Tunnels under pressure in an ultra-deep Witwatersrand gold mine

by D.H. Diering*

Synopsis

The paper takes the reader into the depths of a modern ultra-deep South African gold mine and gives a perspective on the vertical and horizontal extent of the tunnel networks in such a mine.

Depending on the mine design layout employed, tunnels once excavated are subjected to various levels of stress change over their life time, and the support requirements are explained. It is suggested that shotcreting is the only viable ultra-deep level support medium, and after looking at the latest developments, the logistical problems are put forward.

In an effort to overcome most of these problems, the South African ultra-deep mining industry embarked on a collaborative research programme in 1998. The importance of tunnelling and in particular tunnel support as a critical technology for future successful ultra-deep level mining is stressed. While not yet fully 'on top of' these problems and challenges, our industry is now fully addressing them and we expect to make significant progress during the next 4 to 5 years.

Introduction

In preparing to write this paper, I thought it necessary to conduct a little 'research' into the broader global tunnelling industry. I was amazed both by the tremendous progress that your industry has made during the past fifty or so years and the degree of technological complexity involved in modern day civil-engineered tunnels.

In contrast, tunnelling in our gold mining industry seems 'low-tech' and uninteresting. What sets us apart however, is the scale of tunnelling that takes place, and the depth at which we make our 'holes in the ground'. Four-km long tunnels are commonplace in your industry, but when you hear of tunnelling taking place 4 km underground, I'm sure the reaction of many of you would be 'Wow!—how do they do that?'.

So while not in any way presuming that I could add to your extensive knowledge-base, I hope that I can give you a different perspective to take away with you—along with the memories of this conference in South Africa.

Now tunnelling at great depth is certainly nothing new to us in South Africa. ERPM in the East Rand passed the 3000 m mark 44 years ago, and reached a world record depth of 3428 m below surface in 1959. Western Deep Levels started sinking in 1958 and reached a new Guinness Book of Records depth of 3597 m below surface 16 years later in 1974.

In 1996 Western Deep Levels announced a R1.1 billion shaft deepening project which would take the No. 1 sub shaft down to ± 3800 m below surface. This project is still under way, and due for completion next year.

And finally, by way of introduction, here are some interesting facts about tunnelling in the South African gold mining industry (during the previous century).

In May 1962 a world record was broken at Loraine Gold Mines Ltd when they advanced a single tunnel 2649 ft (807,6 m) in one month. The end was 3 m × 3,5 m, and they averaged 12,6 rounds (2 m) per day. Drilling was with hand-held compressed air machines and the end was cleaned with a conventional air-operated rocker shovel.

In October 1980 at Randfontein Estates Cooke 3 Shaft, a new record was achieved when 1101,4 m was advanced in a twin end, still using conventional compressed air hand-held rockdrills and a rocker shovel for cleaning. In this case they averaged 16 rounds per day.

By today's standards these are still astounding achievements, and I am not aware of an improvement since then in any of our South African mines, despite all the sophisticated electro-hydraulic drill rigs and trackless equipment which are now available.

There is, of course, one major difference between developing tunnels at 1500 m and

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3000 m below surface, and that is the need for fabric-type support at depth.

Access to 4km

Before I describe the art of tunnelling at ultra depths, it is necessary to explain how we get there in the first place. Western Deep Levels would be a good example to explain access to great depths. (See Figure 1).

During the early 1960s, 2 km was thought to be the maximum length for a shaft, and so the original shafts at Western Deep Levels were designed as a tertiary shaft system—i.e. main, sub and tertiary.

In the 1980s main shafts from surface were extended to 2500 m, and so it was possible to get to 3,5–4 km with a twin shaft system i.e. main and sub shaft only.

In the 1990s, the length of the wind was extended to 3 km, and there are two of these shaft systems being sunk at the moment, namely the Western Areas South Deep shaft, and the Moab Khutsong shaft. This will certainly allow South African mining engineers to get shaft systems down to 4–5 km from a technical point of view; the only limiting factor is going to be economics.

