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# The use of three-dimensional stress analyses in predicting the stability of large open stopes

by G.S. ESTERHUIZEN*

**SYNOPSIS**

An investigation into the stability of large open stopes at Premier diamond mine, Cullinan, South Africa, is described. The open stopes are located in a weak kimberlite orebody, directly underneath a 75 m-thick sill of gabbro. Two- and three-dimensional stress analyses were carried out in a back-analysis of the stresses and failure around the first open stope created under the sill. The results were used in the prediction of the future stability of the planned open stopes, intervening pillars, and sill.

**SAMEVATTING**

'n Ondersoek na die stabiliteit van groot oop-afbou uitgrawings op Premier diamantmyn, Cullinan, Suid-Afrika word beskryf. Die uitgrawings is in 'n swak kimberliet ertsliggaam geleë en kom direk onder 'n 75 m dik gabbro plaat voor. Twee- en drie-dimensionele spanningsanalises is uitgevoer om die swigting en spannings rondom die eerste oop uitgrawing wat onder die plaat geskep is te analiseer. Hierdie resultate is gebruik om die toekomstige stabiliteit van die oop uitgrawings, die pilare en die gabbro plaat te bepaal.

## Introduction

Premier Mine produces diamonds from an oval-shaped kimberlite pipe situated 35 km east of Pretoria. At a depth of 370 m, the pipe is completely cut off by a younger gabbro sill, which is approximately 75 m thick and is almost horizontal. The sill created a major mining problem, but the presence of high-grade ore below it justified the establishment of virtually a new mine below the sill.

Long-hole bench mining and block caving[1] account for the production from above the sill. Below the sill, the mining method had to be changed to maintain the stability of the sill while undiluted ore was being extracted from below. A new mining method was designed[2] to permit the extraction of large open stopes separated by pillars, which would support the overlying sill during primary mining. The stope spans were designed to ensure that the sill would not cave into the open stopes, and, after primary mining of the open stopes, the pillars would be extracted, allowing the sill to collapse.

Production from below the sill was planned to start from three large open stopes (the SA1, SA2, and SA3 stopes) in the south-eastern part of the pipe. The stopes were planned to be 80 m wide, 65 to 80 m high, and 125 m long. The pillars were to be 40 m wide and up to 80 m high, and were required to support the sill over a span of some 125 m by 350 m. The layout of the stopes and pillars in relation to the sill is illustrated in Fig. 1.

Production from below the sill started from the SA3 stope in 1983. The stope was still in its initial stages when the sill started to collapse into the open stope. The resultant dilution was a major problem since there were no waste-handling facilities on the production level. It was further found that the kimberlite in the south-eastern part of the pipe was weaker than expected, and deteriorated rapidly when exposed to moisture. It was feared that the pillars in the weak kimberlite would become impossible to mine as the load from the sill increased on the pillars. The mine management therefore decided that the remainder of the ore below the sill should be extracted by the block-caving method.

Owing to production commitments, the open stoping method had still to be used in the areas where the preliminary development had been completed. Three alternative mining sequences were planned for this area in an attempt to improve the stability of the open stopes and the pillars. This paper describes an investigation of the behaviour of the rock surrounding the open stopes, and computer modelling of the proposed open stopes. The investigation was intended to provide information for use in the selection of the most favourable open-stoping sequence.

## Geology

The Premier orebody is roughly oval in plan, with surface dimensions of 900 m by 450 m. The contact between the kimberlite pipe and the surrounding country rock is sharp, with an average dip of 85 degrees. At the current mining depth, the pipe has a long axis of 800 m and a short axis of 350 m, as shown in Fig. 2. The country rock is a massive body of felsite grading downwards to norite at a depth of approximately 350 m. The kimberlite pipe is a multiple intrusion, which contains three major types of kimberlite: grey, black, and brown. The gabbro sill averages 75 m in thickness and dips at about 10 degrees to the north-east. In the south-eastern part of the pipe, the dip increases to 30 degrees. Because of the dip, the sill is encountered between 355 m and 530 m below surface. The lower contact of the sill is fairly regular, while the upper surface has intruded into the kimberlites, resulting in numerous dyke- and sill-like bodies.

* Senior Lecturer, Department of Mining Engineering, University of Pretoria, Pretoria 0001.

