SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

Final Project Report

Title: RELIABLE COST EFFECTIVE TECHNIQUE FOR IN-SITU GROUND STRESS MEASUREMENTS IN DEEP GOLD MINES

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RELIABLE COST EFFECTIVE TECHNIQUE FOR IN-SITE GROUND STRESS MEASUREMENTS IN DEEP GOLD MINES

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EXECUTIVE SUMMARY

The proposed Primary Output of this research project, as indicated in the proposal, is the following:

- a literature survey of existing methods of in-situ stress measurement including an evaluation of the applicability of these methods in the deep level gold mines.
- a theoretical feasibility study of a potential method, which will be cost effective and practical, and applicable to the gold mine situation.

A review of the extensive literature on the subject of in situ stress measurement has been carried out, and a substantial bibliography is included in the report. The majority of methods of in situ stress measurement which are available were immediately rejected as being inapplicable for the deep gold mines. Several methods were identified as having potential applicability from a technical viewpoint and were dealt with in more detail. These methods are:

- borehole overcoring methods, including the CSIR doorstopper strain cell, the CSIR triaxial strain cell, and the CSIRO HI cell
- large diameter overcoring in a bored raise
- hydrofracturing
- back analysis from monitored deformations around excavations.

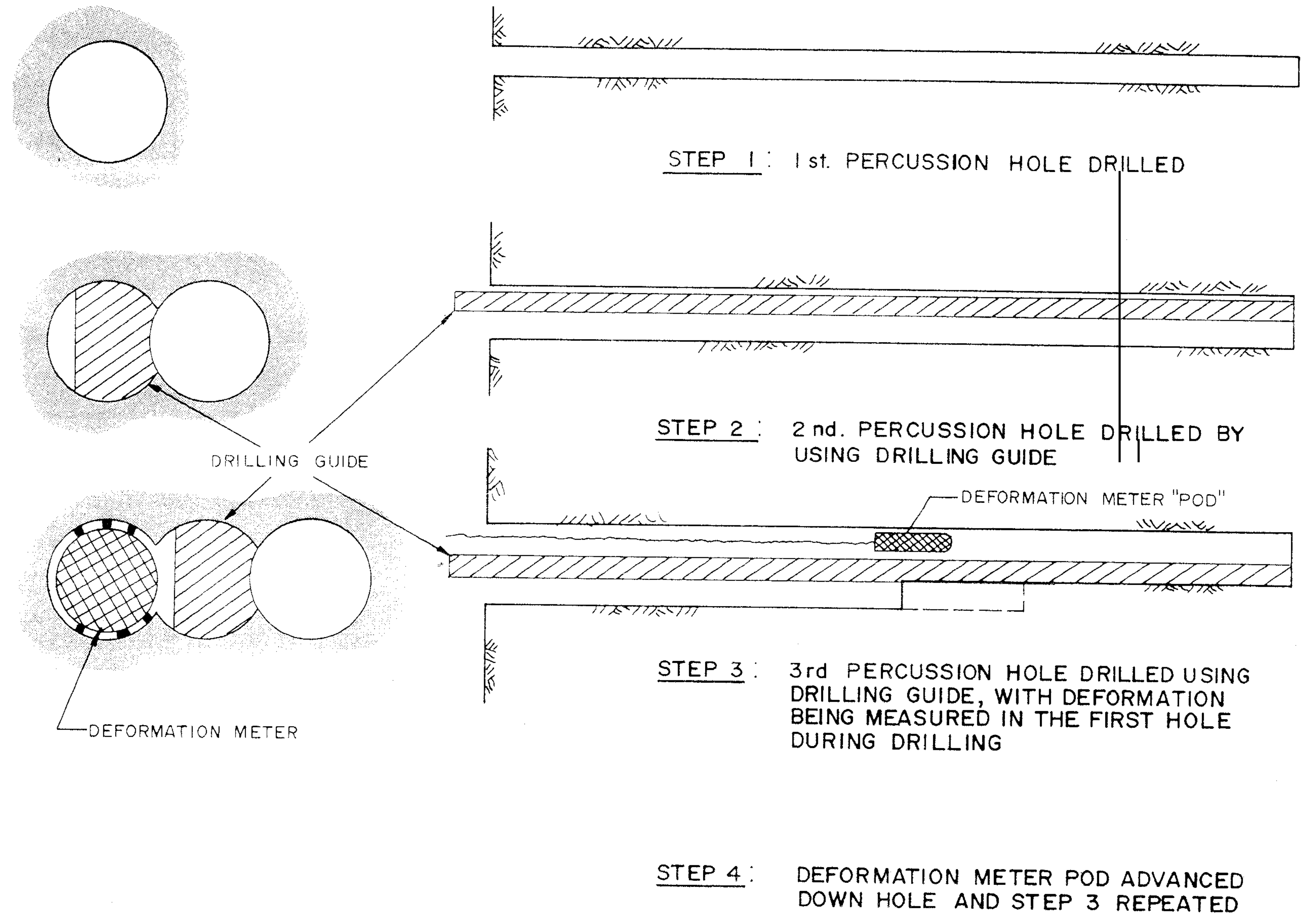
It is considered that the applicability of these methods in the deep gold mines is poor. Reasons for this include their cost, their requirement for significant assistance from mines in terms of services and personnel, and their reliability in general and under the harsh conditions in the mines. Only two of the approaches are considered to have limited application. These are a simplified hydrofracture test, in which only the magnitude of the minimum principal stress is determined, and back analysis from monitored deformations, when suitable excavations are made for other purposes and economic monitoring can be used.

Based on the review of the available methods of in situ stress measurement, and experience of involvement in stress measurement programmes using numerous techniques, the following have been identified as requirements for a reliable, cost effective technique for in situ stress measurement in deep gold mines:

- the technique must be undemanding on the requirement for services and personnel provided by the mine.
- the technique should be low cost with regard to all aspects - cost of preparation, cost of installation, cost of instrumentation, cost per measurement, and economical in terms of time requirements.
- the technique should allow many measurements to be made in a single mining shift. This will allow the results to be treated statistically and therefore avoid localised effects.
- the technique should not be sensitive to high stress effects such as spalling and microcracking of the rock.
- the technique should be flexible. It should be possible to implement at very short notice, require a minimum of preparation, be possible to apply in excavations of limited size and non-restrictive location.
- the technique should preferably not require the retrieval of rock cores and laboratory testing to determine the deformation properties of the rock or rock mass.

Based on these requirements, an in situ stress measurement technique which will be practically applicable in the deep gold mines, has been developed conceptually. Referring to the figure on the following page, this method involves:

- a borehole-based system, using percussion boreholes drilled with a conventional jackhammer
- creating the enlargement, or stress/strain change, not by overcoring, but by drilling parallel, overlapping holes
- control of the direction of adjacent holes, and prevention of movement of drill chips into the measuring hole, by means of a special borehole guide
- measurement of deformation changes in the first borehole, as a result of the drilling of the third borehole, by means of a borehole deformation meter
- sequential deformation change measurements down the length of the borehole, alternately moving the deformation meter and advancing the third borehole
- measurements carried out in three different borehole orientations at each site to provide sufficient data for the complete state of stress to be determined
- calculation of the in situ stress field by back analysis of monitored deformations using an appropriate numerical stress analysis program.
- optimisation of results making use of the redundancy in number of data.



JOB Nº 213413	CONCEPTUAL METHOD OF IN SITU STRESS MEASUREMENT APPLICABLE TO DEEP GOLD MINES

The theoretical feasibility of the method has been proved by carrying out two- and three-dimensional stress analyses. These showed that:

- deformations induced around the first borehole by the drilling of the third borehole are of sufficient magnitude to measure easily
- the effect on the deformations of failure around the boreholes due to overstress is probably less than the variations due to experimental errors and local rock material variations
- approximately 5 measurements per metre length of borehole can be carried out.

It is concluded that a method of in situ stress measurement, based on the percussion drilling of a set of three overlapping boreholes, and back analysing the in situ stresses from the measured deformations in the boreholes, has been developed in concept. By its very nature, being based on low cost drilling and deformation measuring operations, whose application is very flexible, the method will be cost effective. In concept, the method overcomes the disadvantages of most of the available methods of in situ stress measurement, and therefore should be reliable. It is also aimed at being specifically applicable under the conditions which occur in deep mines, and its feasibility has been proved theoretically.

In the SIMRAC proposal document it is stated that the primary output of the research project would be at feasibility level, and that further development would be required for the technique to be developed for routine use. It is recommended that this development should proceed, and several aspects are identified as needing development to ensure that the method can be applied practically:

- the development of a suitable drilling guide which can cope with variation in the straightness of the holes, some variation in the diameter of the holes, and "wedging" due to some closure of the holes, impact of the drill and packing of the drill chippings.
- development of a suitable deformation meter.
- development of the standard back analysis procedure. The approach, and an appropriate simple stress analysis program, need to be adapted for the specific in situ stress measurement application.

1 INTRODUCTION

Knowledge of the in situ state of stress in a rock mass is essential for the proper planning and design of mine layouts to optimise stability and safety of mining operations. The in situ stresses are essential boundary conditions for all design and analysis methods making use of stress analysis, and the use of incorrect boundary conditions will provide invalid design results which could be significant with regard to stability and safety.

The in situ state of stress in a rock mass can be determined by direct measurement, and there are numerous methods of measurement which are currently in use. A review of some of these methods is included in the following section. Although some measurements of in situ stress were carried out prior to 1950, significant research into methods of in situ stress measurement began in the 1950's and has continued to the present time. In South Africa, research in the 1950's and early 1960's led to the development of borehole strain cells for the measurement of both two- and three-dimensional states of stress. This work was completed in mid-1960, and at that stage South African expertise was probably the best available in the world. It is interesting to note that Leeman (1965), referring to some minor outstanding instrumentation problems, concluded, "Once this is achieved it can be said that the problem of measuring the stress in rock is, to all intents and purposes, 'licked'!" The requirement for the present research project clearly disputes this statement.

It is unfortunate that no significant research in the field of in situ stress measurements has been carried out in South Africa since that time, in spite of the fact that, in the past 30 years, mining has progressed to much greater depths, where stress conditions are even more critical. The consequence of this is that, whereas South Africa was a leader in the 1960's and 1970's, today most in situ stress measurements carried out internationally make use of non-South African technology. A further consequence is that techniques that are appropriate for the very high stress conditions in our deep level mines have not been developed.

This is some of the background to the present SIMRAC research project, the title of which is "Reliable cost effective technique for in-situ ground stress measurements in deep gold mines". A copy of the research proposal is contained in Appendix A for record purposes. The proposed Primary Output, as indicated in the proposal, is as follows:

i) a literature survey of existing methods of in-situ stress measurement including an evaluation of the applicability of these methods in the deep level gold mines.

ii) a theoretical feasibility study of a potential method, which will be cost effective and practical, and applicable to the gold mine situation.

More specifically, the output from the research project will include the following:

- a review of existing methods of in situ stress measurement
- identification of those methods which are possibly more appropriate in South African gold mines
- assessment of the applicablity of these more appropriate methods, and identification of the advantages and disadvantages of each method
- definition of the requirements, both theoretical and practical, for in situ stress measurements in deep level mines
- based on these requirements, conceptual development of a reliable and cost-effective method of in situ stress measurement

2 REVIEW OF METHODS OF IN SITU STRESS MEASUREMENT

Significant reviews of methods of in situ rock stress measurement have been carried out previously by Leeman (1964a), Leeman (1964b), Obert (1967), and Leeman (1969a). A repetition of these exhaustive reviews of the literature is not considered to be appropriate for this SIMRAC research project. An extensive, but not exhaustive, bibliography of literature on in situ stress measurements is included in this report.

It is also not considered necessary to include details of stress-strain relationships and equations involved in the various methods of in situ stress measurement, since these are readily available in documents which will be referred to in the text. Instead, information from the previous reviews will be summarised, and particular attention will be paid to relevant methods which have been developed since the reviews were carried out.

Most of the methods of in situ stress measurement involve the observation of a change in deformation or stress resulting from a change in the geometry of an opening in the rock, and the subsequent calculation of the field stresses from those measured changes. Most of the methods are associated with boreholes as the "opening" in the rock mass.

2.1 Borehole-based methods of in situ stress measurement

With regard to measurement of changes in boreholes, there are methods which measure borehole deformation, borehole strain, borehole surface strain, and stress change.

2.1.1 Borehole deformation and strain

This group of methods is probably the most common type, and there is a variety of different methods based on the concept. In all of the methods, deformations or strains are measured, and stresses are calculated from these measured values by means of elastic theory. In all cases the closed form theoretical solution relating the elastic stresses and strains around the borehole or borehole end is known.

2.1.1.1 Measurement of borehole deformation

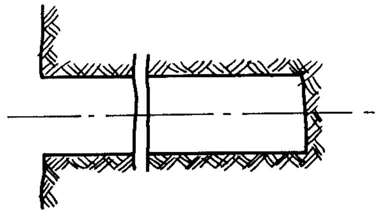
Borehole deformation meter

This instrument measures the change in diameter, at several several angular orientations, of the borehole as a result of the overcoring, and hence destressing, of the borehole. The practical procedure is as follows. A borehole is diamond core drilled, at overcore size, to the required depth so that it is at a sufficient distance to be out of the stress concentrating influence of the excavation from which the hole is drilled. A smaller diameter pilot hole, coaxial with the initial hole, is then drilled into the end of the initial hole, and the deformation meter is placed in this pilot hole. The meter is then overcored, with changes in deformation of the borehole being measured during the overcoring process. The overcore is subsequently tested in the laboratory to determine its deformation properties, and the in situ stresses are calculated from the overcore deformation values using elastic theory. The application of the method is illustrated in Figure 1.

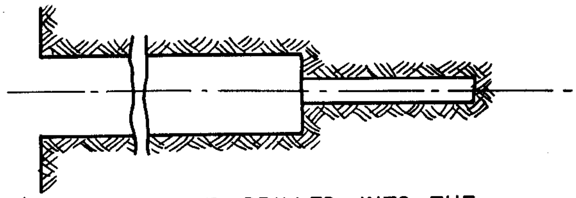
In a single hole the secondary principal stresses acting in a plane normal to the borehole axis may be determined. To determine the complete state of stress in the rock mass, measurements must be made in three differently orientated boreholes. Bonnechere and Cornet, 1977, describe a borehole deformation meter with the capability of measuring deformation change in the axial direction. Such an instrument can be used to determine the complete state of stress in a single borehole.

The most commonly used borehole deformation meter is the United States Bureau of Mines (USBM) deformation meter (Obert et al, 1962, Hooker et al, 1974)). The hole in which the instrument is installed is an EX hole (approximately 38 mm diameter), and the overcore typically has a diameter of 150 mm.

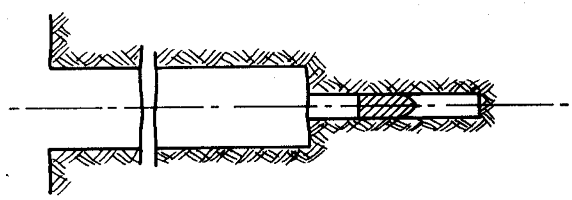
Application of the method requires high quality diamond core drilling, with associated equipment, facilities and sevices, using large diameter (150 mm) bits, and a special device for centring of the pilot hole. Success with the method is also dependent on good quality rock such that intact overcores at least 300 mm long can be obtained. The deformation meter can be used in wet conditions if it has been waterproofed. Since elastic theory is used for the calculation of the in situ stresses from the measured deformations, it is important that no failure of the rock occurs around the borehole which might lead to non-elastic behaviour.



