the form of pillars..* Pillars shall not be less than 4 m square and spaced equidistantly".
- A further provision was inserted which stated that these restrictions were only to be applied where the combined stoping widths exceeded 38 cm for every 30 m of vertical depth or 1,25% of vertical depth.

The pillar support in the area consisted of 5 sq m pillars scattered at random. The extraction in the affected area was in the region of 86,25%. Since the stoping width did not exceed 1,25% of the total depth, the mine was not required to leave any systematic support.

The subsided area was bounded on one side by a dyke, and on the other by a major fault. Block movement occurred along these two major features.

From the data contained in the reports and publications mentioned above, several conclusions can be drawn regarding the applicability of the existing guidelines:

- i) the guidelines have served a very useful purpose in ensuring the stability of the surface in most cases.
- ii) solid pillars are the most effective means of support for preventing subsidence.

- iii) the effectiveness of waste fill as a means of support to prevent subsidence is questionable. It does not provide support equivalent to solid pillars.
- iv) the provision that support is not required where the combined stoping width is less than 1,25% of the depth should be reviewed critically.
- v) most subsidence takes place concurrently with mining or shortly thereafter. Major movements take place at this time. It appears therefore that the existing guidelines are probably under-conservative with regard to the undermining of existing structures. This is particularly the case when major geological planes of weakness are present and could affect the behaviour.
- vi) reactivation of mining operations, including reclamation mining under restricted mining conditions, tends to reactivate subsidence movements.

Many observations of the surface effects of shallow hard rock mining have been recorded, but no prediction models have been established. The main factors that appear to determine subsidence in this environment are so local and variable that a theoretical or prediction model approach is not attainable at present. The conservative approach adopted by the Government Mining Engineer in making use of the guidelines set out in Chapter 2 is based on this unpredictable behaviour. However, there are two areas in which the guidelines would appear to be under-conservative and require critical evaluation.

- i) the clause inserted in undermining permissions allowing 100% extraction below 30 m when the combined stoping width does not exceed 1,25% of the depth has been proved to be incorrect in at least one case.
- ii) the effect of major planes of weakness in new, or reactivated, mining operations can be critical as far as damaging subsidence is concerned. In such situations, the 240 m depth contour, beyond which restrictions are not usually imposed, has been found to be underconservative.

In contrast, in areas not influenced by major planes of weakness, the guidelines, particularly for erection of structures on undermined ground, are probably over-conservative.

It is concluded therefore that there is a need to revise the present guidelines. This need follows from the information contained above and in the previous Chapter, which is summarised as follows:

- there is pressure from the property industry for more efficient use of undermined land.
- the existing guidelines are under-conservative in some cases and probably over-conservative in others.
- in the case of previous mining, except in some special cases, the expected residual subsidence is minimal.
- in the case of future undermining, subsidence can be controlled.
- subsidence movements take place gradually.

5.2 Effects of surface movements on surface structures

The susceptibility to damage of structures on surface depends on the type of structure, its design, the method and quality of construction and the materials used in construction. Future structures may be designed to accommodate specified levels of deformation. This possibility is, however, not available for existing structures.

In this Chapter, quantitative damage criteria will be defined for a range of structures. These can then be applied in two areas:

- i) In areas already undermined, to specify the deformations which developments to be constructed on the undermined land must be capable of withstanding.
- ii) In areas where undermining of existing structures is proposed, to specify limitations on the mining which may take place to ensure that the appropriate damage criteria are not exceeded.

5.2.1 Published data on subsidence damage criteria

There is a considerable body of literature dealing with damage to structures as a result of subsidence over mine workings or of undermining of existing structures. In addition, there are many publications dealing with associated fields of foundation movements, such as heaving soils, subsidence due to groundwater extraction, chemical attack, poor construction methods etc. Use has been made of this large body of literature in assessing appropriate damage criteria for South African non-coal shallow mining conditions. Although most of the work is directed towards coal mining, much of it is very relevant to the problems of undermining in South Africa.