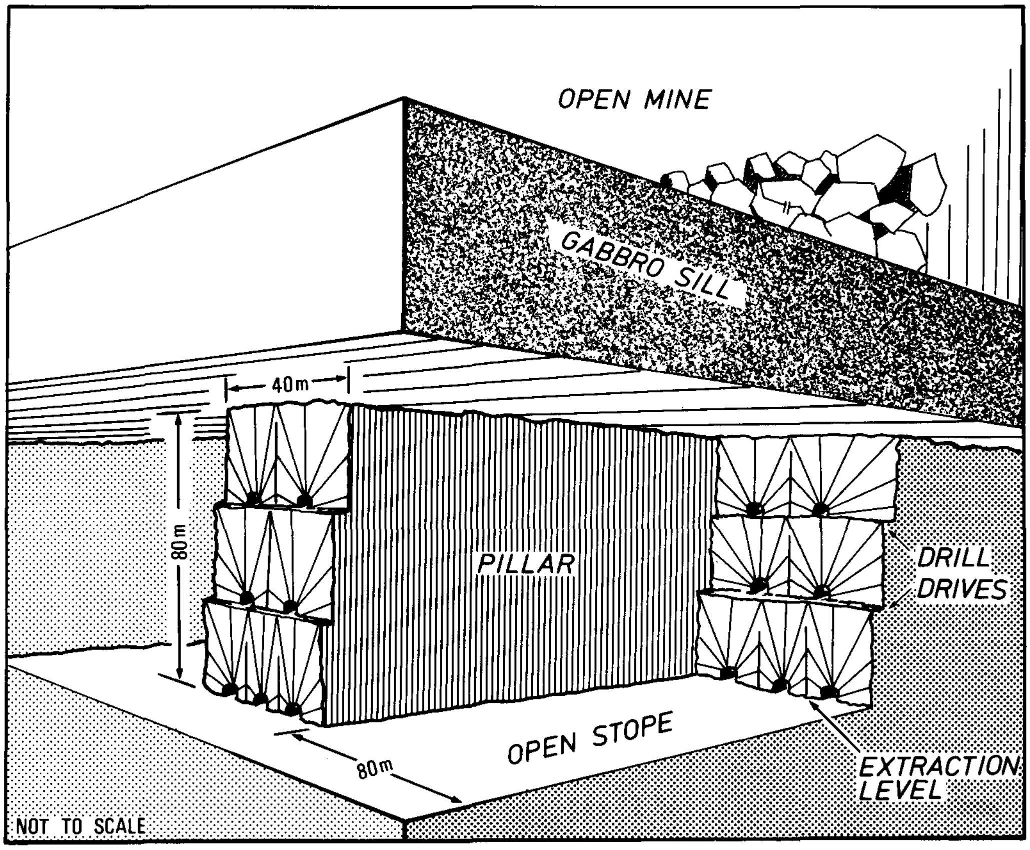


**Fig. 1—Layout of the open stopes and pillars beneath the gabbro sill**

*Properties of the Main Rock Types*

Some of the physical properties of the rock types are listed in Table I. These properties are based on small-scale intact rock samples tested in the laboratory. The table illustrates the large variation in the elastic properties and strengths of the rock types.

TABLE I

PHYSICAL PROPERTIES OF ROCKS AT PREMIER MINE

| Type | Tensile strength MPa | UCS* MPa | Young's modulus GPa | Poisson's ratio |
|---|---|---|---|---|
| Black kimberlite | 13,7 | 176 | 58,4 | 0,34 |
| Grey kimberlite | 6,7 | 129 | 29,4 | 0,17 |
| Brown kimberlite | 7,9 | 71 | 16,0 | 0,27 |
| Gabbro (sill) | 24,0 | 284 | 119,4 | 0,33 |
| Felsite | 16,8 | 263 | 62,0 | 0,29 |
| Norite | 16,6 | 160 | 74,0 | 0,25 |

* Uniaxial compressive strength

*Characteristics of the Rock Mass*

The strength of the gabbro sill is high, but there are four dominant joint sets that are consistent throughout the sill. Three of these are steeply dipping, resulting in columnar structures typical of intrusive dykes and sills. The fourth set is shallow-dipping, and is important from a stability point of view. The joints are generally tight, with negligible fill material. Occasional shear zones have developed parallel to the joint directions. Where shearing has occurred, the infill is hard and dry.

The kimberlites are of medium strength, but tend to decompose to varying degrees when exposed to water. Jointing is random, with occasional shear zones that are continuous over distances of up to 20 m. The kimberlite below the sill is generally dry, while that above and below the sill has been thermally metamorphosed for a distance of 15 m in either direction. The metamorphosed kimberlite is strong, and the joints are fused.

Of the different types of kimberlite, the grey variety is the most abundant in the pipe. It is a relatively strong rock and decomposes slowly when exposed to water. Brown kimberlite, which is found in the south-eastern part of the pipe, has a lower strength and decomposes rapidly when exposed to water. During the process of decomposition, it swells and can exert pressures of up to 40 MPa under total confinement. Moisture in the mine air is sufficient to cause the total collapse of an unprotected drive in brown kimberlite. Black kimberlite is massive and has high strength. It is encountered in the western part of the pipe, where it has intruded the grey kimberlite.

The country rocks are norite and felsite, both of high strength and good quality. Heavily jointed areas are encountered occasionally, which create problems of tunnel stability.