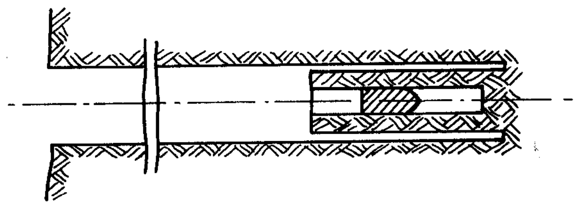
a) BOREHOLE DRILLED TO THE DEPTH AT WHICH THE STRESS IS TO BE DETERMINED



b) PILOT BOREHOLE DRILLED INTO THE END OF THE BOREHOLE



c) DEFORMATION METER PLACED IN THE PILOT BOREHOLE



d) PILOT BOREHOLE OVERCORED AND STRAIN RELIEF MONITORED

JOB Nº		FIG. Nº
213413	APPLICATION OF BOREHOLE DEFORMATION METER	1

Solid inclusion gauges

A solid inclusion gauge, which contain wire resistance strain gauges to measure deformation across the axis of the borehole, has been developed by Blackwood (1977). The geometry of the strain gauges in this cell is shown in Figure 2.

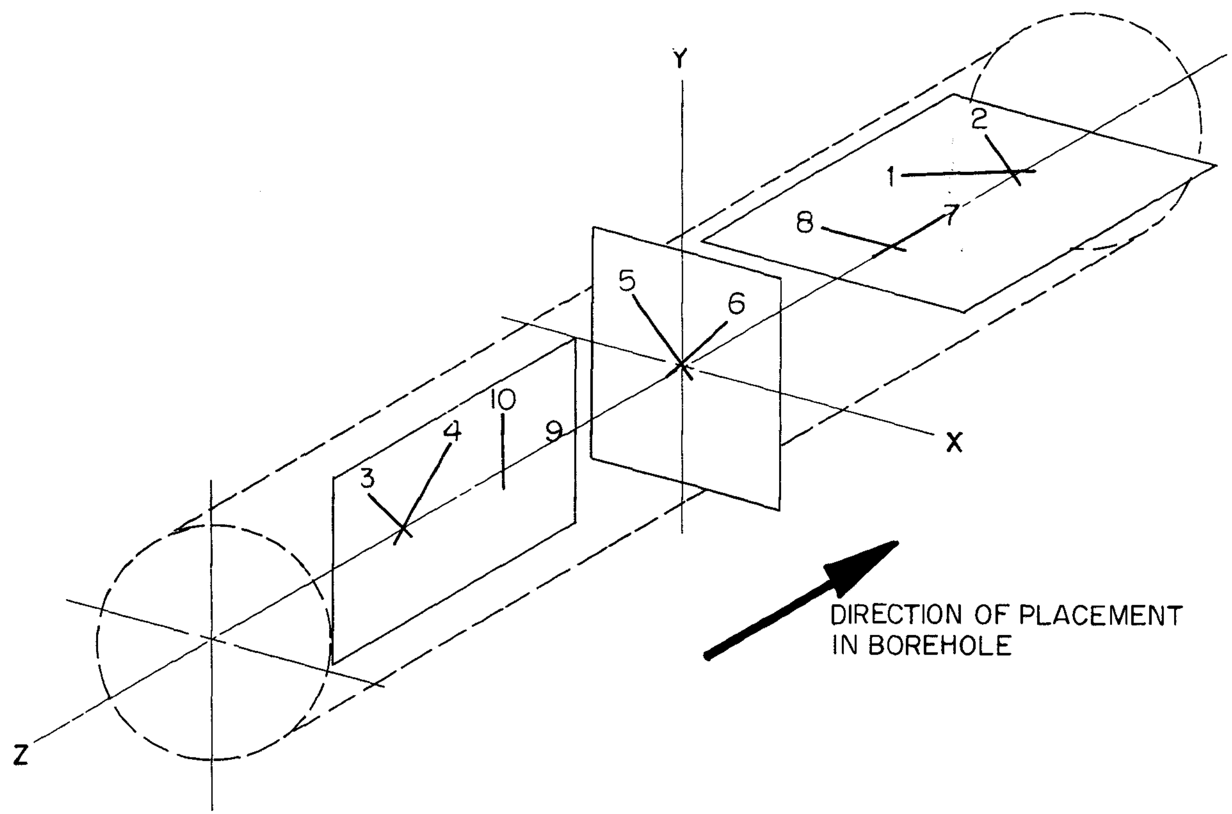
The application is similar to the borehole deformation meter, but the solid inclusion unit is bonded into the pilot hole. The tolerance between the borehole and the outer diameter of the cell is important. After installation, the cell is overcored, with strain changes being monitored during overcoring.

Since there are sufficient strain relief components measured, the method allows the complete state of stress to be determined in a single borehole.

As with the deformation meter, diamond drilling equipment is a requirement. The bonding between the cell and the rock is critical, as was found by Rocha and Silverio (1969), and problems in this area led to the design of a new cell by LNEC. It is likely that this type of problem would be present in high stress conditions in which rock failure may occur and differential deformations would be significant.

2.1.1.2 Strain measurement on the borehole end

In this method strain is measured by strain gauges bonded directly onto the rock forming the end of the borehole. The most common method of this type is the CSIR Doorstopper strain cell (Leeman 1964c, Leeman 1969b). This method is illustrated in Figure 3. A BX sized borehole is diamond drilled to a depth which is beyond the influence of the excavation from which the hole is drilled. The end of the borehole is then flattened with a special diamond flattening crown, cleaned, and the "doorstopper" cell, which houses a 4 element wire resistance strain gauge rosette, is bonded onto this surface. Initial strain readings are taken, and the cell is then overcored to produce a short length of core stub. Strain readings give the strain relief due to the overcoring, and the corresponding in situ stresses are calculated using elastic theory.



JOB Nº 213413

SOLID INCLUSION GAUGE (AFTER BLACKWOOD, 1977)

FIG. Nº 2

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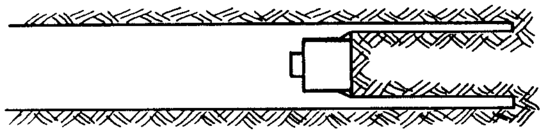
a) BX BOREHOLE DRILLED TO THE REQUIRED DEPTH AND END FLATTENED AND POLISHED WITH DIAMOND TOOLS

b) STRAIN CELL BONDED ON TO END OF BOREHOLE AND STRAIN READINGS RECORDED



c) BOREHOLE EXTENDED WITH BX DIAMOND CORING CROWN THEREBY STRESS RELIEVING THE CORE

d) BX CORE, WITH STRAIN CELL ATTACHED, REMOVED AND STRAIN READINGS TAKEN

JOB Nº		FIG. Nº
213413	CSIR DOORSTOPPER STRAIN CELL SYSTEM	3

CSIR triaxial Strain Cell/CSIRO HI Cell

These two approaches are considered together since they are the same in principle, the differences being in the structure of the cell and in the detail of their practical implementation. The former approach was developed in South Africa (Leeman and Hayes 1966, Leeman 1969b, van Heerden 1976) and the latter in Australia (Worotnicki and Walton 1976).

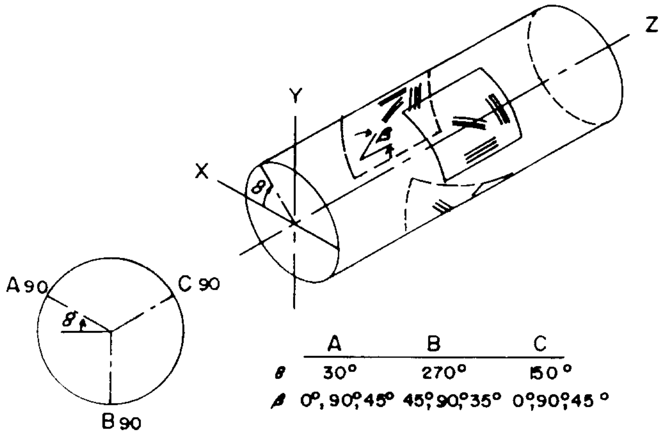
The preparation for measurements using these methods is very similar to that for the borehole deformation meter, and the steps in making a measurement are summarised in Figure 4. The walls of the pilot hole must be thoroughly cleaned since the strain gauges are bonded to these surfaces. The cells include three wire resistance strain gauge rosettes, consisting of 3 or 4 elements each, which are located at specific angles around the borehole circumference, as illustrated in Figure 4.

Once the gauges are bonded and initial strain readings recorded, the cell is overcored. With the CSIRO cell, strain readings are recorded during the progress of the overcoring. In situ stresses are calculated from the measured strain reliefs using elastic theory. The complete state of stress in the rock is determined by the single measurement.

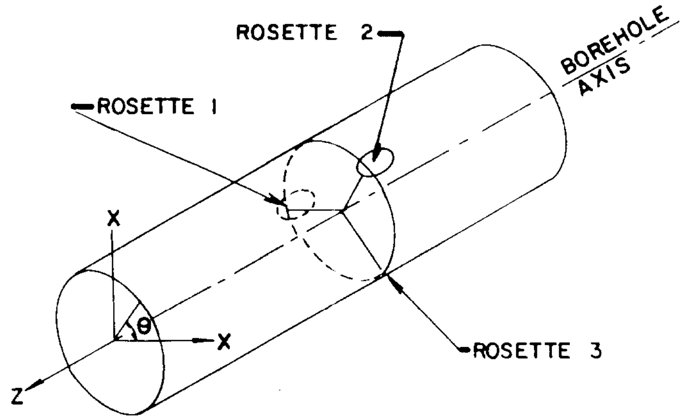
The method requires the same drilling facilities as the borehole deformation meter. In good rock conditions it is possible to use a smaller diameter overcore such as an NXCU or even an NXC size.

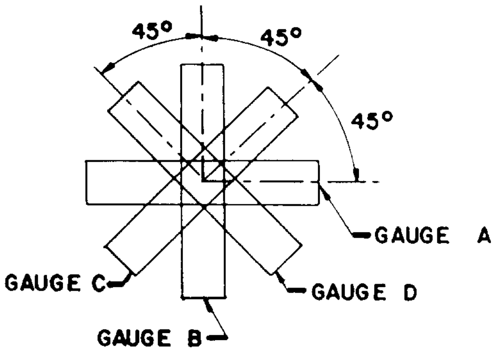
Amongst the many practical factors necessary, successful measurements are dependent on obtaining a sufficient length of intact overcore. It has been found that this is difficult to obtain under high stress conditions when discing of core may occur (Worotnicki 1993) or dog earing may be incipient or present on the walls of the borehole.

It is very unlikely that more than one measurement will be obtained in a single borehole in one mining shift.

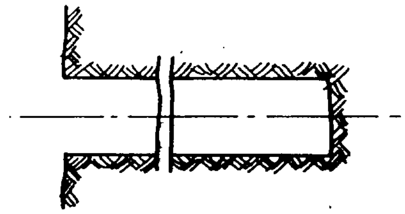


STRAIN GAUGES IN THE CSIRO HI CELL

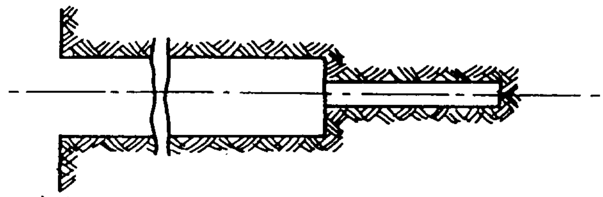




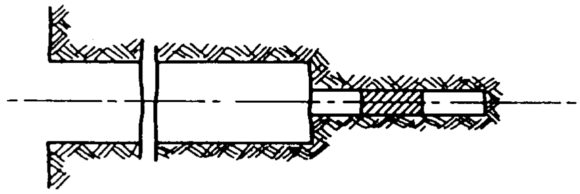
STRAIN GAUGES IN THE CSIR CELL



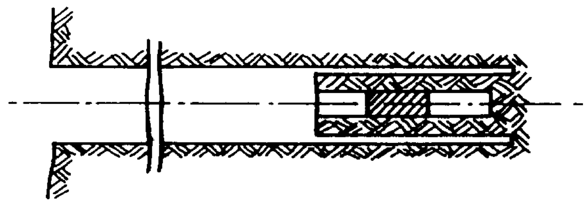
a) BOREHOLE DRILLED TO THE DEPTH AT WHICH THE STRESS IS TO BE DETERMINED



b) EX BOREHOLE DRILLED INTO THE END OF THE BOREHOLE



c) STRAIN CELL GLUED IN THE EX PORTION OF THE BOREHOLE AND STRAIN READINGS TAKEN



d) EX PORTION OF THE BOREHOLE OVERCORED AND STRAIN RELIEF MEASURED

JOB Nº		FIG Nº
213413	CSIR AND CSIRO TRAXIAL STRAIN CELL SYSTEM OF IN SITU STRESS MEASUREMENT	4

Bored raise rosette overcoring

This method is essentially the application of the CSIR or CSIRO triaxial cell approach, but on a large scale (Brady et al 1976, Chandler 1993). It requires the presence of a bored raise or tunnel, that is, a circular opening with smooth surfaces, which is effectively a very large diameter borehole.

The rosettes are of long gauge length, which can be 200 to 300 mm, and are located at three angles around the periphery of the circular excavation. In the original application (Brady et al, 1976) the rosettes consisted of sets of pins into the rock, with the distance between the pins being measured using a mechanical gauge. In the more recent application (Chandler, 1993), wire resistance strain gauges with a gauge length of 120 mm were bonded to the rock surface.

The individual rosettes are overcored using a large diameter coring bit and the resulting strain relief measured. In the original application a 360 mm diameter thin walled bit was used for overcoring. To provide additional data, and a check on results, pins can be installed on a larger diameter, outside the overcore diameter. They will then be undercored, but will also reflect the strain relief.

The in situ stress is calculated from the strain relief measurements using elastic theory, and the complete state of stress in the rock is yielded.

The method requires special drilling equipment and the availablity of a bored raise, and would be a costly method to apply in the gold mines. It is therefore unsuitable as a routine application method. It has the advantage, however, of taking into account a large volume of rock. Surfaces of the bore can be inspected to select suitable locations for the rosettes, and the effect of local material and structural variation can be avoided.

Interfels Borehole Slotter

In this system, the stress and strain relief is created by cutting a slot in the wall of the borehole (Bock and Foruria 1983, Bock 1986). The strain relief adjacent to this slot is measured during the slotting process. The method is illustrated in Figure 5.

Measurements from three slots are required to enable the calculation of the secondary principal in situ stresses in a plane normal to the axis of the borehole. To obtain the complete state of stress in the rock, slotter measurements need to be carried out in boreholes drilled in three different orientations.

The method is attractive from a practical point of view in that many slots can be cut during a mining shift, and many slots can be cut in a single borehole. Typically 20 to 30 slots can be cut in hard rock during a shift, which corresponds with the equivalent of about 8 doorstopper measurements. The method requires a diamond core drilled hole with a diameter of between 95 and 103 mm. The holes need to be drilled carefully to ensure that they are straight, since the equipment "pod" inserted into the hole is 1,3 m in length. Holes for measurements may be pre-drilled, and the presence of a coring machine during the measurement process is not necessary. There is no requirement for overcoring. The presence of water is not detrimental to a measurement unless it is of sufficient volume to interfere mechanically, in terms of flow forces, with the equipment and measuring strain gauge.