Some of the information available is intended to assist regulatory authorities in developing guidelines for underground mining operations as well as to permit mine operators to assess the potential for material damage to surface features overlying proposed underground mining operations. This is identically the requirement of the Commission, and therefore significant use has been made of certain publications.

The literature covered is a review of more than 200 publications, mainly related to coal mining, but also covering ground movements caused by tunnelling, groundwater abstraction, consolidation and settlement of soils, and permanent earthquake effects. Information comes from many countries, including the major coal mining countries - United Kingdom, West Germany, Russia, United States of America and Australia. Selected results, which are considered to be most relevant to the shallow, non-coal, mining conditions in South Africa, have been incorporated into this Chapter. The approach has been to identify several classes of structures relevant in South Africa, identify appropriate descriptors (criteria) of damage, and finally to quantify the magnitudes for these criteria recommended for application in the proposed new guidelines.

5.3 Proposed categories of structures

There are many different types of structures which may interact with undermining. Four main groups have been identified as being applicable in the South African context.

5.3.1 Buildings

A large variety of construction methods exists for buildings in South Africa. These range through very flexible steel structures, reinforced concrete structures, inflexible brick and masonry structures, and finally massive rigid concrete structures. It is considered that all of these types are, and will be, associated with undermined land in South Africa. For the purpose of drawing up the new guidelines, it is proposed that buildings are considered to fall into one of three categories:

CATEGORY 1 - brick and masonry structures with brick load-bearing walls.

CATEGORY 2 - steel and reinforced concrete frame structures.

CATEGORY 3 - massive structures of considerable rigidity, including those of central core design.

5.3.2 Roads

Roads can tolerate a large amount of deformation before the safety of traffic is brought into question. Such deformations can also usually be catered for in routine road maintenance programmes. It is proposed therefore that two categories of roads are considered:

CATEGORY 1 - low volume gravel roads and paved roads. These roads would not normally have kerbs, nor rigid storm water drainage systems.

CATEGORY 2 - high volume paved roads. These would have kerbs and comprehensive storm water drainage facilities.

Bridge structures would fall into category 2 or 3 of the building section as appropriate.

5.3.3 Railway lines

Railway tracks are more sensitive to deformations than roads particularly if surface movements occur suddenly. The risk is related to the possibility of derailment of trains. Deformations of tracks can easily be corrected by ballasting during routine maintenance. The following two categories are proposed:

CATEGORY 1 - goods lines and lines carrying low volume passenger traffic, on which speed limits can easily be imposed.

CATEGORY 2 - main lines and lines carrying high volume passenger traffic. On such lines it will not normally be practical to impose permanent speed limits from a system operating point of view.

5.3.4 Pipes

There are two main problems which could occur with pipelines. The first is the possibility that damage could result in the release of water or other liquids which may percolate into the old mine workings and result in adverse surface effects. The second is that movements may lead to changes in the grade of the line which could be detrimental to the performance of the pipeline. This is particularly the case for sewers and stormwater drains. Two categories are proposed:

CATEGORY 1 - secondary sewers, water supply pipelines and stormwater drains,

and all steel pipelines carrying non-hazardous materials.

CATEGORY 2 - main sewers, water supply pipelines, stormwater drains and pipes carrying hazardous fluids.

Special structures, for example tunnels, should be treated as special cases.

6.4 Proposed parameters for quantifying damage

There are many parameters which can be used to describe ground movements and which have been correlated with damage to structures. These include vertical subsidence, horizontal strain, tilt, radius of curvature, differential settlement etc. Of the available parameters it is proposed that only two should be adopted for the purposes of the new guidelines. These two are the horizontal strain and the tilt. The reason for this choice is that they are both readily measured, both can easily be calculated from mining simulation stress analyses, and, since they have been commonly used, there is a substantial volume of data available in which they have been correlated with observed damage to structures. The definition of the two parameters is as follows:

HORIZONTAL STRAIN is the difference between the horizontal displacements of two points on the ground surface divided by the horizontal distance between the two points.