Stresses in the gabbro sill were measured by the Chamber of Mines Research Organization before mining started below the sill. The results showed that the vertical stresses in the sill were determined by the overburden (measured as 4,5 MPa), while the horizontal stresses were higher than expected (10 to 17 MPa). The stresses in the kimber-

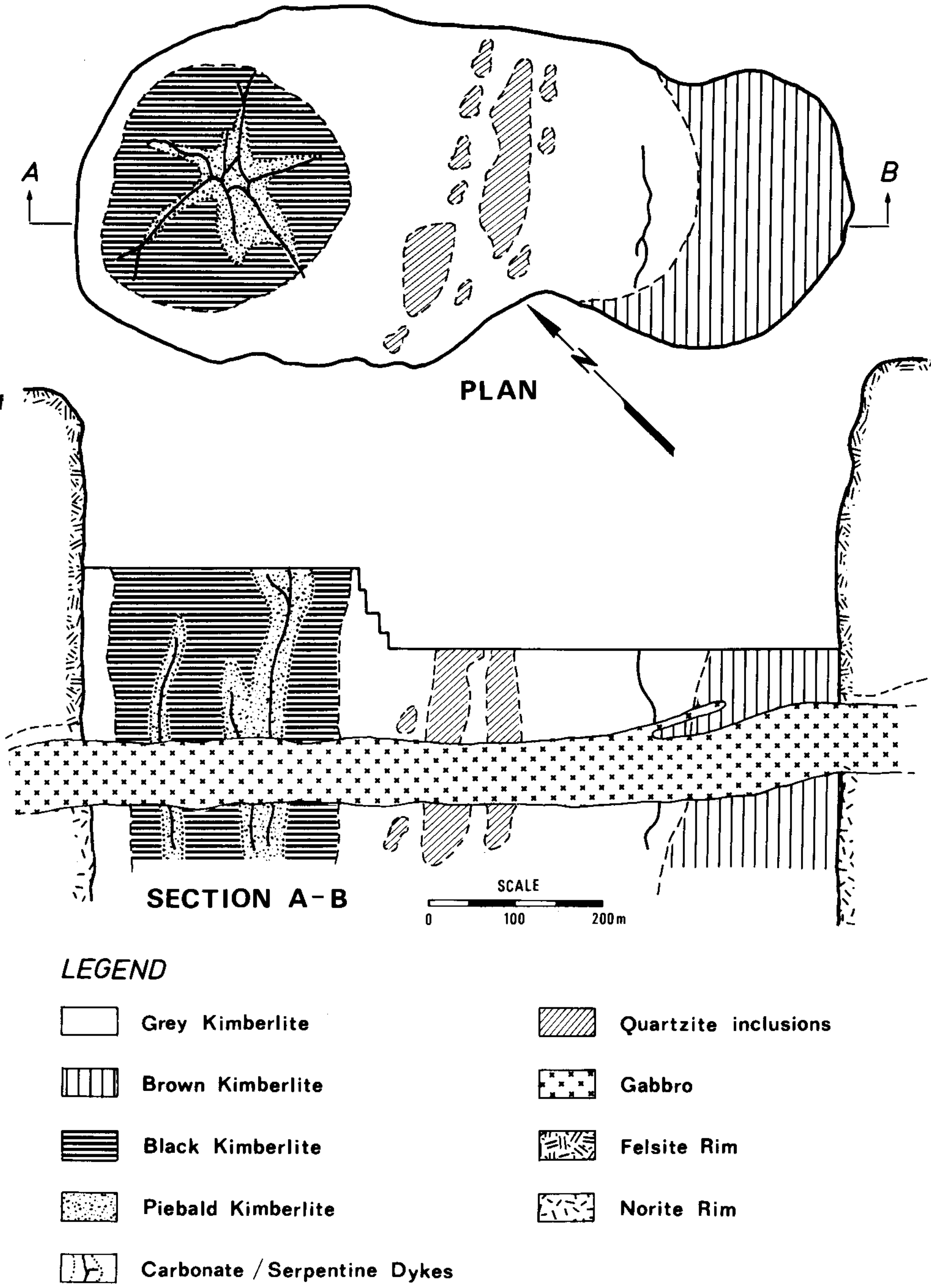


Fig. 2—Simplified geology of Premier Mine (after McMurray[2])

lite were not measured, mainly because of the difficulty associated with the deterioration of the kimberlite on being exposed to moisture.

### State of Stress below the Sill

Stress analyses of the stopes below the sill require that an accurate estimate should be made of the stresses in the kimberlite below the sill. It was decided that a numerical model based on the stresses measured in the sill should be used in this estimation. The modelling method was required to be able to include the different material properties of the sill, the country rock, and the kimberlite orebody. In addition, the three-dimensional geometry of the pipe had to be included in the model.

To satisfy these requirements, a finite-element[3] analysis was conducted, in which, by the use of axi-symmetry, the elliptical pipe was approximated to a cylindrical body. This allowed an unlimited number of rock types to be modelled.