Since the measurement of strain relief is by means of a mechanical contact strain gauge, the condition of the rock on the wall of the borehole is critical to a good result. Cracking or spalling, which might occur under high stress conditions, will have an adverse effect on the measurement and could invalidate the result. The method can be successful in significantly jointed rocks in which other strain relief methods will probably be unsuccessful.

2.1.2 Borehole inclusion stressmeters

As with the strain instruments dealt with above, borehole stress meters depend on the deformation of the borehole as a result of an overcore to obtain the result. A strain cell is a "soft" instrument which deforms with the rock and offers no effective resistance to this deformation. A stress meter is a "rigid" instrument which provides considerable resistance to the deformation of the borehole. As a result of this

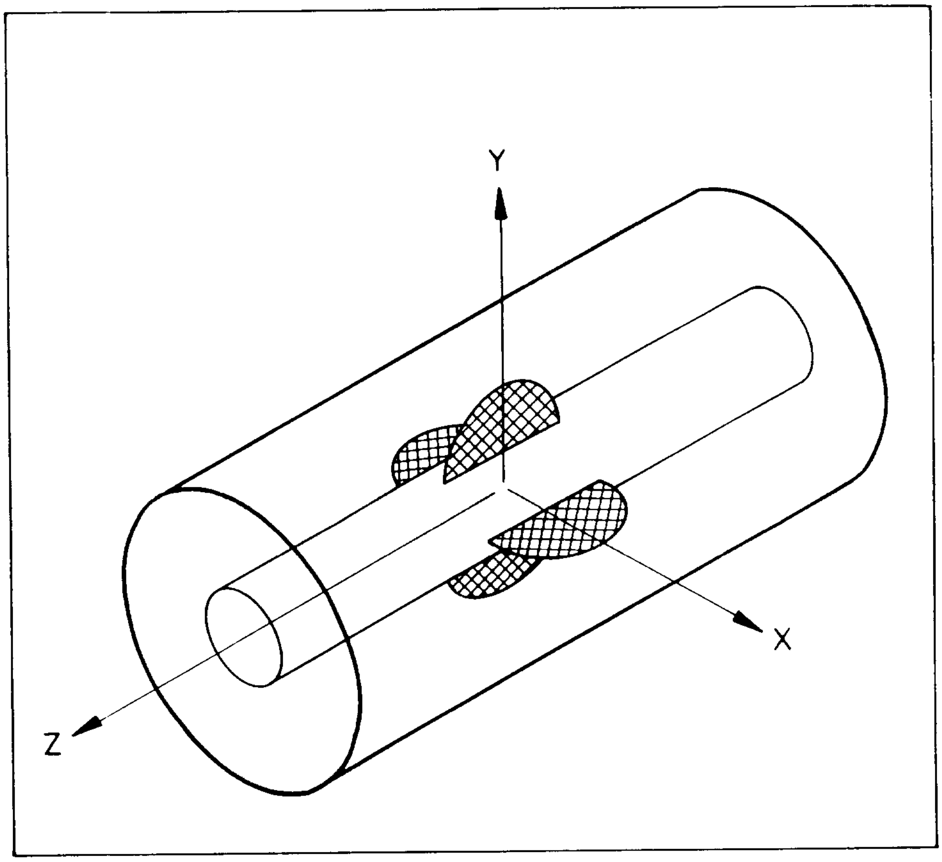
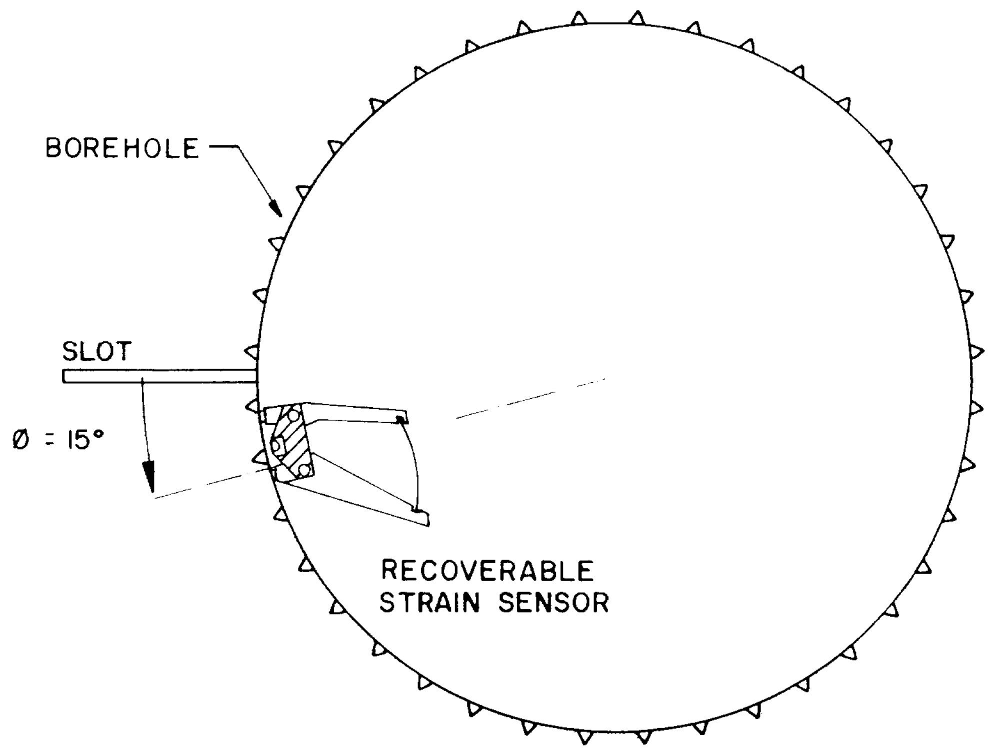


ILLUSTRATION OF SLOTS CUT INTO THE SIDE OF A BOREHOLE



SECTION THROUGH A SLOT, SHOWING THE STRAIN MEASUREMENT DEVICE

JOB Nº		FIG. Nº
213413	INTERFELS BOREHOLE SLOTTER SYSTEM OF IN SITU STRESS MEASUREMENT	5

STA-DRAFT

resistance a stress is induced in the instrument which gives a measure of the stress in the rock.

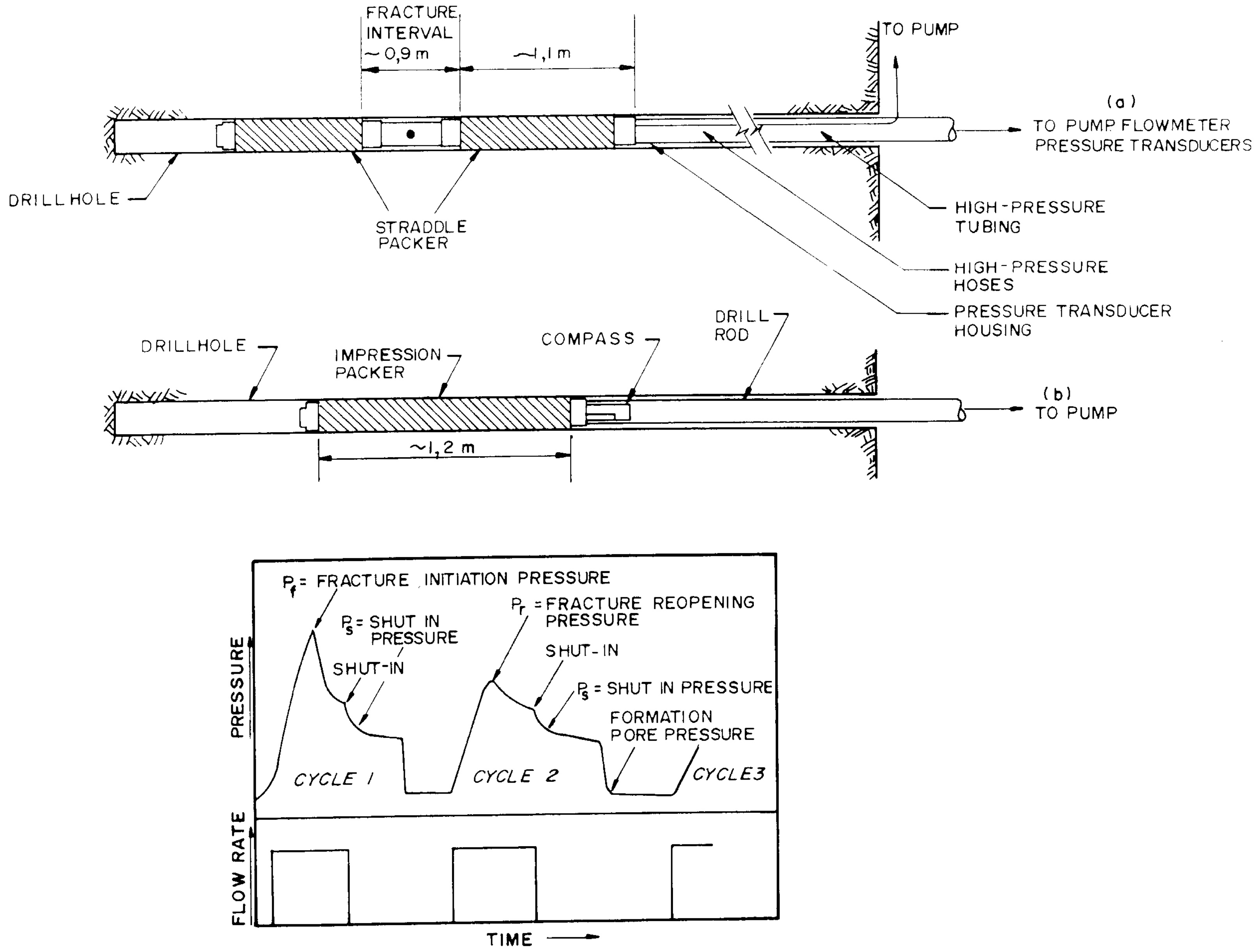
Since borehole stress meter instruments deform differently from the actual rock, they have to be calibrated before use. If the effective modulus of elasticity of the instrument is greater than five times the modulus of the rock, it is not necesary to know the modulus of the rock accurately. The stressmeter can be calibrated in material having a modulus approximately the same as the rock. If the effective modulus is similar to that of the rock, the calibration becomes very sensitive to variations in the rock modulus, and the accuracy of results suffers.

For these reasons it is unlikely that stress meters would be successful in the high modulus quartzites occurring in gold mines. They have not been widely used for in situ absolute stress measurement in rock, but appear to have greater application for the measurement of stress changes.

2.1.3 Hydraulic fracturing method

Hydraulic fracturing, as a method of in situ stress measurement, is relatively new. In his detailed consideration of methods of in situ stress measurement (Leeman 1964b, 1964c, 1964d), and his detailed literature review (Leeman, 1969b), Leeman made no mention of the hydraulic fracturing method. It appears that Fairhurst (1964) was the first to suggest the method for in situ stress measurement, and early research in the field was carried out by Haimson (1968) and Von Schoenfeldt (1970). Hydraulic fracturing is now the best known method for assessing in situ stress at great depth and is in common use (Haimson, 1993). It is the one stress measurement method that gives a direct output of stress without the need for calibration or calculation of stress from measured strain using appropriate stress-strain theory.

In the method, fluid pressure is applied to a test section of a borehole isolated by borehole packers in a series of pressurisation cycles. This is illustrated in the sketches in Figure 6. The pressures which are required to generate, propagate, sustain, and reopen fractures in the test section are related to the in situ stress field.



JOB Nº		FIG. Nº
213413	HYDRAULIC FRACTURING METHOD OF IN SITU STRESS MEASUREMENT	6

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In particular, when the induced fracture is sub-parallel to the borehole axis, the minimum principal stress is equal to the measured shut-in pressure (see Figure 6).

A significant amount of equipment is required to carry out a full scale hydrofracture test, including the following: inspection equipment in the form of a borehole television camera or an impression packer system, which is required to observe the orientation of the induced fracture; a double packer system with sufficient capacity to cater for pressures corresponding with the in situ stresses; a high pressure pumping system and associated rods, tubes and fluid reservoir; measurement equipment including fluid pressure transducers, pressure gauges for the packer inflation, fluid flow meter and chart recorder or equivalent.

Core drilling is preferable, but not essential, particularly if borehole television inspection equipment is available.

Figure 6 illustrates idealised hydraulic fracturing pressure records. Often, results are not distinct, and considerable interpretation and experience is required to determine a representative shut-in pressure (Guo et al 1993a).

To be able to interpret the orientations of the in situ principal stresses, it is necessary that the borehole is drilled in the direction of one of the principal stresses. This is considered to be a disadvantage for application in the gold mines in that the orientations of the principal stresses are not known, and their determination is one of the aims of the in situ stress measurement. However, if the induced fracture is propagated sufficiently to ensure that it is in the plane normal to the minimum stress, then the shut-in pressure should give an accurate measure of the minimum principal stress. The method, in a simplified form, is widely used for this purpose in civil engineering projects involving pressure tunnels and shafts (Vik and Tunbridge 1986, de Witt 1992). In these cases the minimum principal stress, or the ability of the rock mass to contain the water pressure in the tunnel or shaft, is the important factor. A similar simplified test was used by Ortlepp and Bristow (1990) to determine the minimum principal stress in three different mining environments. The simplified test involved grouting a high pressure steel tube into the borehole, the end of the borehole being pressurised by pumping in the fluid through the steel tube.

Only the hydraulic pressure is monitored. The necessary amount of equipment and instrumentation is therefore substantially reduced and the test can be carried out in a percussion hole.

A variation on the standard hydraulic fracturing method is the HTPF method (hydraulic tests on pre-existing fractures) described by Cornet and Valette (1984), Cornet (1986) and Cornet (1993). As the name indicates, tests are carried out on clearly identified individual pre-existing joint planes. The section of borehole containg this plane is packed off and hydraulically pressurised to reopen the joint plane. The pressure at which this occurs is the stress acting normal to that plane. Additional tests are required across different planes of different orientations to provide sufficient data to determine the complete state of stress in the rock. Cornet (1986) indicates that a minimum of 15 tests is necessary for this. This implies that the method would be very time consuming as well as requiring a significant amount of quality drilling. Visual observation of the joint planes, by means of a television camera, is almost essential to determine the orientations of the planes.

2.1.4 Other borehole methods

The literature contains a large number of papers dealing with different types of strain and stress cells, and many of these are referenced in the bibliography to this report. They deal with different geometries of cells, different types of strain gauges, different installation techniques, etc. Many of them are described in theoretical or prototype form, and have never been applied in real in situ stress measurement situations. They may all be considered as variations of the methods which have been described above. The methods described above are those that have been proved in practice and are most widely used. Their advantages, disadvantages, merits and shortcomings are therefore representative of what is currently available in the field of in situ stress measurement using boreholes, and this will form the basis of an assessment of their applicability in the deep level gold mines.