TILT is the difference between the vertical displacements of two points on the ground surface divided by the horizontal distance between the two points.

The horizontal distance referred to in the two definitions above is that distance between adjacent foundations, footings, support points etc of the structure. For continuous structures such as roads railways and pipelines the horizontal distance applicable should be 3 metres.

6.5 Proposed damage criteria

The above sections of this Chapter have defined several categories of structures and parameters to describe ground movements. The purpose of this section will be to define values of the two parameters which will correspond with several levels of damage to the structures.

6.5.1 Buildings

Two levels of damage are considered to be appropriate for buildings. These are :

- i) Superficial damage in which some plaster cracks may be observed and some sticking of doors and windows may occur.
- ii) Hazardous damage which includes jamming of doors and windows, breaking of window panes, structural damage and possibly failure of structural members.

The table below summarises the recommended limits on ground movements applicable for buildings in South Africa.

Building Category	Damage Level	Horizontal Strain ($\times 10^{-3}$)	Tilt ($\times 10^{-3}$)
1	Superficial	0,5	1,0
1	Hazardous	2,0	3,0
2	Superficial	2,0	1,5
2	Hazardous	4,0	3,5
3	Superficial	1,0	1,5
3	Hazardous	3,0	3,0

5.5.2 Roads

Two levels of damage are recommended for roads.

- i) Minor damage describes minor cracking of the road pavement or damage of little consequence that will be unlikely to be observed by road users, and that will be automatically remedied during road maintenance.
- ii) Severe damage refers to disruption of the road surfaces, causing undulations adversely affecting drainage and driving dynamics.

The following are the recommended limits for roads:

Road Category	Damage Level	Horizontal Strain (X10-3)	Tilt (X10-3)
1	Minor	2,0	10,0
1	Severe	5,0	15,0
2	Minor	1,0	5,0
2	Severe	2,0	10,0

5.5.3 Railway Lines

Only one level of damage is suggested for each of the categories. This corresponds simply to a different factor of safety for each of the two categories.

Railway Line Category	Horizontal Strain (X10-3)	Tilt (X10-3)
1	3,0	10,0
2	2,0	5,0

5.5.4 Pipes

As for railway lines only one damage level is suggested for each of the categories of pipelines. This provides a higher factor of safety for those situations in which the consequences of failure are more serious.

Pipe Category	Horizontal Strain (X10-3)	Tilt (X10-3)
1	2,0	4,0
2	1,0	2,0

5.6 Damage criteria for special structures

The effects of subsidence can be catered for in the design of structures by incorporating special construction techniques. Under these circumstances the structures may be able to withstand far greater ground movements than have been identified as criteria for damage above. In such cases it is recommended that each case be treated on merit and that the designed deformation capabilities be taken into account in considering relaxation of undermining restrictions. Examples of such techniques are given below for information.

Buildings and similar structures

Special techniques include the division of structures into separate sections. Sections can then move independently of each other. Flexible connections between the sections to cater for access, services etc will conceal the fact that the building consists of several independent sections, and prevent unsightly cracks and the consequences of damaged services. Examples of structures making use of this technique to cater for potential effects of subsidence are the Standard Bank Superblock and the Priceforbes Federale Volkskas headquarters building, both in central Johannesburg.

The provision of spherical bearings within a structure will allow considerable deformation to take place without damaging the structural capability of the elements of the structure. Again architectural techniques will conceal the effects of any deformations and prevent the appearance of unsightly cracking. The Edgars head office building in Edgardale, Johannesburg, is an example of a structure making use of this special technique.

When tilting is particularly undesirable, jacking facilities can be incorporated into foundations to allow the effects of movements to be corrected from time to time. This facility exists in the M2 Motorway structures in Johannesburg, and permits three-dimensional adjustments to be made to the "position" of the structures.