When we think of tunnels, we usually think on the horizontal plane, but these vertical tunnels really are something special; consider a 10 m diameter, 3000 m deep shaft!

Figure 2 shows a cross-section through a typical large shaft.

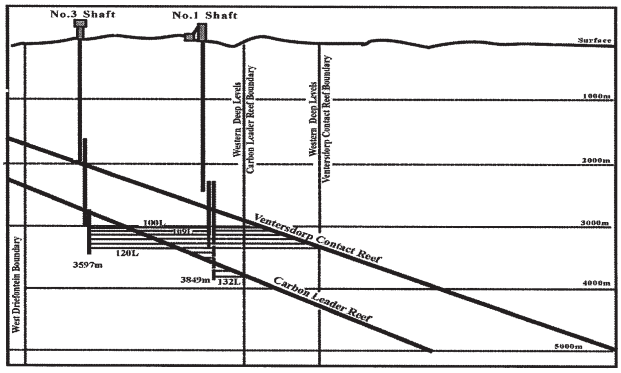

Figure 1—A section through Western Deep Levels

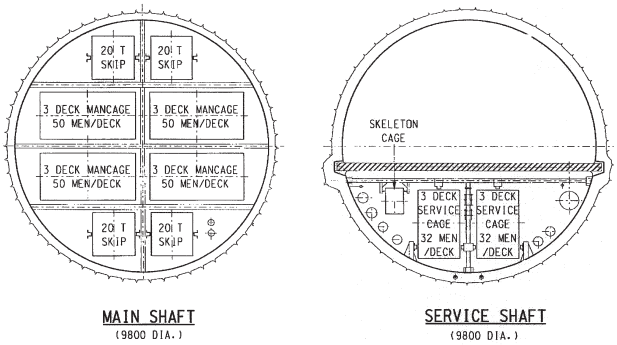

Figure 2—A plan view of a large deep shaft system

In this field of tunnelling at least, I suspect South Africans are world leaders.

Tunnel networks

Well, what does an extensive tunnel network in a large South African gold mine look like? I'll show two typical layouts, one from an older longwalling layout (Figure 3), and the other a more modern sequential grid-type layout. (Figure 4).

The most important feature of this layout is the fact that all of the tunnels are 'tucked in' underneath the mined out area, and as such are de-stressed. This is one of the main reasons why longwall mining has been the primary deep to ultra-deep (2500–3500 m) mining method used during the past 40–50 years. Most of the haulages (horizontal access tunnels) lie ± 30 m below the ore body plane, and so the actual depth that mining is taking place is to a large extent irrelevant.

In contrast to the previous layout, the primary development is out ahead of the mined area. For reasons that will be explained later, the main access tunnels are now ± 100 m below the plane of the ore body. Figure 5 shows a more detailed layout.

From the haulage, cross-cuts are developed every 180 m on strike to the ore body, and out of the cross-cut, boxholes are developed up to the reef plane. This allows the ore to be transported from the reef plane down to the crosscut and through the haulage back to the shaft for hoisting. Once the