2.2 The flat jack stress measurement technique

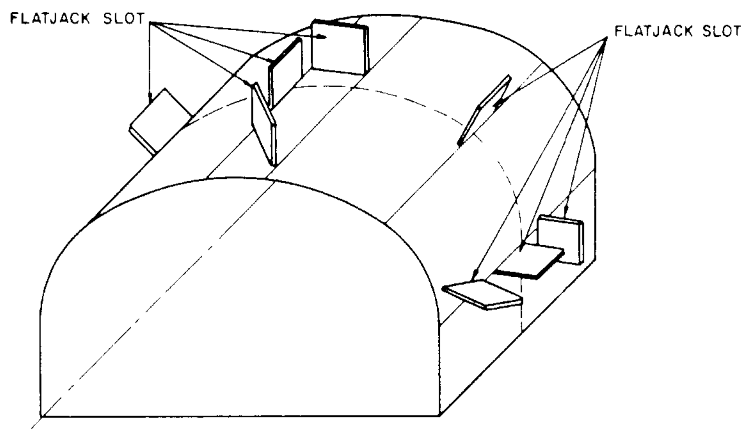
This method is one of the oldest methods of stress measurement and was developed in France (Tincelin 1952, Habib and Marchand 1952). The method involves the cutting of a small slot into the surface of an excavation, with the deformation of the rock adjacent to the slot, as a result of the cutting of the slot, being monitored. The geometry of the method is shown in Figure 7. Two or more pins are inserted into the rock on either side of the slot and are used as the measurement points. After the slot has been cut a small flat jack is grouted into the slot and then pressurised, with the pin separation again being monitored. When the separation is the same as existed before the slot was cut, the magnitude of the pressure represents the in-situ stress magnitude in the excavation wall at that location normal to the plane of the slot.

The method requires special jigs to set up the geometry for mounting the pins and the location of the slot. A special saw is required for cutting the slot. Alternatively it is possible that a series of overlapping holes can be drilled to produce the slot. Grout of similar strength to that of the rock is required. Separations between the pins are measured by means of a removable mechanical or electrical strain gauge.

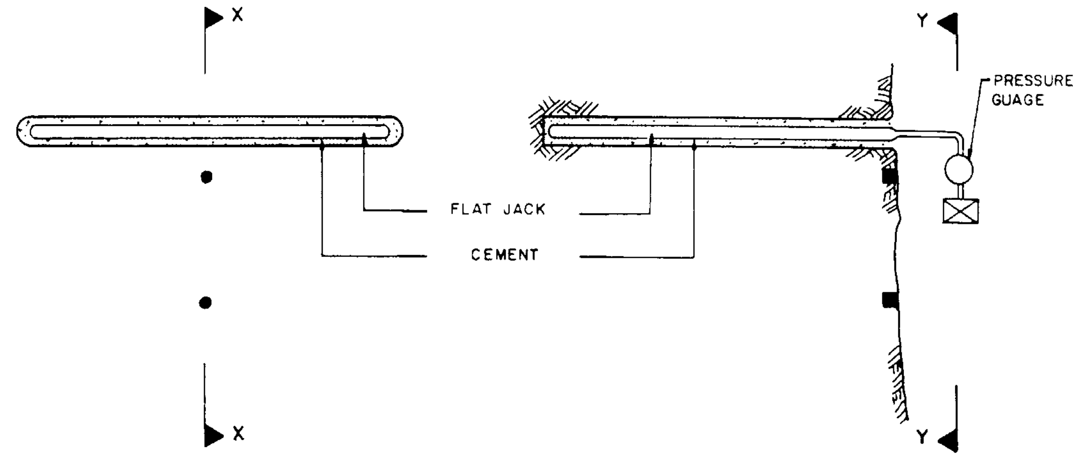
The method provides a direct measure of the stress acting in the skin of the excavation. Each flat jack yields one component of this stress. To obtain the complete state of stress, at least 6 flat jack tests, but preferably more, must be carried out at different orientations, as shown in Figure 7. This stress field is the disturbed stress field around the excavation. To determine the virgin in situ stress, the stress field around the excavation has to be extrapolated by application of the theory of elasticity or by use of numerical modelling techniques.

It will be clear that, for the method to be applied successfully, the rock quality on the surface of the excavation must be in very good, unfractured and unbroken condition. With regard to the deep level gold mines this is considered to be a major disadvantage, and it is unlikely that flat jack tests will have any chance of success under these conditions.

A variation on the use of flat jacks is the use of curved jacks that can be installed in boreholes (Jaeger and Cook, 1963; Bowling, 1976). These do not appear to have been commonly used.



EXAMPLE OF THE LAYOUT OF SLOTS FOR FLAT JACK TESTS



SECTIONS THROUGH INSTALLED FLAT JACKS

JOB Nº		FIG. Nº
213413	FLAT JACK METHOD OF IN SITU STRESS MEASUREMENT	7

2.3 Back analysis of in situ stresses from field measurements

Back analysis is a technique which has been developing over the past 20 years, and has been made feasible by the availability of computers and numerical stress analysis techniques. Kavanagh (1973) appears to have been the first to use the technique, and Kirsten (1976b) was the first to apply it in the rock mechanics field for determination of rock mass deformation properties. The principle of the method is that the in situ stresses and the deformation characteristics of the rock mass interact and thus, when an opening is created, the resulting deformation or stress changes can be used to back-calculate the stresses and deformation properties.

The method makes use of the measured response of the rock mass, by means of installed instruments, as a result of an adjacent excavation or step in excavation excavation. For example, this could be produced by the advance of a tunnel, the excavation of a chamber in stages, or the advance of a stope face. The meaurements that could be used are displacements, strains or stresses, or a combination of them.

Sakurai and Shimizu (1986) describe a simplified form of in situ stress determination using back analysis. In this approach two assumptions are made - the value of Poisson's ratio is assumed not back calculated, and the vertical stress is calculated from the overburden. The modulus of elasticity and the in situ stresses are then back analysed making use of a boundary element numerical analysis formulation.

Zou and Kaiser (1990), Kaiser et al (1990) and Wiles and Kaiser (1994a, 1994b) deal specifically with the determination of in situ stress from excavation induced changes, using monitored data from installed instruments, mainly strain cells.

It is preferable if the response of the rock is elastic, but non-linear (Sakurai, 1979) and elasto-plastic behaviour (Akutagawa, 1991) can be accommodated in back analysis approaches.

The method requires a situation in which facilities and time exist for the installation of suitable instruments, as well as the facility of careful additional excavation to create the deformation response. The appropriate numerical analysis technique and computer facilities are also required.

Compared with strain cell overcoring systems, a large volume of rock is involved in this method, particularly if the excavations are of significant size.

2.4 Borehole observational methods

Leeman (1964b) drew attention to the possibility of estimating rock stress from borehole sidewall fracture and from diamond drill-core fractures, and Cloete et al (1972) used the latter to estimate the magnitude of the in situ stress field.

In South Africa borehole sidewall fracture is usually referred to as "dog earing", but in the international literature this phenomenon is described as "borehole breakout". As indicated by Leeman, dog earing is a very useful indicator of level of stress, and the observations can be made in any boreholes that are available. The fact that the dog earing occurs indicates that the stresses are high enough to cause failure of the rock in the stress concentrated zone on the wall of the borehole. In addition, the alignment of the dog ears gives the orientation of the minimum secondary principal stress in the plane normal to the borehole axis.

Zoback et al (1985) and Haimson and Herrick (1986) extend the above thinking to the possibility of relating the dimensions of the breakouts to the principal stress magnitudes. From laboratory investigations the latter authors found that the depth and circumferential extent of the completed breakout were directly proportional to the state of stress normal to the borehole axis. Zoback et al (1986) indicate the possibility of using breakouts for in situ stress estimation when, due to the occurrence of breakouts, the application of hydraulic fracturing is very difficult. They believe that the approach deserves further attention.

At this stage, the use of observations of dog earing for in situ stress estimation remains very qualitative. It nevertheless is a valuable indicator of stress magnitude and, particularly, stress direction. It is naturally of no use in situations where breakouts do not occur.

Discing of borehole core is also an indicator of high stress. It is often the case that, where dog earing is observed in a borehole, discing of the core occurs. However, it is most unlikely that core discing behaviour could be used as a quantitative means of determining in situ stress. Stacey (1982) indicates that discing depends significantly on the properties of the rock and the stress in the direction of the borehole axis. In addition, the type and technique of drilling, including the drill thrust, can affect the occurrence of discing significantly (Kutter, 1991). With regard to determination of principal stress directions, however, Dyke (1989) considers that the shape of discs can provide a good estimate of these directions, even in cases in which the borehole axis is not in one of the principal stress directions.

2.5 Other methods

Many other methods for determination of in situ stresses have been proposed, developed theoretically, developed experimentally, and applied occasionally.

These other methods include the use of geophysical techniques (sonic method, for example, Obert, 1939; Buchheim, 1953; resistivity method in coal, for example, Brown et al, 1958), analysis of micro-cracking in destressed rock samples (Charlez et al 1986b), measurement of anelastic strain recovery (Enever and McKay, 1976; Matsuki and Takeuchi, 1986), a dilatometer instrument or similar to pressurise a borehole (Helal and Schwartzmann,1983; Charlez et al, 1986a; Ljunggren and Stephansson, 1986), Kaiser effect gauging by monitoring acoustic emissions (Hughson and Crawford, 1986), and borehole deepening (De La Cruz and Goodman, 1970).

It is unlikely that any of these methods will be used commonly, and therefore no significant description of them is given.

3 APPLICABILITY OF EXISTING METHODS OF IN SITU STRESS MEASUREMENT TO DEEP LEVEL GOLD MINES

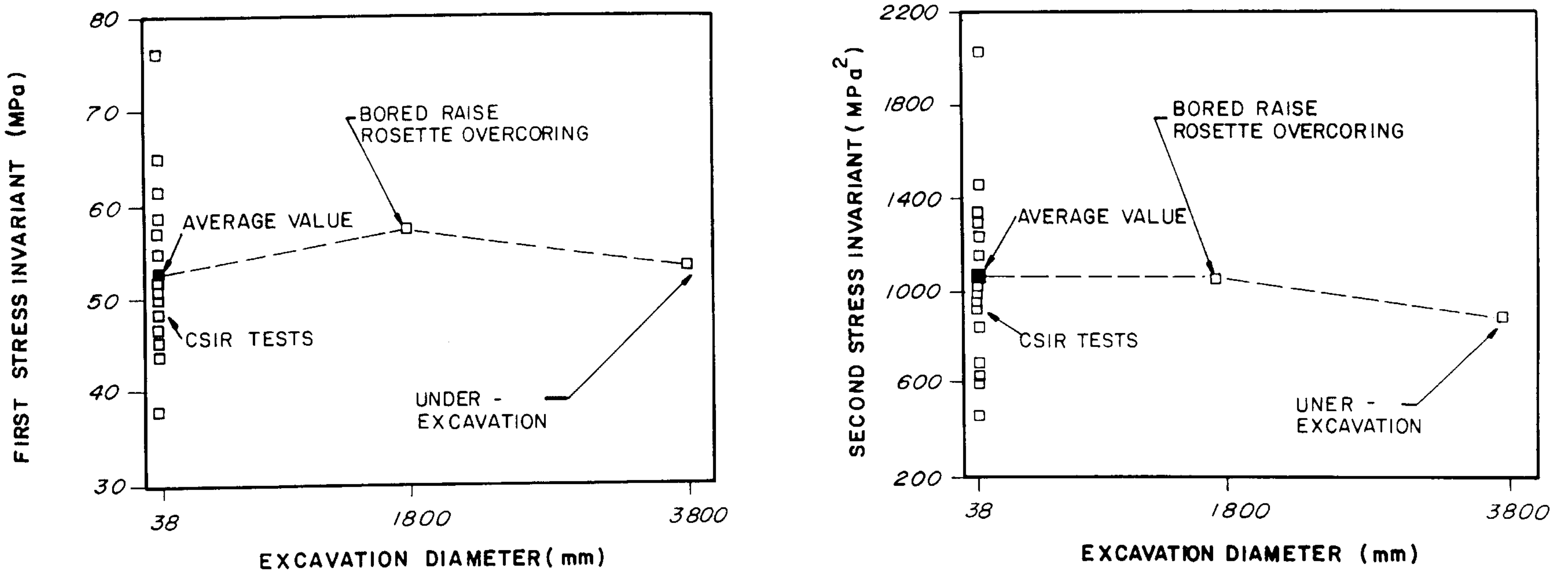
Many existing methods of in situ stress measurement have been outlined above. It is considered that a limited number have application to the deep level gold mines. Methods that may have application from a technical point of view are as follows:

- borehole overcoring methods, including the CSIR doorstopper strain cell, the CSIR triaxial strain cell, and the CSIRO HI cell
- large diameter overcoring in a bored raise
- hydrofracturing
- back analysis from monitored deformations around excavations.

In the following sections the practical applicability of each of the above four groups in deep level gold mines will be considered.

3.1 Borehole overcoring methods

Borehole overcoring methods rely on the measurement of small changes in strains on the surfaces of the boreholes, or changes in diametral dimensions. The volume of rock involved in each measurement is very small, and the actual measurements made are therefore significantly influenced by the local behaviour of the rock at the measurement location. In fact the measurements can be affected by the grain size in the rock and strain gauges can be of similar size to grains. In addition, the condition of the rock at the measurement location can affect the results considerably. For example, the occurrence of minor micro-cracking beneath a strain gauge or diametral measurement point can affect the magnitude of the strain or deformation reading considerably. This is illustrated very clearly by the results reported by Chandler (1993), which are reproduced in Figure 8. The in situ stress measurements descibed by Chandler were carried out in massive granite rock, which could be considered to be a "perfect" medium for measurements. In spite of this, microcracking in the granite led to large variations in the apparently good quality results obtained (Martin and Christiansson, 1991). In this good quality rock, variations of more than 50% in measured in situ stresses were obtained in a single hole. Variation in results obtained by different overcoring methods, under laboratory conditions, are presented by Cai et al (1995). These results show a maximum error of about 30%, and a typical error of about 10%, even under the controlled laboratory test conditions.



	JOB Nº 213413	VARIATION OF RESULTS FOR OVERCORE METHODS COMPARED WITH BORED RAISE OVERCORING AND BACK ANALYSIS TECHNIQUE	FIG. Nº 8

STA-DRAFT

Under very high stress and less perfect rock conditions, large variations in apparently good measurements can be expected. Under such conditions, it is difficult to determine which are the "correct" values. A possibility is to apply statistical techniques, but this implies that a large number of results will be obtained on which to base the analyses. This has a significant disadvantage since overcoring measurements require a diamond drill, special bits, and associated services (water, compressed air and electricity usually) to be on standby for the duration of the measurement programme. An experienced driller and measurement technician are also required for the duration of the programme. Measurements can typically be carried out at the rate of one per shift for triaxials, and about two for doorstoppers. Time is also required after the site work to carry out laboratory core testing and to calculate and interpret the results. Strain cells, particularly the CSIRO HI cells, are expensive items. In addition to the above, there are many experimental difficulties which can develop, for example, breaking of the core during overcoring; instrumentation problems due to the harsh underground environment; the presence of water in the hole; glue creep and debonding. All of these can result in a failed measurement. It may be concluded that a successful overcoring programme will be expensive.

Overcoring methods measure strain or deformation, and the in situ stress has to be calculated from these values using elastic stress-strain theory. This requires the deformation properties of the rock to be determined, as well as the assumption that the properties determined are representative for each measurement. With the triaxial approaches this can be overcome to a certain extent by testing the actual overcore, with the cell still in place, and monitoring the deformation behaviour at each gauge location.

It may be concluded from the above that, although overcoring methods are theoretically applicable in deep level mines, and have been used under these conditions, they have many disadvantages which make them non-ideal for this purpose. In summary, these disadvantages are their variability, their cost and the experimental reliability.