Commonly used techniques to cater for large movements include the use of special foundation measures such as reinforced rafts and special pile solutions. The former are often used for dwelling units.

Roads, railway lines and pipes

These three types of structure are grouped together since many of the special techniques are common to all. Road pavements can be constructed of flexible materials and, similarly, pipes and services can be sleeved or laid in beds containing a backfill which allows

movements to take place. Slots can be provided in road pavements to accommodate potential movements - this is equivalent to the expansion joints which are used in bridges and other concrete structures to allow for the effects of temperature. Kerbs and gutters should similarly have suitable expansion joints. Pipes can be provided with flexible joints with expansion capability as well. The use of short lengths is preferable, and pipes can be articulated if necessary.

When grades are important for drainage (eg road surfaces, sewers and storm water drains) designs can allow for initial grades which exceed normal requirements. Subsequent ground movements will then not be detrimental.

The effect of tilt on railway lines can be decreased by providing "bridging". This increases the base length over which the slope of the line will change and therefore will alleviate any problems which could occur. An example of the use of this technique is the rail crossing of the steep outcrops in the Denver area of Johannesburg.

5.7 Conclusions regarding deformation capabilities of structures

Structures can accommodate substantial deformations before they approach a dangerous condition. Typical limits for such deformations, established from a review of literature, are presented above. It has also been noted that special construction techniques can be used to extend considerably the inherent deformation capabilities of structures. Therefore, although deformation limits for various types of structures (buildings, roads, railway lines, and pipes) are set in the Sections above, almost unlimited deformations can be accommodated by appropriate design and construction techniques.

6 RECOMMENDED GUIDELINES

The aims of the existing guidelines are implicit in the manner in which they have been implemented. For clarity of understanding, the aims of the proposed new guidelines are stated explicitly as follows:

- I) to ensure the safety of human lives
- II) to ensure that the risk of damage to private property owing to the presence of shallow mine workings is minimised
- III) to allow the ground surface overlying shallow undermining to be developed to its optimum potential

- iv) to allow optimum exploitation of the gold reserves before, during and after development of the surface
- v) to reduce as rapidly as possible the number of unsafe outcrop areas and old unstabilised shafts
- vi) to obviate areas of inflow of surface water into underground workings.

6.1 Proposed new guidelines for development over previously undermined ground

6.1.1 Zoning of the surface for the proposed new guidelines for development over previous undermined grounds

Based on the information above, it is possible to define several zones in which different restrictions on surface development will apply. The following zone definitions take into account specifically three main conclusions from above, namely, that surface movements, if any, are gradual, that total surface movements are a small fraction of stope widths, and that changes in surface movements after completion of mining are very small:

Outcrop Zone

This zone would extend from 3 m on the footwall side of the stope (reef), as in the existing guidelines, to points where the depth of mining, measured vertically, is 25 m. When more than one reef has been mined, depending on the middlings between the stopes, the one extreme will be for each stope to occur separately in its own outcrop zone, and the other will be for all stopes to occur in a single outcrop zone. This means that there may be more than one outcrop zone on a single site.

Shallow Zone

This zone will extend from the outcrop zone where the mining depth, measured vertically is 25 m, to points where the mining depth, measured vertically, is 200 m.

Deep Zone

This zone will include all areas where the mining depth, measured vertically, is greater than 200 m.

Special Zones

All ground within 5 m of the perimeters of shafts and winzes, including the openings themselves, and within 5 m of significant dyke or fault contacts, and the dykes themselves, will be included in special zones.

6.1.2 Central Witwatersrand region

By using the depth of mining for definition of development zones, as in Section 6.1, the dip of the reef and the distance from the outcrop are automatically taken into account. By relating the potential surface movement to the total stoping width, the extent of mining is taken into account. This approach is adopted below. The following are the proposed new guidelines relevant to the Central Witwatersrand region.