The finite-element model was set up to simulate the geometry of the mine at the time of the stress measurements. The inner portion of the finite-element mesh used in this analysis is shown in Fig. 3. The model was initially loaded by gravity alone, but the resultant stresses in the sill were well below the measured stresses. Forces to simulate tectonic stresses were then applied to the boundaries of the model and were increased in steps until the stresses in the modelled sill were within acceptable limits of the measured stresses. The results showed that the magnitude of the stresses in the kimberlite were related to the mass of the overlying material. The fact that a large amount of overburden material had been removed from the pipe resulted in lower stresses than would be anticipated for the depth. The predicted stress levels were typically 5 MPa at a depth of 350 m below surface, because the depth of overburden was only 150 m. The stresses were approximately equal in all directions.

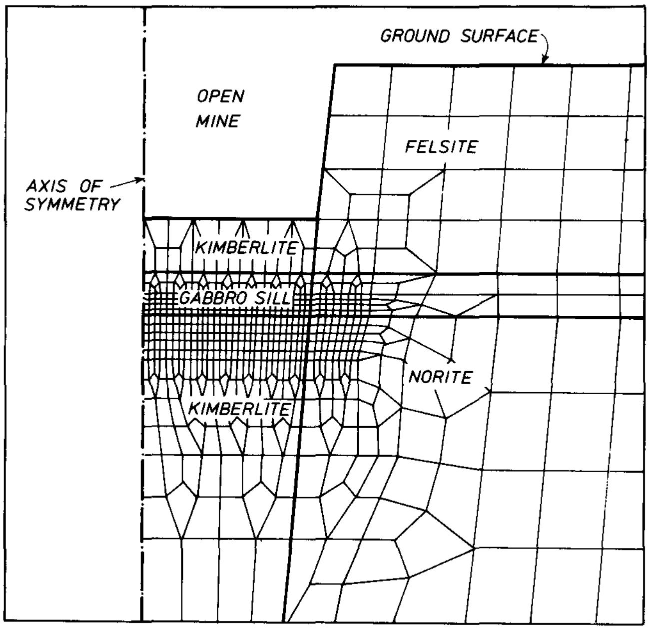


**Fig. 3—Finite-element model of the mine**

Underground observations were made to validate the results of the finite-element model. Observation of the mode of failure in orepasses and drillholes confirmed that there were no abnormal stresses in the kimberlites below the sill. The results of the finite-element analyses were therefore used in the subsequent analyses of the large open stopes.

## Back Analysis of Failure around the Open Stopes

To evaluate the behaviour of the fully three-dimensional stopes, it was decided that a three-dimensional boundary-element program should be used. The program permits the modelling of several three-dimensional excavations. The boundaries of the excavations are discretized into elements, and the intervening rock mass is assumed to be linearly elastic and isotropic. However, this simplification would result in low stress levels in the sill and inaccurate deformation values owing to the absence of the stiff sill material. A known situation had therefore to be modelled according to the three-dimensional program so that the results of the model could be correlated with the actual performance of the rock surrounding the excavation. Future layouts could then be evaluated on the basis of the results for the known case.

The performance of the SA3 open stope was used as a benchmark case for the evaluation of the output of the three-dimensional analyses. The SA3 stope was the first open stope to be created underneath the sill. By the end of 1984, the stope had been mined to its full width of 80 m and had advanced 40 m in the longitudinal direction. It had been intended that the height of the stope should be 65 m, but caving of the gabbro sill had occurred to 20 m above the intended roof of the stope, as shown in Fig. 4. The sidewalls of the open stope were unstable, and about 10 m of the western wall had fallen into the stope. Other smaller collapses had also occurred. The collapses appeared to be controlled by the joints and shear zones in the kimberlite. Open cracks developed in the drill drives, which caused falls of ground, and drillholes were often closed off as a result of relative shear displacement across joints.