3.2 Large diameter overcoring in a bored raise

Many raises are excavated by raise boring on the deep level gold mines. There is thus a source of measurement sites for application by this method. The method involves a much larger volume of rock than the borehole overcoring method, and thus overcomes the problem of small scale variability of rock material. This is clear from the results shown in Figure 8. In addition, a considerable amount of redundancy of measurement values can be introduced into the method, and this will allow dubious individual values to be eliminated, and statistical optimisation to be applied.

A disadvantage of the method is that it is dependent on the location of raise bores, and cannot be carried out at a specific location at which in situ stresses are required.

The method requires physical access to the actual measurement location, and, for safety purposes, this may require special support to be installed in the raise. In addition, special large diameter overcoring equipment is required, with the associated services and personnel. Laboratory testing of the overcores, or of cores taken from the overcore, is required. It is clear from the above that, even to obtain one in situ stress measurement result, the method will be very expensive. At best, such a measurement will be inconvenient for a mining operation.

As with the borehole overcore methods, the in situ stresses are calculated from the measured strain reliefs. The results are therefore dependent on the measured rock stress-strain relationships, and on the validity of the elastic solution used for in situ stress calculation.

In conclusion, the method is likely to provide a more reliable stress measurement result than borehole overcoring. However, it is much less flexible, and likely to be very expensive.

3.3 Hydrofracturing

In Section 2.1.3 it was stated that hydraulic fracturing is the best kown method for assessing in situ stress at great depth. This statement applies to the determination of crustal stresses in vertical boreholes. If the method has been applied in deep level gold mines, no results have been published.

The method requires special equipment, and associated services and personnel, to carry out a measurement. The borehole must be diamond drilled, or inspected with a television camera if percussion drilled. Since packers are inserted in the borehole to seal off the test sections, the straightness and wall quality of the borehole are important. In boreholes in which spalling is occurring, there may be a risk of not being able to insert (or recover) the packers, and it may also not be possible to seal off the borehole satisfactorily. In vertical boreholes in the oil industry in which hydrofracturing is usually carried out, drilling fluids are usually present which help to maintain the integrity of the borehole. Special techniques such as this may be necessary if the method was to be applied in the gold mines.

After hydrofracturing, the borehole has to be inspected again, using a television camera, or a special impression of its surface taken using an impression packer, to determine the orientation of the induced fracture.

Interpretation of hydrofracture records can require expert input if the shut-in pressure is not distinct. Interpretation of test results is not a straight-forward activity, and the experience of the interpreter has some effect on the in situ stress values ultimately determined. Different interpreters may derive somewhat different results from the same set of field data.

It is clear from the above that the application of the hydrofracture method in deep level gold mines would be expensive, and demanding on services. Perhaps the most severe restriction, however, is the requirement that the borehole be drilled in the direction of one of the principal stresses. In general in the gold mines this is not known and is one of the in situ stress parameters to be determined. The HTPF variation of the hydrofracture method described in Section 2.1.3 above, which does not have this requirement, is not seen as a practical alternative owing to the number of boreholes required for a full in situ stress measurement.

It may be concluded from the above that the hydrofracture method is not likely to provide a practical method for application in the deep level gold mines. However, the simplified approach described in Section 2.1.3 above is considered to have significant merit for determining the magnitude of the minimum principal stress, since it provides a direct measurement of stress rather than a strain from which the stress is calculated. Such a test could be implemented in percussion boreholes with a very limited requirement for services. Although the test will yield only the magnitude of the minimum principal stress and not its orientation, it will provide an absolute stress magnitude which can be used to "calibrate" the results obtained from other in situ stress measurement methods. For this reason it is considered to be a practical addition to any other method of in situ stress measurement.

3.4 Back analysis from monitored deformations around excavations

The use of a back analysis technique, based on measured deformation or stress changes around an excavation, has the advantage of testing a large volume of rock. The larger the excavation involved the larger the volume of rock that will be affected. The benefits of such an approach compared with other methods of in situ stress measurement have been outlined by Wiles and Kaiser (1994). The result from the use of this technique is compared, in Figure 8, with those of borehole overcoring and large diameter overcoring in a bored raise.

The method involves the instrumentation of an excavation, whose dimensions will be enlarged in some way, such as for example, the face advance of a tunnel, the excavation of a tunnel out of a larger excavation, the sliping of an opening, etc. Instrumentation must be chosen carefully, and the whole programme well planned to obtain the most appropriate deformation and stress data (Akutagawa, 1991). Several stages of excavation may be monitored if applicable, and the data obtained used to make several predictions of the in situ stresses. In this way, with an excess of instrumentation, and several stages of back analysis, the reliability of the method may be evaluated in each particular application.

From a practical point of view, the calculation of in situ stresses requires linearly elastic rock deformation behaviour. This may be restrictive in very high stress environments, but, if required, it should be possible to engineer the enlargement such that the induced deformations being measured are essentially in the elastic regime.

The application of the method is restricted to the availablity of sites at which excavation enlargements are being made (unless enlargements are made specifically for the purposes of in situ stress measurement). This will have a large interference factor on mining operations. Sophisticated instrumentation is required, with associated special borehole drilling, and this implies significant cost.

The reliability and survivability of instrumentation in deep level gold mines is known to be a serious problem, particularly if it is required over a significant period of time.

It may be concluded that back analysis as a method of in situ stress determination has significant applicability in the deep level gold mining environment if suitable opportunities arise. However, it is inflexible in that it would not, under normal circumstances, be practical to implement the method only for the specific purpose of in situ stress measurement, since the costs will be high and the interference factor will probably be significant.

3.5 Summary regarding the applicability of existing methods of in situ stress measurement

Of the many methods of in situ stress measurement that are available and have been published in the literature, the majority have been rejected immediately as not being practically applicable in the deep level gold mines. Only a few of the methods have been identified as being possibly applicable, and their advantages and disadvantages have been dealt with in more detail above. In summary, the applicability of these few methods is as follows:

- Borehole overcoring methods: have been and can be used, but suffer from the disadvantages of poor reliability, requirement for services, and high cost per successful measurement programme. Applicability is considered to be poor.

- Large diameter overcoring: greater reliability, but is inflexible in terms of location, is demanding in terms of services, and hence is costly. Applicability is considered to be poor.
- Hydrofracturing: demanding in terms of services, specialised equipment and expert interpretation, and has a major drawback in that the borehole must be drilled in the direction of one of the in situ principal stresses. Applicability is considered to be very poor. However, applicability of a simplified method, in which only the magnitude of the minimum principal stress is determined, is considered to be significant. This, however, does not on its own satisfy the requirements of the SIMRAC Project.
- Back analysis from monitored deformations around excavations: to implement excavation enlargements, with associated instrumentation, specifically for the purposes of in situ stress measurement is not considered to be practically applicable. Costs will be high and flexibility low. Where appropriate opportunities arise to use the method, ie, when the excavation is going to be enlarged anyway and instrumentation can be installed economically, it is considered that it is applicable. General applicability in the deep level gold mines is considered to be poor.

4 REQUIREMENTS FOR A RELIABLE COST EFFECTIVE TECHNIQUE FOR IN SITU STRESS MEASUREMENT IN DEEP GOLD MINES

None of the existing methods of in situ stress measurement is considered to have practical applicability in deep gold mines. This is for a variety of reasons which have been outlined above. From experience of involvement in numerous in situ stress measurement programmes in mines and tunnels, using a range of the techniques described above, the following are considered to be the requirements for a reliable, cost effective technique for in situ stress measurement in deep gold mines:

- the technique must be undemanding on the requirement for services provided by the mine. It would probably require the provision of compressed air, but should not require water or power. It must have as little impact as possible on the mining production and exploration operations, and should require no input of time from these personnel. If possible, it should require no attendance by any mine personnel during the measurement programme. Mine personnel should clearly be welcome to participate, should they wish to do so, but there should be no requirement for their involvement. In summary, the technique should, as far as possible, minimise the input required from the mine in terms of personnel and services.

- the technique should be low cost with regard to all aspects - cost of preparation, cost of installation, cost of instrumentation and cost per measurement, and economical in terms of time requirements.
- the technique should allow many measurements to be made in a single mining shift. The preference is for a large number of lower accuracy measurements rather than one or a few apparently high accuracy results. This will allow the results to be treated statistically and therefore avoid localised effects.
- the technique should not be sensitive to high stress effects such as spalling and microcracking of the rock.
- the technique should be flexible. It should be possible to implement at very short notice, require a minimum of preparation, be possible to apply in excavations of limited size, and be non-restrictive in terms of location. It should also be able to be implemented on a stop-start basis, not requiring a long continuous period for a measurement programme, ie it should be able to fit in with the availablity of measurement sites, transport, personnel etc.
- the technique should preferably not require the retrieval of rock cores and laboratory testing to determine the deformation properties of the rock or rock mass.

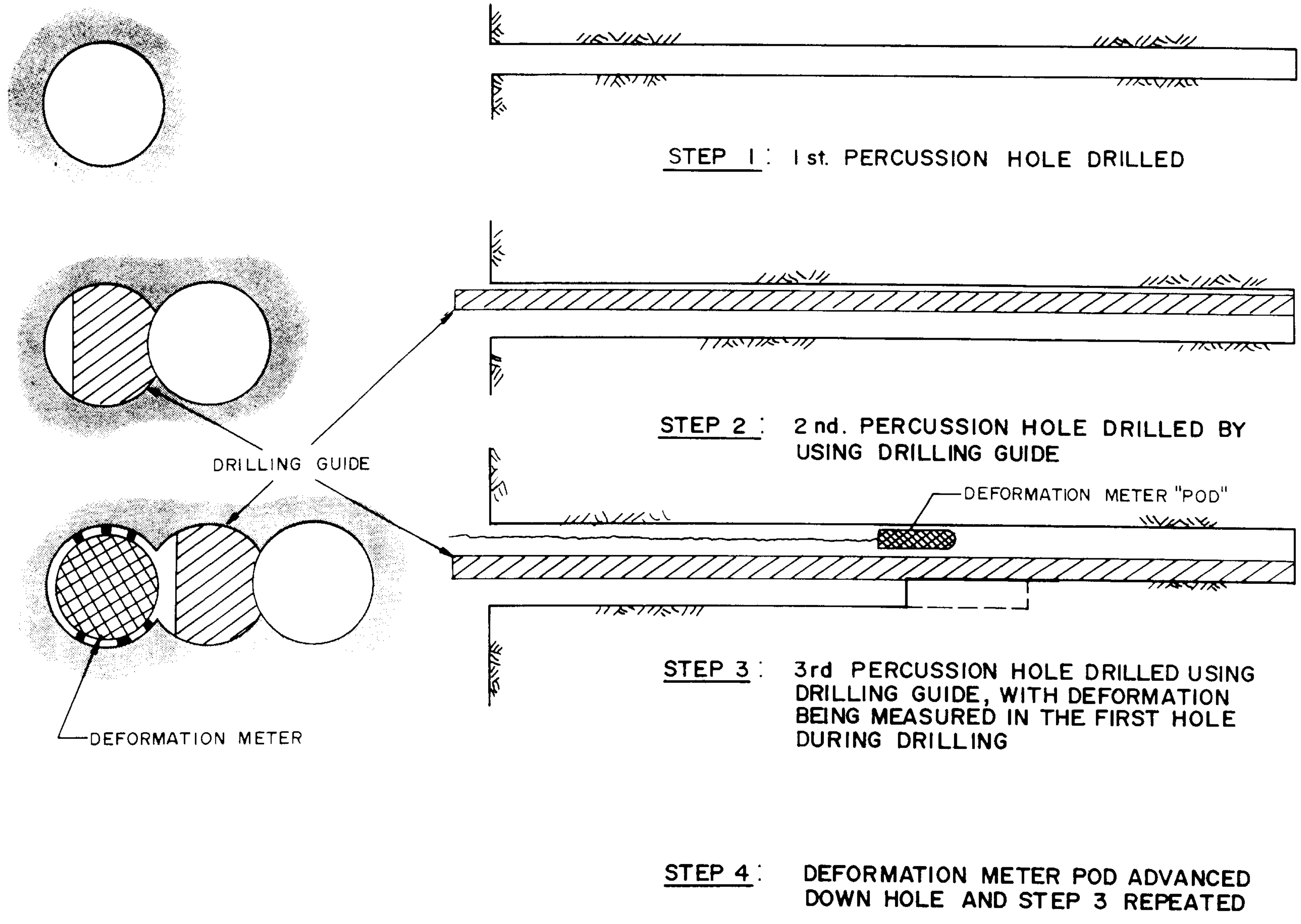
Based on the above requirements, an in situ stress measurement technique which will be practically applicable in the deep gold mines has been developed conceptually, as required in terms of the SIMRAC proposal submitted. The proposed method, and the theoretical feasibility analyses that have been carried out, are given in the following section.

5 CONCEPTUAL DEVELOPMENT OF A RELIABLE COST EFFECTIVE TECHNIQUE FOR GROUND STRESS MEASUREMENTS IN DEEP GOLD MINES

The conceptual method of in situ stress measurement, which has been developed from consideration of existing methods, and from the requirements set out above, is as follows (this should be read in conjunction with the illustrations in Figure 9, and the geometry of the method is illustrated in Figure 10):

- a borehole-based system, using percussion boreholes drilled using a conventional jackhammer
- creating the enlargement, or stress/strain change, not by overcoring, but by drilling parallel, overlapping holes
- control of the direction of adjacent holes, and prevention of sideways movement of drill chips, by means of a special borehole guide
- measurement of deformation changes in the first borehole, as a result of the drilling of the third borehole, by means of a borehole deformation meter
- sequential deformation change measurements down the length of the borehole, alternately moving the deformation meter and advancing the third borehole, thus obtaining numerous individual results in a single borehole set
- measurements carried out in three different borehole orientations at each site to provide sufficient data for the complete state of stress to be determined
- calculation of the in situ stress field by back analysis of monitored deformations using an appropriate numerical stress analysis program. Sufficient data would be obtained to allow the deformation properties to be determined as part of the back analysis procedure
- optimisation of results making use of the redundancy in number of data.

It is considered that the technique defined by this concept will satisfy all the requirements identified in Section 4 above. Specifically, the use of jackhammers to drill percussion holes means that the operation will be quick and low cost. The jackhammer could even be provided by the stress measurement operator, and the mine would then only have to provide compressed air at the measurement site.



JOB Nº		FIG. Nº
213413	CONCEPTUAL METHOD OF IN SITU STRESS MEASUREMENT APPLICABLE TO DEEP GOLD MINES	9

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The use of percussion drilling also means that many measurements can be made in one shift - probably three to four per hour. The implication of this is that more than 20 results could be achieved per day. If the sites are pre-drilled, a sufficient set of measurements could probably be completed in two days.

The use of a reusable deformation meter "pod" rather than disposable cells means that instrumentation costs will be maintained at a low level.

All operations could be carried out by personnel from the measurement operator without any requirement for personnel from the mine.

It should be possible for back analysis predictions to be calculated each day after in situ deformation results have been obtained. This will allow predictions to be updated progressively, decisions to be made on the requirement for further data, and hence for the programme to be completed at the earliest opportunity thus minimising cost.

Previous borehole methods of in situ stress measurement have depended on the availability of a closed form solution for the stress distribution around the borehole. This allowed solutions to be developed for the end of the borehole (for doorstoppers or hemispherically shaped cells), the surface of the borehole (for CSIR and CSIRO triaxial strain cells, and for the borehole slotter), and for diametral deformation changes (for borehole deformation gauges and for solid inclusion cells). The method proposed above has become possible because of the development of the back analysis technique. The application of this technique does not depend on the availablity of a standard elastic stress distribution solution, but on the availability of a numerical stress analysis technique, for example a finite element or boundary element method.