OUTCROP ZONE

From 3 m on the footwall side of the outcrop to where the shallowest depth of mining, measured vertically, is 25 m, no development will be permitted, unless the outcrops have been stabilised to the satisfaction of the Inspector of Mines. If the outcrops have been stabilised, developments will be designed to accommodate, without distress, a localised differential settlement of 100 mm/m of the total stoping width beneath the outcrop zone, and associated tilt, and a horizontal strain of 35 mm/m. The potential differential settlement will be assumed to occur across a base length of 5 m. In addition, the development must accommodate three times the above amounts of deformation without endangering life or limb.

No buildings greater than two storeys in height, and no basements, shall be permitted.

Special consideration will be given in the case where stabilisation measures are carried to a significant depth in the old stopes. Examples of this are the Standard Bank Superhock and the PFV Headquarters building.

SHALLOW ZONE

Developments will be designed to accommodate, without adverse effects perceived by the owner, the following deformations:

- a localised differential settlement, assumed to occur across a base length of

5 m, calculated using the following relationship:

where $S = 11 \cdot 0,03D$

S is the value of differential settlement expressed as a percentage of the total sloping width beneath the shallow zone

D is the vertical depth to the shallowest slope

For example, at a depth of 90 m, S is calculated to be 8,3%. If the total sloping width beneath the site is 2,5 m then the localised differential settlement that must be accommodated without distress to the structure is 0,21 m, or 42 mm/m across a 5 m base.

- the structures must be designed to accommodate a horizontal strain of $(S/3)\%$ without distress.

In addition to the above requirements, in the case of buildings the developments must be designed to accommodate three times the above deformations without endangering life or limb.

No limits will be placed on the heights of buildings in this zone. No limits will be placed on the number of basements, provided that the closest distance from the basement to the shallowest hangingwall is at least 25 m.

DEEP ZONE

No restrictions are placed on development within this zone.

HAZARD ZONES

Shafts will be located, and stabilised to the satisfaction of the Inspector of Mines. Founding on stabilised shaft locations will be permitted provided that specific professional design consideration has been given, by the designers, to the possibility of differential founding conditions in this location.

In the outcrop zone, no buildings will be permitted to straddle significant dyke and fault contacts. Contacts will be located on surface, and no building foundations will be located closer than 3 m to the contact. This restriction may be reviewed if it can be proved that specific professional design consideration has been given, by the designers, to the possibility of differential settlement at the contact. This relaxation

also applies to the development of other structures across contacts.

In the shallow zone, significant fault and dyke contacts will be located. Buildings will not be permitted to straddle the contact if the angle between the contact and the stope, on the mined out side, is uncertain or is less than 95 degrees. Other structures will be permitted to cross the contact, and the restriction on building development will be reviewed, provided that specific professional design consideration has been given, by the designers, to the possibility of differential settlement at the contact. If the angle as described above is greater than 95 degrees, then buildings and other structures will be permitted to cross the contact, provided that specific professional consideration has been given, by the designers, to the possibility of differential settlement at the contact.

6.1.3 Bushveld Complex region

There is much less experience regarding the behaviour of the ground surface over shallow undermining in the chrome and platinum mines of the Bushveld Complex. Owing to the pervasive presence of major geological features, it is recommended that, when the depth of mining is less than 200 m, no development of buildings on surface should be allowed unless the average support underground exceeds 20% of the mined out area. Of this figure of 20%, a minimum of 5% (ie a quarter of the minimum total underground support) must be in the form of solid pillars on a regular layout with a minimum width to height ratio of 4. If the layout of solid pillars is irregular, approval of the Inspector of Mines for the proposed developments may only be granted if satisfactory technical justification is provided. The remaining support may be in the form of waste rock packs or backfill.

The restrictions on development, and the associated depth ranges, defined for the Central Witwatersrand Region above, namely for the Outcrop Zone, the Shallow Zone, the Deep Zone and the Hazard Zones, will be applicable also for the Bushveld Complex mining areas.