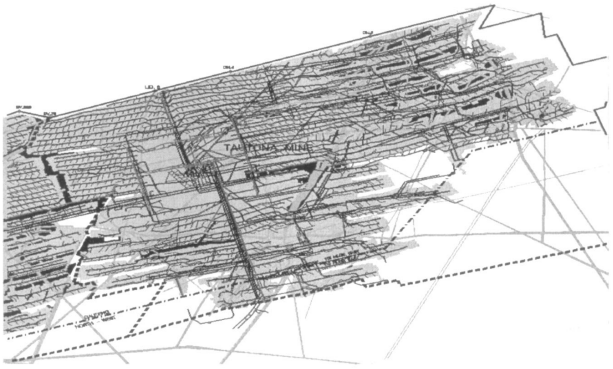

Figure 3—A longwalling tunnel network

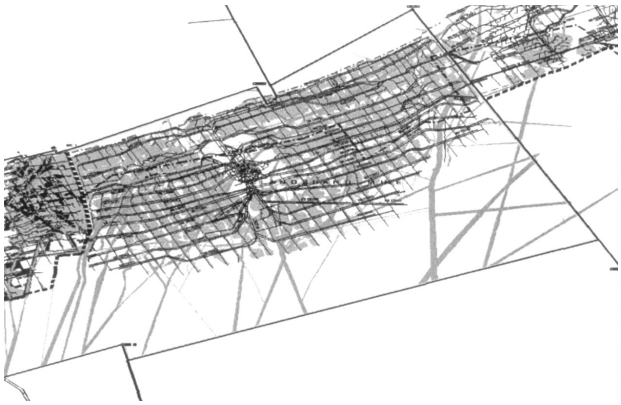

Figure 4—A 'Sequential Grid' mining layout

crosscut intersects the reef plane, another tunnel called a reef raise is developed up on the plane of the reef at ± 22° to the level above. The stoping operations to extract the ore are then conducted from the tunnel network.

The main tunnels are kept sufficiently far ahead of the stoping to prepare for future production as blocks of ore between raise connections that are mined out.

This then is the major difference between the older longwall layouts and the newer 'sequential grid' type layouts. In the former case the tunnels are underneath and behind the overstoped ground and as such are not 'under pressure' *per se*, whereas in the latter case they are out ahead of the stoping operations, and are therefore subjected to moderate to severe stress changes as the mining passes overhead.

And so, whereas tunnelling at great depth was not a critical technology area before (the tunnels didn't 'realize' how deep they actually were), successful ultra deep-level mining can now only take place if we can excavate our tunnels relatively quickly and economically, and with support systems in place that will ensure that they remain intact and serviceable (free of maintenance) for the duration of their lives (usually 30–40 years).

I suppose this begs the question—'Why then did you change from longwalling to sequential grid?' The answer is: 'Because of geology (faults and dykes) and seismicity, and the unacceptably high fatality rates in longwall mining, as well as a total lack of flexibility when the grade gets 'patchy'. The major cause of seismicity in our deep and ultra-deep mines is mining near or through geological discontinuities, and whereas longwalls have to 'plough' through faults and dykes, often with disastrous consequences, sequential grid-type layouts, because of the fact that the development is out ahead, and the position of faults and dykes is largely known ahead of time, allows mining to take place between the geology which is then 'tied up' in stabilizing or 'bracket' pillars between the mining blocks.

The stress environment and support requirements

So what happens to one of these ultra-deep (3000 m–5000 m) tunnels lying ± 100 m below the mining operations? Figure 6 shows the various phases of mining taking place over the tunnel.

Phase 1

The tunnel is developed ahead of mining in virgin ground (quartzite with UCS ± 200MPa) at stresses of 80MPa at 3000 m and 110MPa at 4000 metres, with peripheral stresses of approximately 240MPa and 330MPa respectively around the tunnel edges. At 3000 m moderate to severe scaling will take place, and at 4000 m very severe or heavy scaling will result.

Conventional bolting on its own will not suffice, and fabric support of some kind will be required to contain this scaling. Provided this is done timeously, there will be no further problems until mining takes place.

It is important to note that during the early stages of a mine's life, most of the infrastructural development falls into this category—i.e. developed in virgin stress, no mining-induced stresses later on, and relatively easy to support.

Phase 2

Mining now starts to take place up-above, and as the stope faces move out beyond the original raise position, first in one direction and then the other, stresses are transmitted to the tunnels below.

At 3 km, because the haulage is 100 m below the reef plane, these induced stresses on the haulage are relatively minor, but are severe on the boxholes and portions of the cross-cut. This can be minimized by stoping in both directions immediately so as to create an over-stoped 'shadow' above these excavations.

At 4 km, however, the effects on the tunnels below are more serious. As the stress 'wave' moves (at ± 15 m per month) towards the pillar position on one side (See Figure 5), the field stresses will increase to ± 140MPa on sections of the haulage. Thereafter, as mining proceeds in the other direction and the block is mined out, the field stresses towards the centre of the block reduce to ± 90MPa, because the tunnels are totally overstoped.