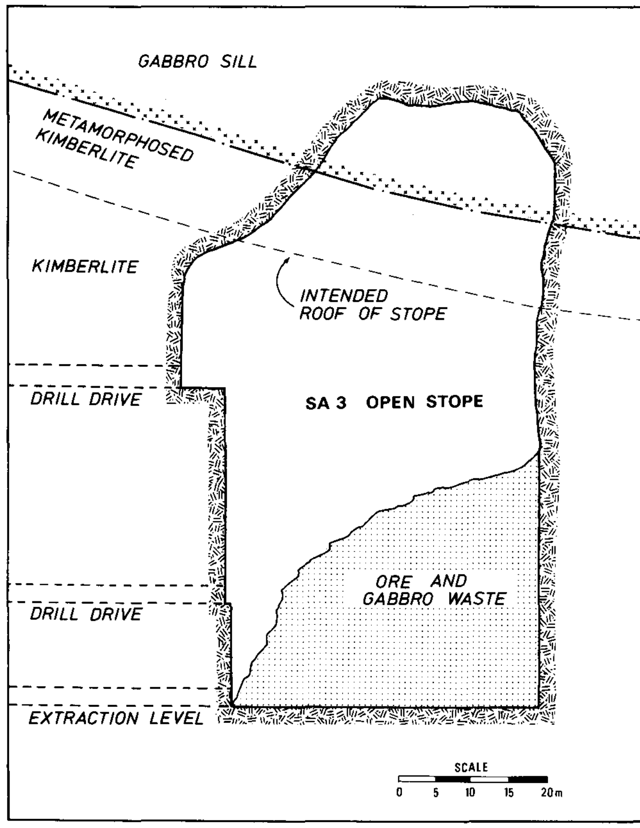


**Fig. 4—Extent of the collapse of the gabbro sill into the SA3 stope**

The SA3 stope was modelled as at the end of 1984 by use of the three-dimensional boundary-element program MBEM[4]. The model included 300 m of the ground surface around the pipe, the mined-out pipe, and the SA3 stope, as shown in Fig. 5. The material properties for the model of grey kimberlite were used to define the material, since the SA3 stope is located in the grey kimberlite. Field stresses were applied as estimated for the kimberlite below the sill. The program calculated the stresses and displacements at selected points in the rock mass surrounding the stope, and the results were correlated with the observed behaviour of the rock mass.

### *Failure in the Kimberlite*

The main cause for concern was failure of the rock mass around the open stopes. The failed rock mass collapsed into the open stope and reduced the strength of the pillars. An empirical criterion of rock-mass failure

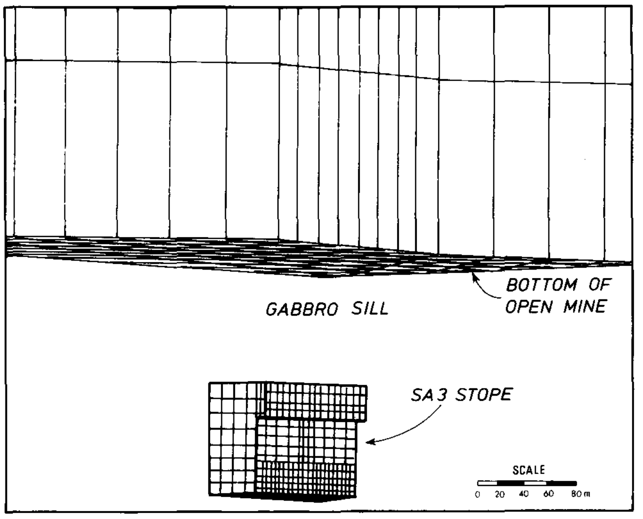


**Fig. 5—Three-dimensional boundary-element model of the SA3 stope**

(that of Hoek and Brown) was used in evaluating the performance of the model. The input required for this criterion is the classification of the rock mass and the uniaxial compressive strength of the intact rock. The rock mass was calculated as having a CSIR Geomechanics rating of 44 (fair-quality rock mass) for the kimberlite. The uniaxial compressive strength used was that shown in Table I. The criterion was then used in the calculation of the strength of the rock mass at a point such that, if the maximum principal stress at the point were greater than the strength, the rock mass would fail at that point. A useful indicator of the degree of failure is the 'excess stress', which is the amount by which the maximum principal stress exceeds the calculated strength of the rock mass.

The degree of observed failure in the kimberlite was correlated with the magnitude of the excess stress determined by the model. The relationship between excess stress and rock-mass condition is shown in Table II.

TABLE II
RELATIONSHIP BETWEEN EXCESS STRESSES AND ROCK-MASS CONDITION IN KIMBERLITE

| Excess stress | Condition of rock mass |
|---|---|
| Less than 5 MPa | Minor failure, cracking through intact rock, and shear movement along planes of weakness. |
| Between 5 MPa and 10 MPa | Moderate failure, cracking through intact rock, and pronounced movement along planes of weakness, possible collapse into open stopes. |
| Greater than 10 MPa | Severe failure, crushing of rock mass, with associated loss of strength, collapse into excavations. |

*Failure in the Gabbro Sill*

The failure of the gabbro sill predicted by the model was far less than the observed failure. The reasons were as follows: firstly, the stresses in the model had been reduced to satisfy the reduced stress state in the kimberlites; and, secondly, the model was homogeneous. As a result, the horizontal stress in the model at the location of the sill was 7 MPa, instead of the measured 14 MPa. In the evaluation of the potential failure of the sill, the field stresses had been left unchanged, but the strength of the sill had been reduced in the calculations. Decreasing values of uniaxial compressive strength for the sill had been used until the failed zone agreed with the height of collapse above the stope. It was recognized that this approach would not result in accurate forecasts of the sill behaviour, but it extended the usefulness of the three-dimensional models. It had been necessary for the uniaxial compressive strength of the sill to be reduced to 80 MPa to achieve the desired effect.