5.1 Stress analyses of the concept

Stress analyses of the proposed geometry of the method have been carried out to prove its theoretical feasibility. The following were the aims of the theoretical analyses:

- to prove that deformations induced around the first borehole by the drilling of the third borehole would be of sufficient magnitude to measure easily
- to determine the effect on the deformations of failure around the boreholes due to overstress
- to determine the length over which the third borehole must be drilled to influence completely the measurement location in the first borehole.

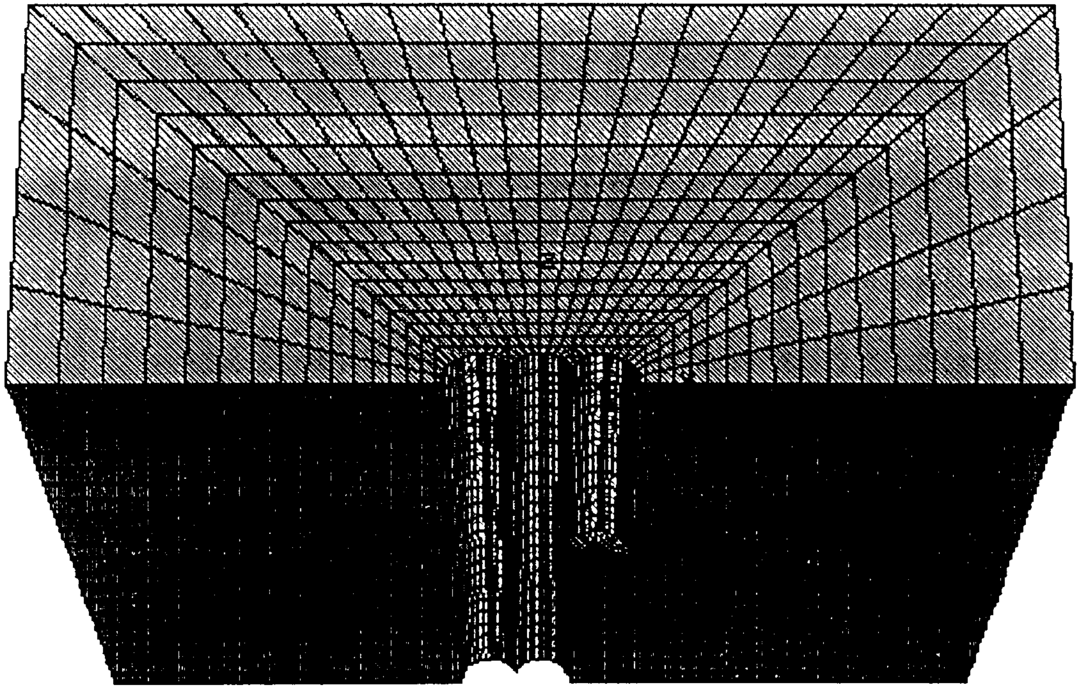
Preliminary analyses for the first purpose were carried out using EXAMINE 2D, a simple two-dimensional boundary element stress analysis program. The indications were positive and subsequent analyses for the first and second aspects were carried out using 2D FLAC. Analyses using 3D FLAC were carried out for the third purpose.

The geometry of the models used for analyses, as illustrated in three dimensions in Figure 10, involved three 40 mm diameter boreholes with a 5 mm overlap. The lengths of the boreholes in the three-dimensional model were 600 mm for the first two holes and about 300 mm for the third hole.

For all analyses the following elastic rock properties were used:

Modulus of elasticity:	70 GPa
Poisson's ratio:	0,2

A mining depth of about 3000 m was assumed for the analyses, corresponding with field stresses of 75 MPa vertical and 37,5 MPa horizontal.



JOB Nº		FIG. Nº
213413	PERSPECTIVE VIEW OF THE PROPOSED METHOD	10

5.1.1 Two-dimensional elastic analyses

Analyses were carried out for both a vertical/horizontal as well as an inclined principal in situ stress field. The vertical and horizontal displacement results from the analyses are presented in Figures 11 and 12. It can be seen from these results that the net closure across the diameter of the first borehole as a result of the drilling of the third borehole is of the order of 0,14 mm. This order of magnitude can easily be measured with the required accuracy for back analysis purposes.

Under an inclined stress field a non-uniform displacement field results as shown in Figures 13 and 14. Again the magnitudes are sufficient to enable the deformations to be determined satisfactorily.

5.1.2 Two-dimensional analyses allowing rock failure to develop

The above analyses were repeated with rock failure being allowed to develop. Strain softening rock behaviour was assumed, and the properties adopted were as used by Raffield et al (1993).

The results of these analyses are shown in Figures 15 and 16. As a result of rock yield and failure the net displacement across the first borehole increases, but the increase is less than 5%. This is less than the likely measured variations in deformation owing to local variations in rock behaviour and experimental factors.

The implication of the above is that the method is not sensitive to the occurrence of rock failure due to overstress in high field stress conditions. This meets one of the requirements set out above for the proposed method. The extent of rock failure can also be restricted by appropriate choices of orientations of the borehole sets, ie so that their axes are not normal to the probable orientation of the maximum principal stress.

FLAC (Version 3.22)

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Boundary plot

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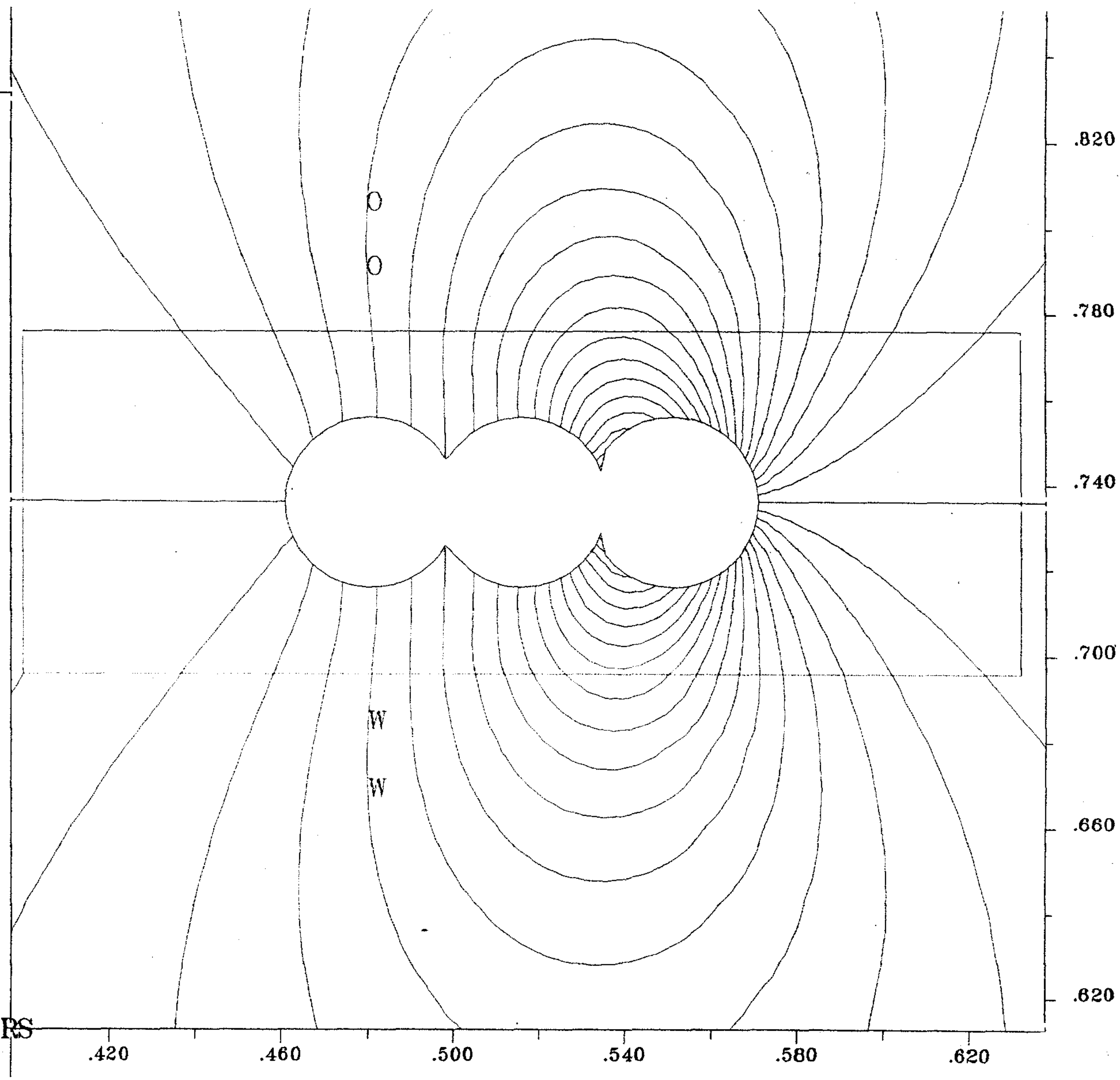

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JOB Nº		FIG. Nº
213413	VERTICAL DISPLACEMENTS AS A RESULT OF THE DRILLING OF THE THIRD HOLE	11

STA-DRAFT

JOB TITLE : ELASTIC MEDIUM

FLAC (Version 3.22)

LEGEND

6/19/1995 11:47
step 8067
4.447E-01 <x< 5.727E-01
6.760E-01 <y< 8.040E-01

Boundary plot

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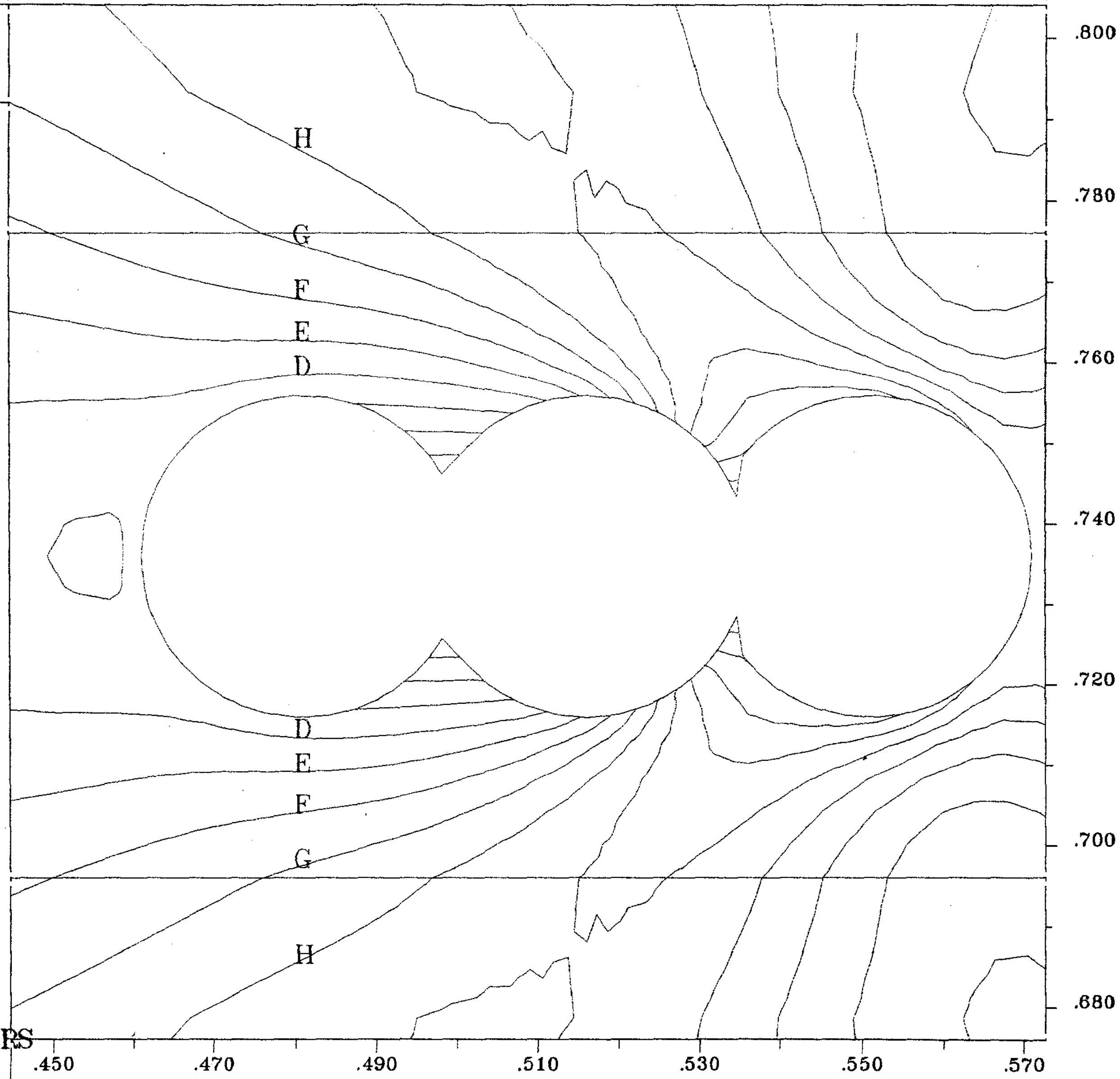
X-displacement contours
Contour interval= 2.00E-06
D: -6.000E-06
H: 2.000E-06



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JOB Nº		FIG. Nº
213413	HORIZONTAL DISPLACEMENTS AS A RESULT OF THE DRILLING OF THE THIRD HOLE	12

FLAC (Version 3.22)