It is this 'flexing' of the tunnels which will cause severe damage to tunnels if they are not adequately supported.

Phase 3

After several years of mining a series of highly stressed dip stabilizing pillars are formed (see Figures 4, 5 and 6), and many of these pillars contain the geology (fault or dyke) which we sought to avoid mining through. Those sections of haulage which traverse the positions below the pillars containing geology, are vulnerable to seismic activity.

At 4 km, therefore, tunnels are excavated at high stress (110MPa), subjected to moderate stress changes (up to

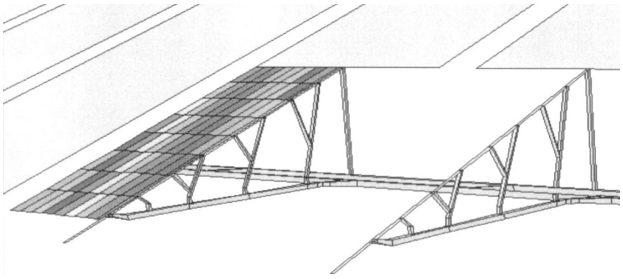

Figure 5—Detailed design for sequential grid mining

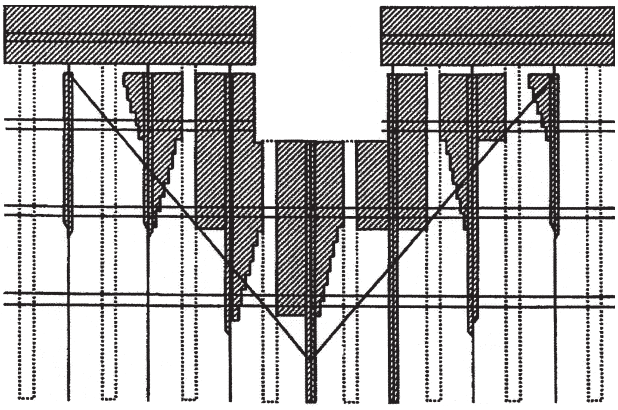

Figure 6—Sequential grid mining—various phases

140MPa and down to 90MPa) at various positions along the tunnel, and susceptible to seismicity below some of the pillars (perhaps 5–10% of the tunnel length).

All of the above makes for quite a challenge to the mining and rock engineers and, unless the tunnels are adequately and timeously supported, this form of mining will simply not be able to take place safely and economically at ultra depths.

So, how do we support these tunnels to ensure that they can put up with all that they are subjected to, and then last for thirty years with minimum additional maintenance? Given that a standard pattern of grouted roof-bolts and/or tendons is mandatory, the following additional 'fabric' support options are available:

- Conventional shotcrete only—referred to as 'pre-shotcrete'
- Pre-shotcrete and subsequent wire mesh and lace (or screening, as the Canadians call it)
- Mesh and lace only (no shotcrete)
- Mesh and lace and post-shotcrete
- Pre-shotcrete, mesh and lace, and post-shotcrete
- Fibrecrete.

In addition to the above, 3 m pre-tensioned anchors will be included where necessary (i.e. those portions of tunnel traversing faults or dykes).

In the ultra-deep level mining environment that I have described in the previous sections, the 'applicability' of the above support systems can be briefly summarized as follows:

Pre-shotcrete (conventional) only

Perfectly adequate for moderate *static* stress environments (i.e. station development and access towards the roof horizon); useless if movement is going to take place (e.g. in the sequential grid mining environment).

Pre-shotcrete and subsequent wire mesh and lace

An 'O.K.' support for moderate stress change. If movement takes place, the shotcrete will fall apart, but the mesh and lace will take over. An important 'plus' with this method in friable ground is that the pre-shotcrete stabilizes the sidewalls and hangingwall and allows for a much better quality wire mesh and lace job to be done. The tunnel will remain serviceable, but repair will be difficult and corrosion of the mesh is always a problem at great depth.