**Prediction of the Stability of the Open Stopes**

The correlations obtained in the above back-analyses were used in predictions of the future behaviour of the open stopes. Six different configurations were modelled, but the results of only two of these are discussed here.

*Prior to Pillar Extraction*

One of the alternative mining sequences was aimed at mining the three primary stopes almost to the rim of the pipe before the extraction of the pillars would start. The geometry just before pillar extraction was scheduled to start was selected for modelling. The three stopes would be nearly at the limits of the kimberlite pipe, and the pillar geometry would be at its most unfavourable. A three-dimensional model was set up to simulate this situation. The layout of part of the model is shown in Fig. 6. The program was used in the calculation of the stresses at selected points in the sill, and in the sidewalls and floor of the stope.

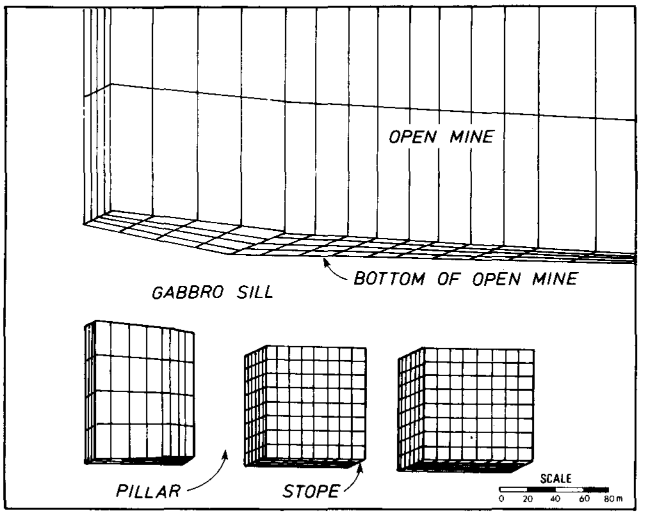


**Fig. 6—Three-dimensional model of the open stopes prior to pillar extraction**

The results for the pillars and the sill are summarized in Fig. 7. The PA2 pillar is shown to have severely failed (i.e. the stresses exceed the strength by more than 10 MPa). This could be interpreted as the collapse of the pillar. The adjacent PA1 pillar is shown to have failed to a lesser extent. However, if the severely failed outer portion of this pillar should collapse, the remaining core