LEGEND

4/11/1995 08:17
step 7645
1.416E-01 <x< 9.174E-01
3.508E-01 <y< 1.127E+00

Boundary plot

0 2E -1

Y-displacement contours

Contour interval= 5.00E-06
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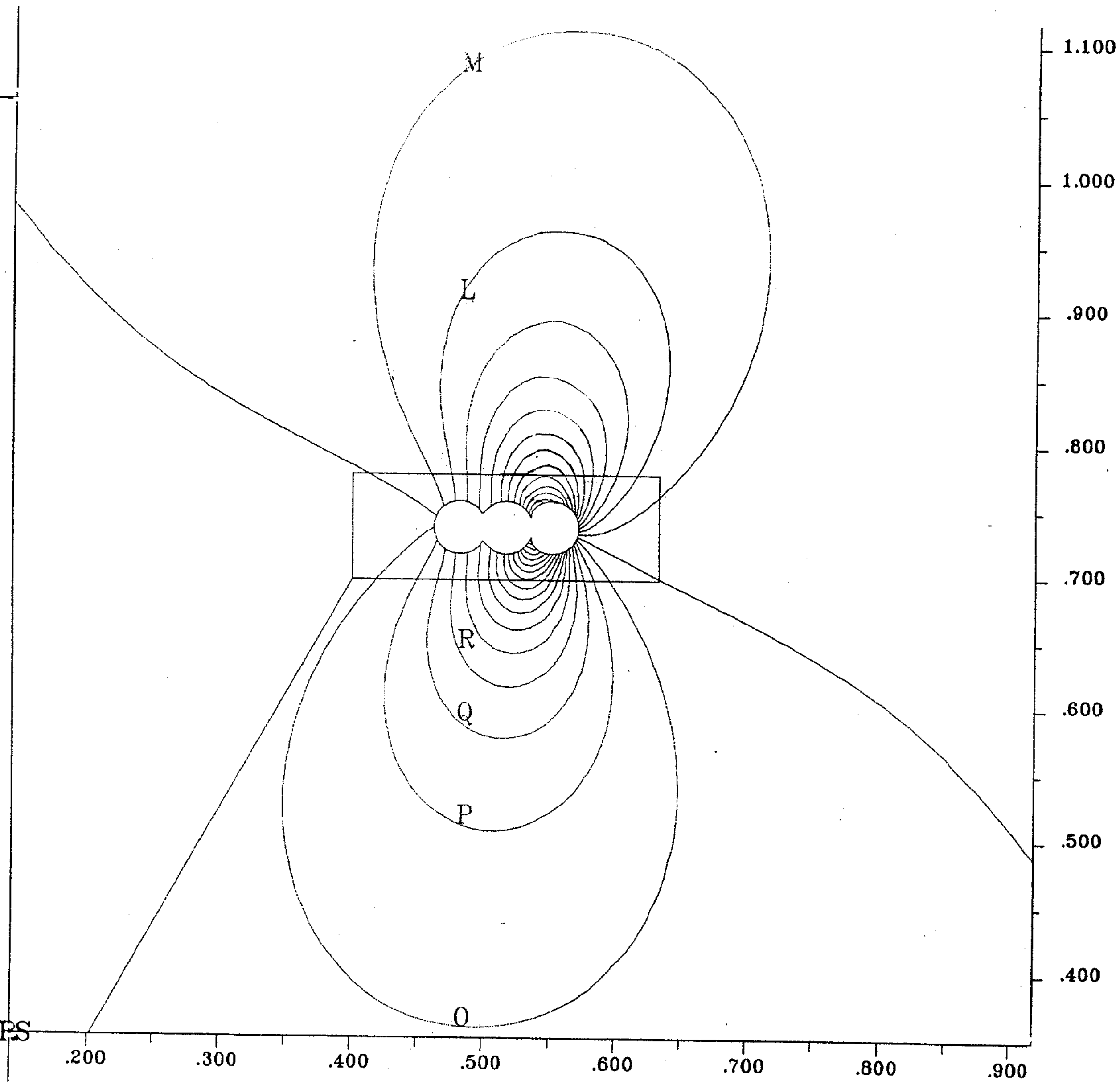
R: 2.000E-05



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JOB Nº		FIG. Nº
21341 3	VERTICAL DISPLACEMENTS AS A RESULT OF THE DRILLING OF THE THIRD HOLE : INCLINED STRESS FIELD	13

FLAC (Version 3.22)

LEGEND

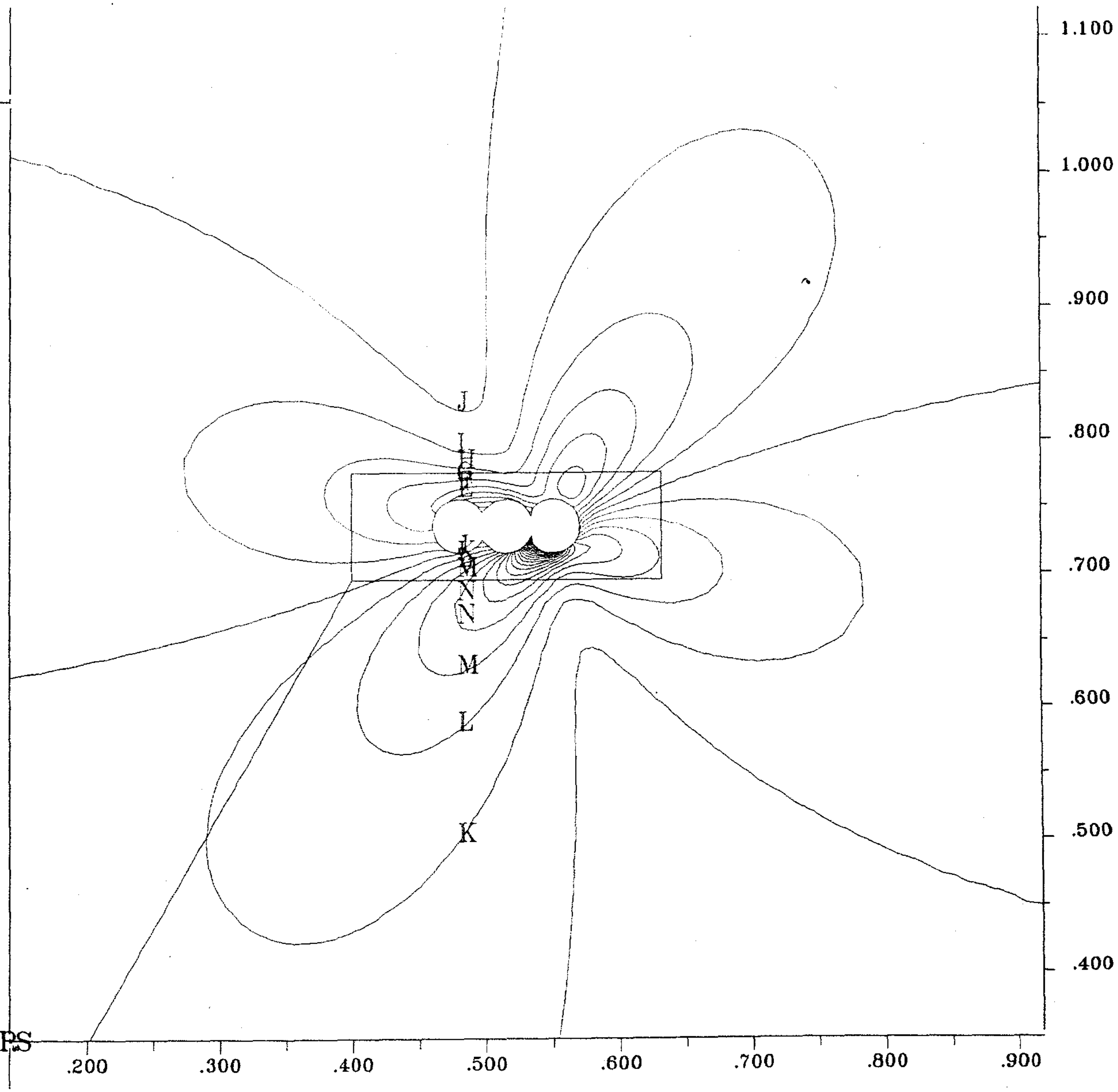
4/11/1995 08:18
step 7645
1.416E-01 <x< 9.174E-01
3.508E-01 <y< 1.127E+00

Boundary plot

0 2E -1

X-displacement contours

Contour interval= 2.00E-06
E: -1.000E-05
N: 8.000E-06



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JOB Nº		FIG. Nº
213413	HORIZONTAL DISPLACEMENTS AS A RESULT OF THE DRILLING OF THE THIRD HOLE : INCLINED STRESS FIELD	14

STA-DRAFT

FLAC (Version 3.22)

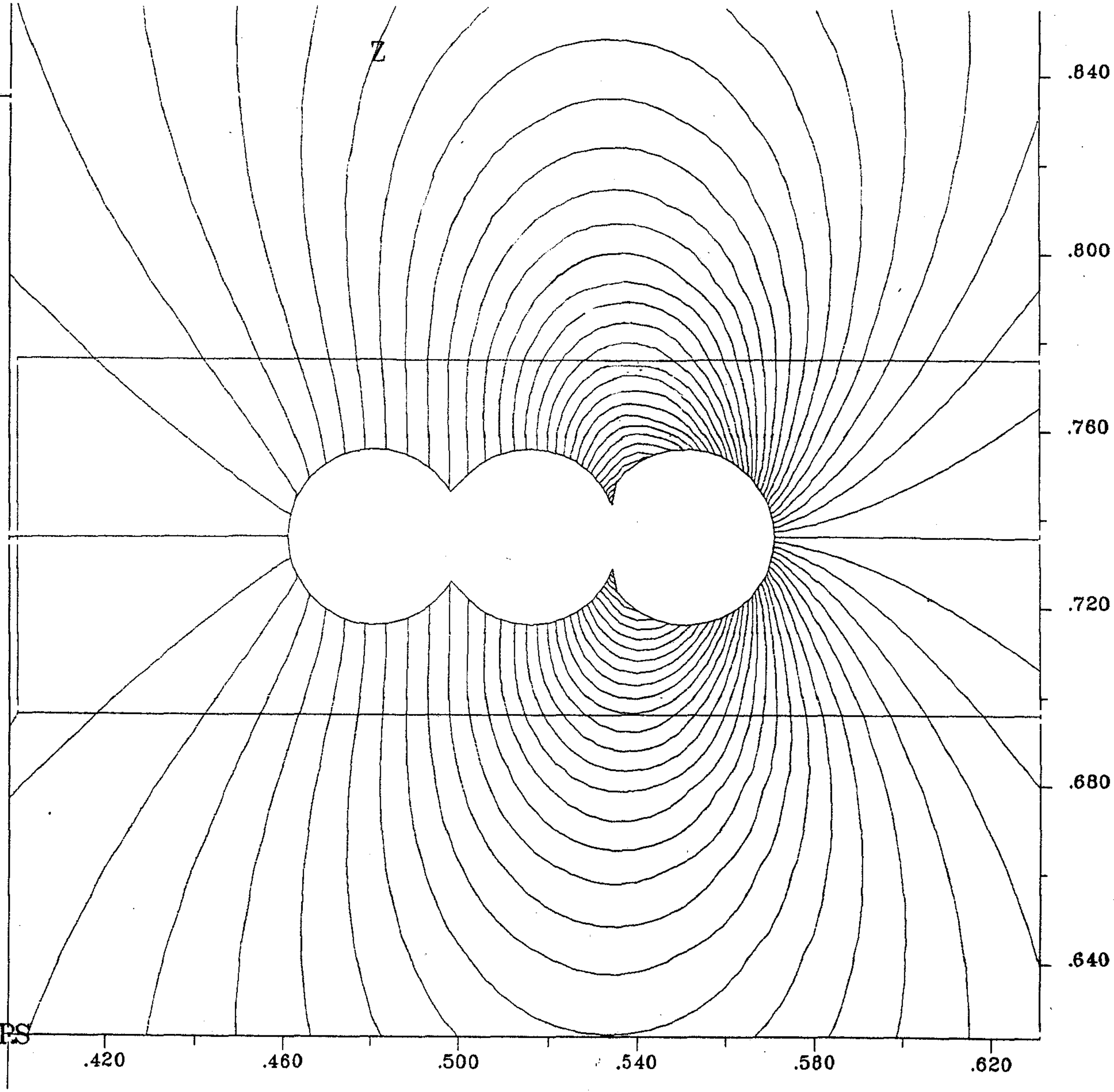
LEGEND

6/19/1995 15:49
step 7003
3.982E-01 <x< 6.309E-01
6.237E-01 <y< 8.563E-01

Boundary plot

0 5E -2

Y-displacement contours
Contour interval= 3.00E-06
Z: -1.800E-05



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JOB Nº		FIG. Nº
213413	VERTICAL DISPLACEMENTS AS A RESULT OF THE DRILLING OF THE THIRD HOLE: STRAIN SOFTENING MODEL	15

FLAC (Version 3.22)

LEGEND

6/19/1995 15:51
step 7003
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6.237E-01 <y< 8.563E-01

Boundary plot

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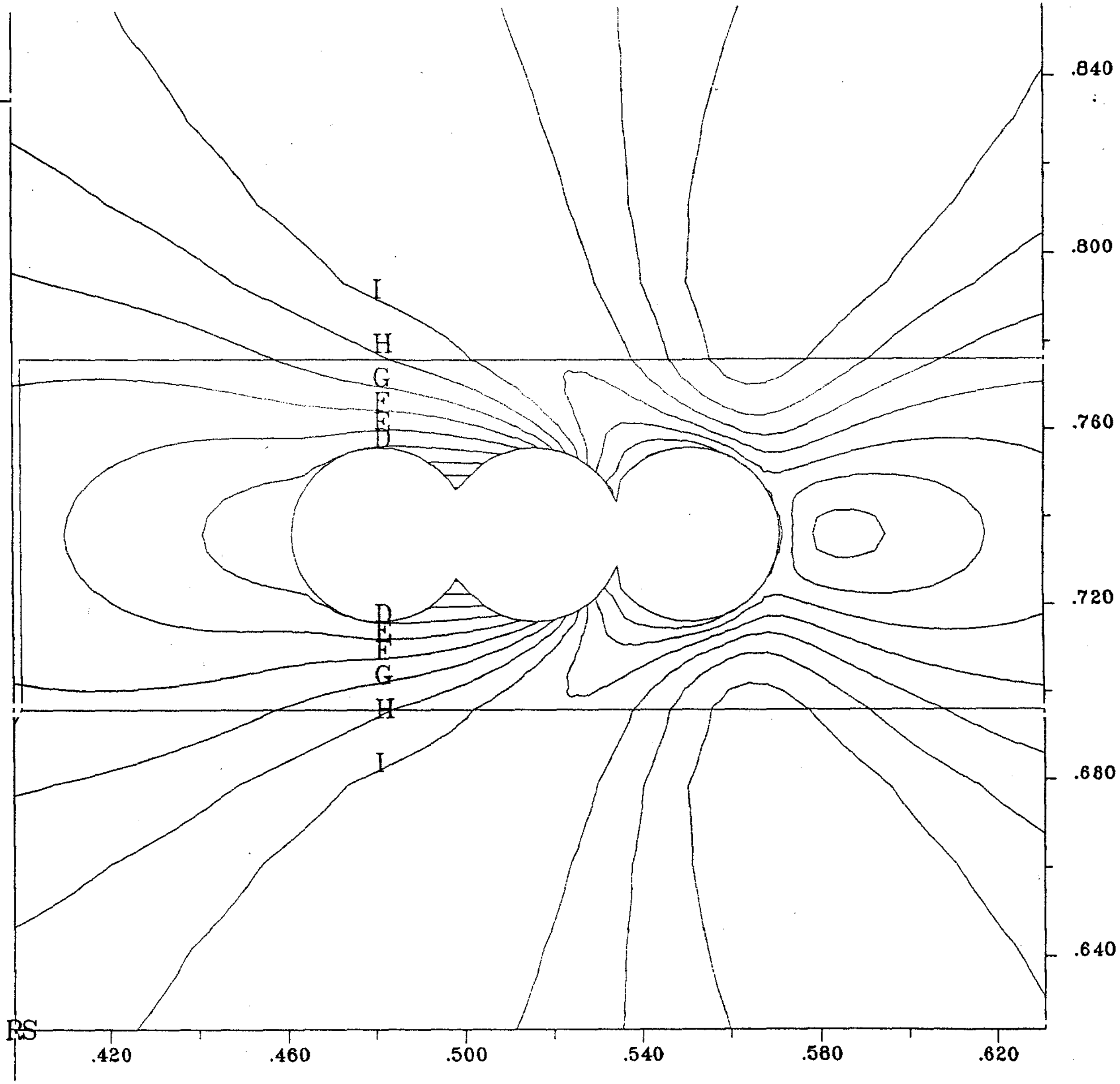
X-displacement contours
Contour interval= 2.00E-06
D: -8.000E-06
I: 2.000E-06



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JOB Nº		FIG. Nº
213413	HORIZONTAL DISPLACEMENTS AS A RESULT OF THE DRILLING OF THE THIRD HOLE : STRAIN SOFTENING MODEL	16

STA-DRAFT

5.1.3 Three-dimensional stress analyses

The purpose of the three-dimensional analyses was to determine the extent of the influence in the first borehole of the face of the third borehole. This is effectively the length of each measurement, which determines the number of measurements that can be carried out in a single hole.