Mesh and lace only

A good support system that has proved itself over the decades. The problem is that once movement takes place, the scaling ends up in 'bags' inside the wire mesh. Nevertheless, the tunnel remains serviceable and people do not get hurt. Repair of damaged mesh and lace is very difficult, dangerous, and expensive. In addition, corrosion is a problem and therefore wire mesh and lace of long-life tunnels which are subjected to large stress changes cannot be recommended.

Mesh and lace and post-shotcrete

This could be a good support system, but more often than not it isn't. Everyone knows that mesh-reinforced shotcrete is a first-class support system for tunnels which are subjected to movement—so why the doubt?

There are two negatives with this method in practice:

If scaling has already taken place and the mesh already contains 'bags', then shotcreting over them does not make for very good support.

Often the mesh (and particularly diamond mesh which vibrates when subjected to shotcrete) is not up against/near the rock face, and so as the shotcreter attempts to cover the mesh, he can waste large quantities of precious material. As he applies layer after layer, the shotcrete sometimes falls off the rock into the mesh—very messy!

The right way to do this, (and a competent side and hangingwall is a pre-requisite), is to apply a flexible weld mesh, and pin it to the sidewall, and then apply the shotcrete; expensive, time consuming—but a good support.

Pre-shotcrete, wire mesh and lace, and post-shotcrete

An excellent support system: the rock is stabilized, and you now have mesh-reinforced shotcrete on top to take care of any movement which might take place, and the mesh is protected against corrosion.

A really excellent support system—BUT—*very* expensive and time consuming, and virtually impossible to install in a 'high-speed', multi-blast, twin-end development.

And, in fact, the same applies to all of these mesh, shotcrete combinations, so this brings us to the last possibility.

Fibrecrete

From the point of view of ultra-deep mining, or in fact any development programme that is going to be subjected to moderate to severe stress change (e.g. a block cave production level while the undercut passes by overhead) this *has* to be the support medium of the 21st century. Major advances have been made in the past 5 years, and here is a material that can perform as well as mesh reinforced shotcrete (See Figure 7), but which can be applied in a one-pass operation and with significant cost savings. In very friable ground, an initial coat of fibrecrete, virtually 'on the face', will stabilize the ground and make the job of bolting so much easier. Then a final coat of up to say 50 mm, provides the tunnel with a permanent support that will put up with almost anything.

Returning to our sequential grid mining environment, all that is required in addition to the fibrecrete are anchors (and

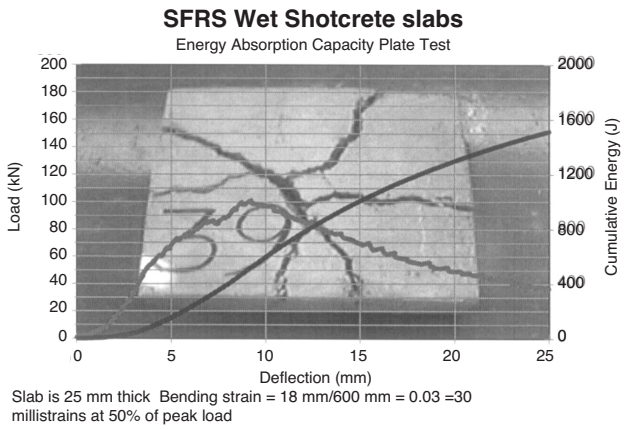

Figure 7—Stress/strain curve for 'Engineered' fibrecrete

possibly mesh and lace) in those sections of haulage which traverse faults or dykes which are also contained in highly stressed pillars up above.

I still see a fair amount of confusion in our industry around support requirements for tunnels under pressure, and in particular in tunnels subjected to changes of stress, notwithstanding the vast numbers of technical papers and MSc/PhD theses that have been published on the subject. I am not advocating that the whole mine gets covered in fibrecrete—that would be hideously expensive—but merely that our rock engineers do a simple analysis of the *work* that the support medium is going to have to do over its lifetime.