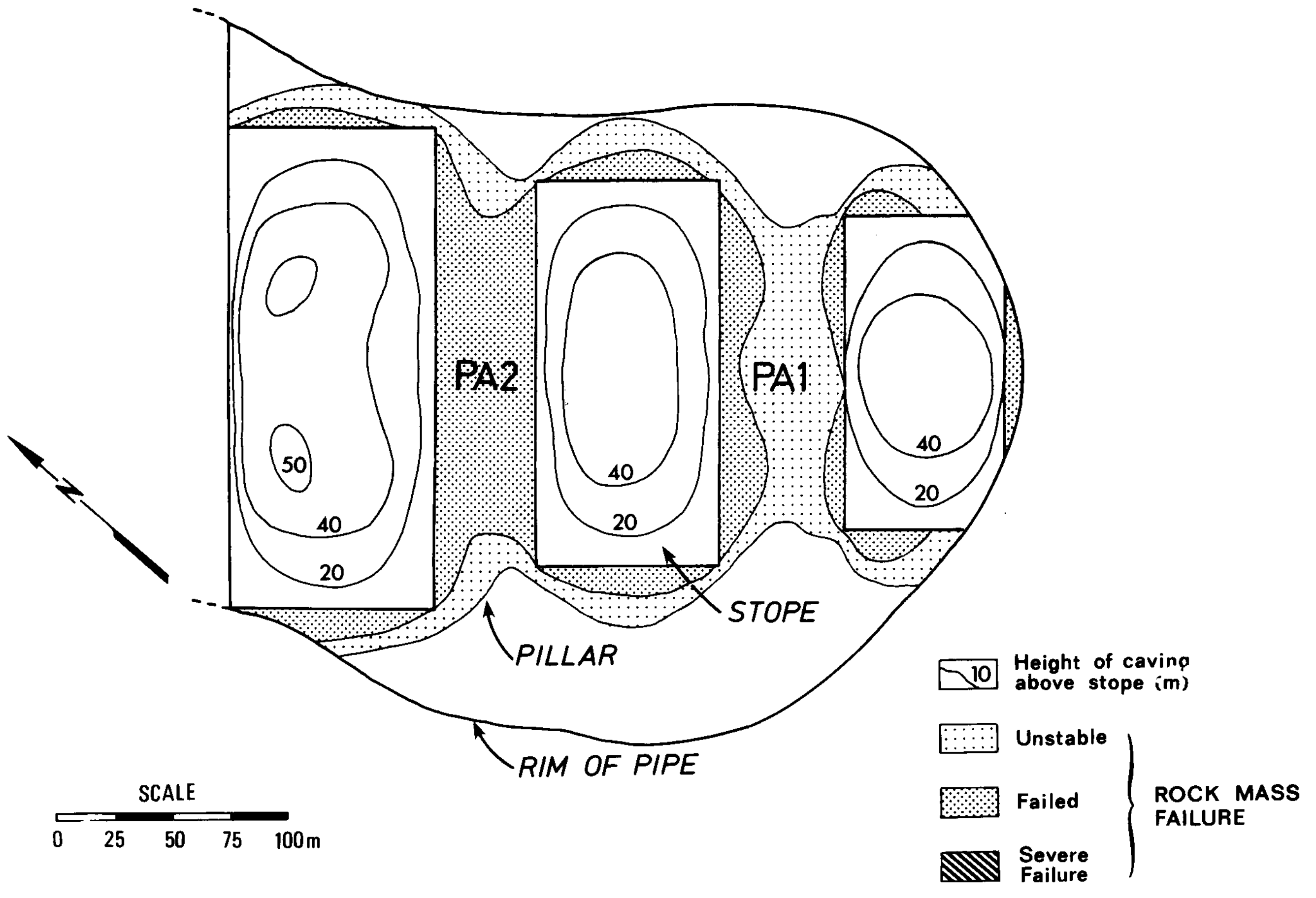


**Fig. 7—Plan showing the predicted failure of the rock mass and the height of caving above the stope roof**

is likely to fail as well. The degree of failure in the pillars would make drilling and blasting very difficult since the drillholes would not be expected to stay open for the required length of time. The stability of the drill drives passing through the failed rock mass questionable, and additional support would be required to maintain safe conditions.

The height of failure in the sill would extend up to 50 m above the top of the stopes, which would result in the open stopes being entirely filled with waste rock. This may have a stabilizing effect on the pillars but would make open stoping impossible.

These results clearly showed that successful recovery of the ore in the pillars would be unlikely.

*During Pillar Extraction*

A second alternative was the mining of the pillars as soon as possible, lagging behind the advancing stope faces by about 30 m. This sequence was aimed at preventing the deterioration of the pillars predicted by the previous model. The layout of the three-dimensional model set up for this analysis is shown in Fig. 8. Again, the stresses were calculated at selected points in the surrounding rock mass.

The results of the second model are shown in Fig. 9. The amount of severe failure in the pillars is now less, but the failure of the sill has increased owing to the larger spans involved.

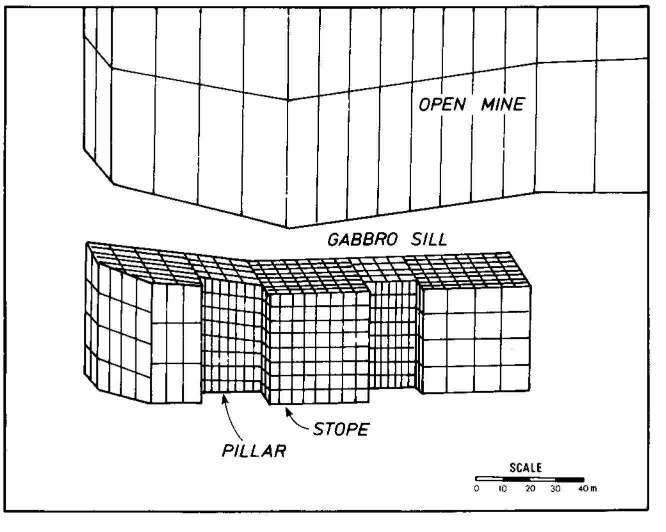


**Fig. 8—Three-dimensional model of stopes and pillars during pillar extraction**

## Conclusions

The investigation demonstrated that a combination of various numerical modelling techniques permits the analysis of complex problems that may otherwise be unsuitable for this approach. However, numerical models are meaningful only if the results can be presented in