The vertical displacements in a vertical plane along the axis of the first borehole are shown in Figure 17. These results show that, per measurement, the minimum length of percussion drilling required in the third borehole is about 200 mm. The implication of this is that about five measurements can be made per metre length of borehole beyond the influence of the tunnel (excavation) from which the boreholes are drilled. In practice, deformations will be monitored during the drilling process and will indicate clearly when the influence is complete. This could be slightly more or less than the theoretical value determined above.

The requirement for a large number of measurements in a single shift is therefore met on the basis of the theoretical analyses.

6 CONCLUSIONS AND RECOMMENDATIONS

A method of in situ stress measurement, based on the percussion drilling of a set of three overlapping boreholes, and back analysing the in situ stresses from the measured deformations in the boreholes, has been developed in concept. By its very nature, being based on low cost drilling and deformation measuring operations, whose application is very flexible, the method will be cost effective. In concept, the method overcomes the disadvantages of most of the available methods of in situ stress measurement, and therefore should be reliable. It is also aimed at being specifically applicable under the conditions which occur in deep mines, and its feasibility has been proved theoretically.

FLAC3D 1.00

Step 10698 Perspective
12:07:52 Thu Jun 15 1995

Rotation:		Normal:	
X:	0.00	X:	-1.00
Y:	0.00	Y:	-0.00
Z:	90.00	Z:	0.00
Center:		Origin:	
X:	-1.526e-05	X:	-3.500e+01
Y:	2.824e+02	Y:	0.000e+00
Z:	-7.221e+01	Z:	0.000e+00

Eye Dist: 2.963e+03
Size: < 3.611e+02, 4.045e+02>
Increment: 10

Contour of Z-Displacement

On Plane

-1.1070e-01	to	-1.1000e-01
-1.0000e-01	to	-9.9000e-02
-8.9000e-02	to	-8.8000e-02
-7.8000e-02	to	-7.7000e-02
-6.7000e-02	to	-6.6000e-02
-5.6000e-02	to	-5.5000e-02
-4.5000e-02	to	-4.4000e-02
-3.4000e-02	to	-3.3000e-02
-2.3000e-02	to	-2.2000e-02
-1.2000e-02	to	-1.1000e-02
-1.0000e-03	to	0.0000e+00
1.0000e-02	to	1.1000e-02
2.1000e-02	to	2.2000e-02
3.2000e-02	to	3.3000e-02
4.3000e-02	to	4.4000e-02
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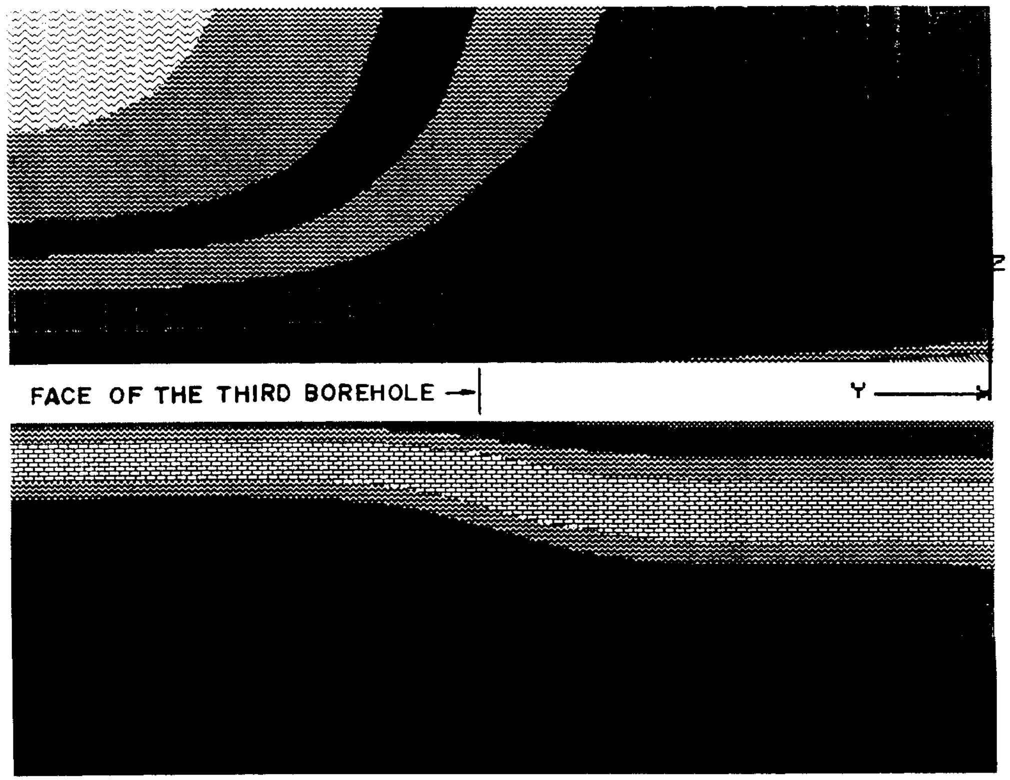

JOB Nº 213413

VERTICAL DISPLACEMENTS IN A VERTICAL PLANE ALONG THE AXIS OF THE FIRST BOREHOLE, AS A RESULT OF THE DRILLING OF THE THIRD BOREHOLE

FIG. Nº 17

STA-DRAFT

It was stated in the SIMRAC proposal document, which is contained in Appendix A, that the primary output of the research project would be at feasibility level, and that further development would be required for the technique to be developed for routine use. It is recommended that this development should now proceed. From a physical point of view there are several aspects which can be identified at this stage as needing development to ensure that the method can be applied practically. These are:

- the development of a suitable drilling guide which can cope with variation in the straightness of the holes, some variation in the diameter of the holes, and "wedging" due to some closure of the holes, to the impact of the drill and to the packing of the drill chippings. This is considered to be the most significant physical challenge.
- development of a suitable deformation meter. This could be based on deformation meters which are currently in use and have proved their practical capabilities.
- development of the standard back analysis procedure. Back analysis has been developed for numerous applications, and is in reasonably common use internationally. The approach, and an appropriate simple stress analysis program, need to be adapted for the specific in situ stress measurement application.

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APPENDIX A

SIMRAC RESEARCH PROPOSAL

RELIABLE COST EFFECTIVE TECHNIQUE FOR IN-SITU GROUND STRESS MEASUREMENTS IN DEEP GOLD MINES

DEPARTMENT OF MINERAL AND ENERGY AFFAIRS
PROPOSAL FOR A PROJECT TO BE FUNDED IN TERMS OF THE MINERALS ACT
- CONFIDENTIAL -

DMEA REFERENCE NUMBER
GAP 220
(FOR OFFICE USE ONLY)

1. PROJECT SUMMARY

PROJECT TITLE : Reliable cost effective technique for in-situ ground stress measurements in deep gold mines.

PROJECT LEADER : T R Stacey

ORGANIZATION : Steffen, Robertson and Kirsten

ADDRESS : P O Box 55291, NORTHLANDS, 2116

TELEPHONE : (011) 441 1143 TELEFAX : (011) 880 8086 TELEX : 4-89763 SA

PRIMARY OUTPUT[1] :
Literature survey of existing methods of in-situ rock stress measurements; evaluation of applicability of existing methods to deep gold mines; feasibility study of potential, reliable, cost effective stress measurement technique.

HOW USED ?[2] : As a basis for developing a routine method for in-situ stress measurement in the deep gold mines

BY WHOM ?[3] : Rock mechanics researchers in the first instance, and when the technique is developed into a routine tool, by rock mechanics practitioners.

CRITERIA FOR USE[4] : The primary output is at feasibility level. Further development will be required for the technique to be developed for routine use.

POTENTIAL IMPACT[5] :
In-situ stress is one of the most important inputs for rock mechanics analyses. At present the in-situ stress field is usually "guessed". Good quality in-situ stress data will provide much more reliable analyses, which will enhance the quality of design, and safety.

FUNDING REQUIREMENTS (R 000's)	YEAR 1	YEAR 2	YEAR 3
TOTAL PROJECT COST	67 830		
TOTAL SUPPORT REQUESTED FROM SIMRAC	67 830		

DURATION (YY/MM) 94/01 TO 94/06

SIMRAC SUB-COMMITTEE :	AU/PT	X	COAL		OTHER		GENERIC	

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2. PROJECT DETAILS

2.1 Primary Output[1]

1. A literature survey of existing methods of in-situ stress measurement including an evaluation of the applicability of these methods in the deep level gold mines.
2. A theoretical feasibility study of a potential method, which will be cost effective and practical, and applicable to the gold mine situation.

2.2 Other Outputs (deliverables)[6]

Not applicable

2.3 Enabling Outputs[7]

NO.	ENABLING OUTPUT	MILE-STONE DATE	MAN DAYS
1	Literature procurement	Mnth 2	4
2	Literature survey and preparation of draft review document	Mnth 3	9
3	Identification of potential in-situ stress measurement methods for theoretical feasibility study	Mnth 3	2
4	Theoretical feasibility study	Mnth 5	11
5	Final report document	Mnth 6	8
			34

2.4 Methodology[8]

NO. OF ENABLING OUTPUT	STEP NO.	METHODOLOGY TO BE USED TO ACCOMPLISH THE ENABLING OUTPUT (INDICATE STEPS/ACTIVITIES)
1	1	Review abstracting journals for references
	2	Identify references from available publiations
	3	Obtain hard copy references through library system
2	4	Review of literature
	5	Preparation of draft literature review document
3	6	From literature review identify potential methods
		for feasibility examination
4 .	7	Preliminary examination of potential methods and
		elimination of unsuitable methods
	8	Theoretical analyses of chosen method or methods
		(expected to be 3D stress analyses)
	9	Evaluation of results
5	10	Preparation of report document including the literature
		survey,and the results and conclusions from the
		theoretical feasibility study.

Key Facilities and Procedures to be used in the Project

Steffen, Robertson and Kirsten library, a registered library, with a full-time professional librarian.

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3. FINANCIAL DETAILS[9]

3.1 Financial Summary

	R000s		
	YEAR 1	YEAR 2	YEAR 3
Project staff costs (from 3.2)	56 000		
Other costs:			
Operating costs (from 3.3)	3 500		
Capital & plant costs (from 3.4)			
Sub-contracted work (from 3.5)			
Value added tax*	8 330		
Total cost of project	67 830		
Less funding from other sources (from 3.6)			
Support requested from SIMRAC	67 830		

*Only for VAT registered concerns

3.2 Project Staff Costs

	MAN DAYS		
NAME AND DESIGNATION	YEAR 1	YEAR 2	YEAR 3
T R Stacey Director	18		
H A D Kirsten Director	1		
P Lourence Senior Ming Eng	12		
S King Librarian	3		
TOTAL (R000s)	56 000		

3.3 Operating Costs (Running)

ACTIVITY/EQUIPMENT (Items above R10 000)	COST (R000s) YEAR 1	YEAR 2	YEAR 3
Literature searches	500		
Computer analysis costs	3 000		
Other miscellaneous items			
TOTAL	3 500		

3.4 Capital and Plant Costs[10]

(i) ITEMS TO BE PURCHASED OR DEPRECIATED FOR MORE THAN R10 000 PER ITEM	COST (R000s) YEAR 1	YEAR 2	YEAR 3
None			
Other miscellaneous items			
TOTAL			

RLS

	COST (R000s)		
(ii) ITEMS TO BE MANUFACTURED WITH ASSEMBLED COST OF MORE THAN R10 000 INCLUDING MATERIAL AND LABOUR	YEAR 1	YEAR 2	YEAR 3
None			
Other miscellaneous items			
TOTAL			
TOTAL (i) and (ii)			

3.5 Sub-contracted Work

		COST (R000s)		
SUB-CONTRACTOR	ACTIVITY	YEAR 1	YEAR 2	YEAR 3
	TOTAL			

3.6 Other Funding

ORGANIZATION	NATURE OF SUPPORT/ COMMITMENT	AMOUNT (R000s)

4. MOTIVATION

(Provide a clear and quantified motivation or justification for the proposal, as well as the main conclusions of a literature survey and the findings of related local and interantional research. The motivation should include a synthesis of previous work in the project area, both locally and overseas, why the project is proposed, what the primary output will achieve and a cost benefit analysis, if applicable. Use continuation pages where necessary but in most cases it should be possible to clearly present the key data and arguments in the space provided.)

Many in-situ stress measurement methods have been developed. The most commonly used methods are the doorstopper and triaxial strain cell (developed in South Africa), the CSIRO hollow inclusion cell, and hydro-fracturing . The first three in particular have been used in South Africa mines while use of other methods (hydrofracture, borehole slotter, USBM deformation meter, and possibly others) has been far more limited.

A good understanding of the in-situ stress field is essential for realisti mine design and planning of mining layouts and sequences. Without this good quality boundary information, output from the sophisticated stress analysis programs available may be in error or possibly invalid.

In-situ stress measurement methods used in the mines usually provide a wide variation in values of in-situ stress, with low measurement success rate and poor reliability and repeatability. With mines going deeper these problems are likely to increase as spontaneous fracturing is likely to occur around any opening. Existing methods are therefore likely to be less effective in the future. To provide the data required for design under the future stringent mining conditions, a new approach is likely to be required. This must take into account the accessibility of sites, interference with mining operations, availability of, and requirement for services, and time required for measurements. The propose research programme will answer these factors in principle.

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5.2 Revelant Experience and Publications (one page for each individual listed in 5.1)

NAME: T R Stacey

Relevant Experience:

1. Hands on experience with CSIR doorstopper and triaxial strain cells in-situ stress measurements.

2. Developed computer programme to calculate 3D state of stress from 3 doorstopper measurements.

3. Involvement in stress measurement programmes, in a supervisory and evaluation position, with doorstopper, CSIRO HI cell, and borehole slotter methods.

4. Involved, at an expert consultant level, with hydrofracture stress measurements and large diameter overcore measurements (in a bored tunnel).

5. Familiarity with literature on all the above methods, as well as other lesser used methods such as borehole deepening, back analysis from measured deformations, flat jacks, and others.

Relevant Publications: (Includes those of H A D Kirsten)

1. Selected aspects of rock stress measurements in South Africa, Proc. Symp. Exploration for Rock Engineering, AA Balkema, 1977, pp 55-65.

2. Slotter stress measurements at Palabora Mine, Interfels News, No. 7, February 1993, pp 15-16.

3. Course of instruction in execution of doorstopper stress measurements for El Teniente Mine, Restricted Report 4071, Steffen, Robertson and Kirsten.

4. Measurement of in-situ stresses at Palabora Mine, Restricted Reports 179447/2 and 179447/5, Steffen, Robertson and Kirsten.

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6. DECLARATION BY THE PROPOSING ORGANIZATION

I, the undersigned, being duly authorized to sign this proposal, herewith declare that:

- The information given in this proposal is true and correct in every particular.

- This Organization has the basic expertise and facilities required for satisfactory completion of the project and will adhere to the program of activities as set out in this proposal.

- The costs quoted are in accordance with the normal practice of this Organization and can be substantiated by audit.

Signed on this 29 day of July 19 94 for and behalf of

STEFFEN, ROBERTSON AND KIRSTEN

SIGNATURE: [signature]

NAME: T R STACEY

DESIGNATION: DIRECTOR

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