6.1.4 Other regions

There are no data available with regard to subsidence which may have occurred in areas others than those considered above. Each situation must therefore be considered on merit following the principles set out in this document.

6.1.5 Responsibility clause

In all cases of development on undermined ground, the owner and the designer of the development will sign a statement, which will include the following:

- that cognizance has been taken of the fact that the land is undermined
- that it is accepted that movements of the surface are possible
- that the designer accepts professional responsibility for the performance of the structures he has designed.

6.2 Proposed new guidelines for the undermining of existing structures

The records of subsidence behaviour have all indicated that the occurrence of subsidence is greatest during active mining, and that renewed mining activity, such as reclamation mining, reactivates subsidence movements. The records also indicate that large differential movements can occur across major planes of weakness, but that, in other areas beyond the outcrop zone, subsidence behaviour is uniform. Since these movements will be active during any mining activity, their control must be catered for in the guidelines for the undermining of existing structures.

6.2.1 Definition of restricted mining area

Protection must be provided along the rise, dip and strike directions. When the dip of the reef is greater than 20° , the extent of the restricted area will be defined as follows in terms of d , the depth to the footwall of the deepest reef being mined beneath the site:

- i) rise side: a distance of $d/2,7$ measured up and at right angles to the strike of the reef
- ii) dip side: a distance of $d/10$ measured down and at right angles to the strike of the reef
- iii) strike sides: a distance of $d/5$ measured along the strike of the reef.

When the dip of the reef is less than 20° , the restricted mining area will be defined by a distance in all directions of $d/2,7$.

The definitions above will result in discrepancies for reefs dipping slightly steeper and slightly shallower than 20° . In such cases, the largest area defined will be taken to be the restricted area.

^{2.2} 6.1.1 Support required during primary mining

Within the restricted mining area, mining may take place only under the following conditions:

- i) no mining shall be permitted at depths less than 25 m measured vertically below the ground surface.
- ii) between mining depths of 25 m and 100 m solid support in the form of regularly spaced pillars shall be provided to the extent of 25% of the mining area. The width to height ratio of pillars shall not be less than 4.
- iii) between mining depths of 100 m and 500 m solid support in the form of regularly spaced pillars shall be provided to the extent of 15% of the mining area. The width to height ratio of pillars shall not be less than 4.
- iv) on dyke contacts, when the dyke is not stoped through, and on fault contacts on which a displacement exceeding 5 m has occurred, pillars will be left to ensure, to the satisfaction of the Inspector of Mines, that differential displacements will not occur on such contacts.
- v) the above conditions will also apply when more than one reef is being mined, with the additional requirement that pillars must be superimposed vertically when the separation between the reefs, measured normal to the reef plane, is less than 25 m.

^{2.3} 6.1.2 Support required during reclamation mining

Reclamation mining represents a reactivation of mining which is likely to cause a reactivation of subsidence movements. The following conditions are to be imposed on mining within the restricted mining area.

- i) where dykes, which have not been stoped out, or faults which show a displacement exceeding 5 m, occur in the restricted mining area, no reclamation mining will be permitted.
- ii) at vertical depths shallower than 500 m, existing solid pillars shall not be reduced in size to a width to height ratio of less than 4.

- iii) no reclamation mining shall be carried out when the depth of mining is less than 25 m measured vertically.
- iv) between a mining depth of 25 m and 100 m, the total area of support, including solid pillars, waste rock packs and backfill, shall not be less than 25% of the mined out area. The support shall be regularly distributed.
- v) between a mining depth of 100 m and 500 m, the total area of support, including solid pillars, waste rock packs and backfill, shall not be less than 15% of the mined out area. The support shall be regularly distributed.
- vi) Where stopes overlap areas of proposed reclamation mining, such reclamation mining will be subject to the written approval of the Inspector of Mines.

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