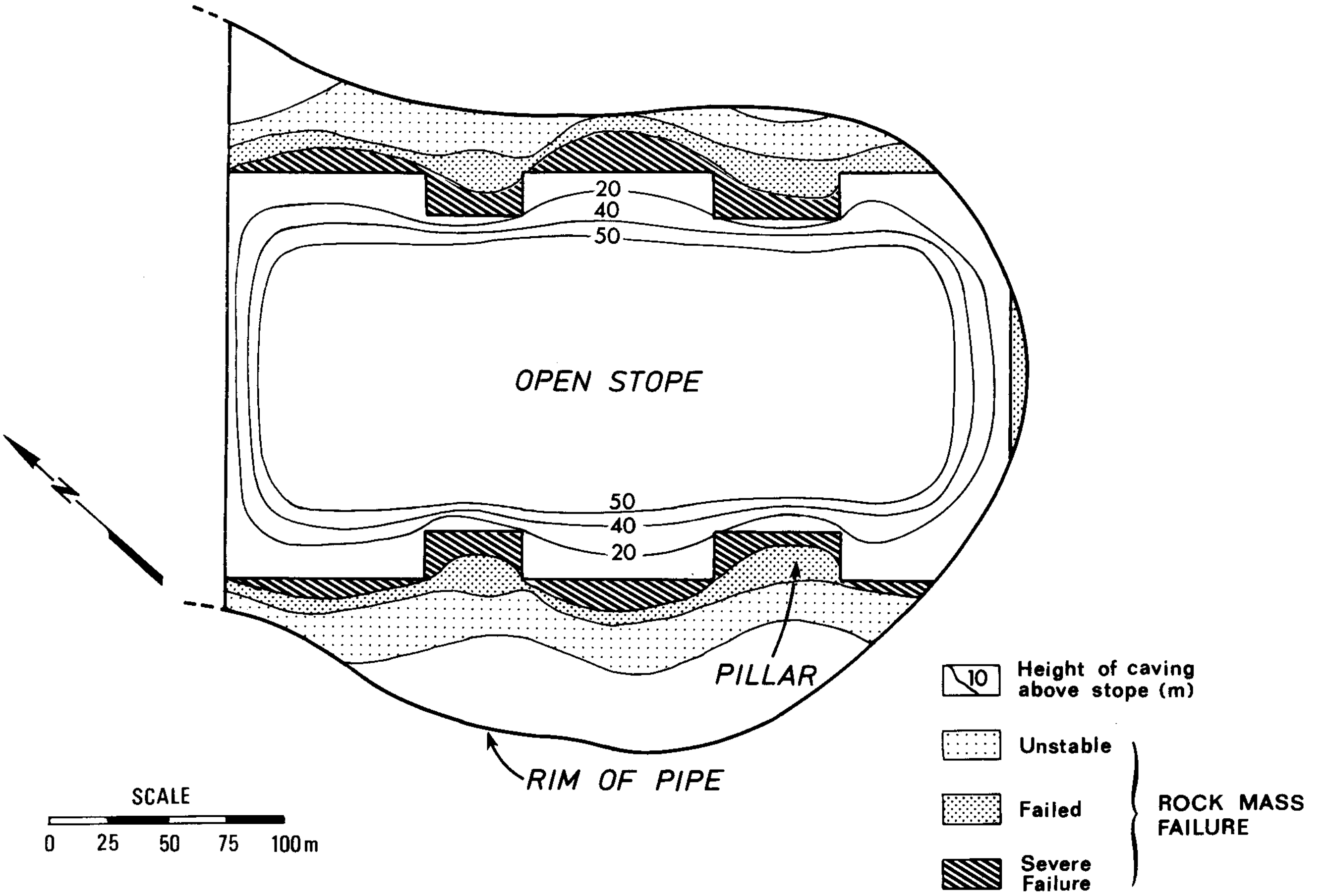


**Fig. 9—Plan showing the predicted failure of the rock mass and the height of caving above the stope roof with reduced lead between stopes and pillars**

terms of the actual performance of the excavations. In this respect, failure criteria are useful in the determination of the potential extent of failure, but do not indicate actual conditions in the excavations. This problem can be alleviated by the application of the back-analysis technique, in which a known situation is modelled as a reference case and the results are then applied to the evaluation of predictive models.


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## References


1. OWEN, K.C. Block caving at Premier Mine. *Design and operation of caving and sublevel stoping mines.* New York, Society of Mining Engineering, 1981.
2. MCMURRAY, S. Mining below the gabbro sill, Premier Mine, Cullinan, South Africa. *Underground mining methods handbook.* Hustrulid, J.W. (ed.). New York, Society of Mining Engineering, 1982.
3. DIERING, J.A.C. QUAD program documentation. Johannesburg, Gemcom (Pty) Ltd, internal report, 1983.
4. DIERING, J.A.C. User documentation for MBEM. Johannesburg, Gemcom (Pty) Ltd, internal report, 1984.
5. OZBAY, M.U., and LILLY, J.D. Investigation of the geological structure in portion of the main gabbro sill, Premier Mine, Cullinan, South Africa. Johannesburg, University of the Witwatersrand, 1980.

# Five stars for fifth time

Mineral Processes, Impala Platinum's metallurgical plant in Bophuthatswana, was awarded five stars under the International Safety Rating (ISR) System for the fifth consecutive time. The certificate was presented to the General Manager, Mr C.A. Roode, by the President of the Chamber of Mines, Mr E.P. Gush, on 22nd January, 1987.

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**Mr Carel Roode (centre) with Mr Peter Gush, President of the Chamber of Mines, (right) and Mr Carl Netscher, Chairman of Impala Platinum.**

# Chemical-reaction engineering

A five-day intensive course on the above subject will be held in Amsterdam from 1st to 5th June, 1987. The language to be used is English.

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