One of the major problems which we face in our industry, is that the people applying the support at the development stage are not the same people who have to use these tunnels during their production lifetime. I call this supporting for 'NOW' versus supporting for 'THEN'. One of the most difficult and time-consuming and expensive undertakings is to rehabilitate/repair/support a tunnel once the damage has taken place—it is infinitely preferable to do it up-front before the damage takes place.

So why then, if it is so simple and logical, do we more often than not fail to properly support our tunnels which are going to be subjected to major stress changes later on, with good quality ('engineered') fibrecrete at the development stage?

There are several answers that come to mind.

- We don't know what is going to happen later (or don't care–'or I'm a development contractor').
- We don't believe the fibrecrete will work.
- We can't do it—LOGISTICS simply won't permit it.

The first two are inexcusable, the third is *reality* in most of our deep, multi-shaft, complex-infrastructure mines.

Logistics

In order to put these problems into perspective, consider first a new multi-level, multi-blast, access development programme opening up a new ultra-deep section of an existing high production mine—this implies that the shaft systems are already very 'busy'. We have 5 levels, with twin ends going east and west—that's 20 ends, going say 60–80m per month. It is into this environment that we have to create fully supported, and fully constructed tunnels which are ready and able to support the production as soon as it begins.

There are really three problems with 'getting it right' up-front:

- Application
- Integration
- Supply of material.

Some very brief comments on the first two.

Application

Historically, most of our shotcreting in the South African gold mining industry has been done with small dry-mix machines. These machines are ideal for smaller application jobs, and, of course, there's the problem of dust. There is little doubt that the answer to high volume, good quality, quick time application, lies in modern wet-mix shotcrete pumps—the only problem is *cost;* with 20 ends you would need 10 machines.

Integration

Shotcreting, or worse still, double-shotcreting a 4 m × 4 m × 3,5 m advance end is not something that readily 'happens by itself'. And so, provided the 'now' conditions are reasonable, neither mine crews nor contractors are going to enthusiastically volunteer to include shotcreting into their already frenetic multi-blast cycle.

Consequentially the shotcreting has to move from a voluntary activity to a compulsory activity that is written into the contract. Now the contractors and mine management will sit down and very carefully work out just exactly HOW shotcreting CAN and WILL be integrated into the cycle, and preferably without any loss of metres. This brings us to the third and most serious problem for ultra deep level shotcreting programmes—SUPPLY LOGISTICS.

Supply of material

Assume a moderate programme of 1500 m per month from 20 ends, which would only require 1 × 3 m round per end per day over 25 shifts. If the ends were 4 × 4, and 50 mm of shotcrete was required, this would require 1000 m^3 of material per month (including say 10% wastage), or 40 m^3 per day, or 20 m^3 per shift assuming only 2 shifts available for material transport.

The standard means of supply of shotcrete material in our mines is with bagged material in material cars. 40 m^3 equates to 2500 bags, which would require 50 material cars per day.

This is not an inconsiderable amount of material, and would place severe constraints on most busy shaft systems.

The answer therefore lies in either creating the material underground using run of mine waste passing through a suitable crushing and screening plant, or piping the material underground from a surface plant.

Both have been successfully implemented on South African mines, but for limited application projects; by this I mean shaft sinking projects or dedicated twin ends on a particular level. I am not aware of a successful implementation programme for a deep/ultra-deep, widely-distributed, multi-level, multi-end, 'high speed', multi-blast access development programme. This is not to say that it can't be done—I'm just not aware that it has been done. In my opinion, and I've stated this publicly on quite a few occasions, far too much time has been spent by our engineers on tunnel shape design, and shotcrete material specification, and far too little time on distribution/logistics design. What is required is a holistic systems-engineering approach to the problem.

The future ultra-deep mine

Shortly after the Western Deep Levels (now Mponeng Mine) R1,1 billion shaft deepening project to 3800 m was initiated in 1996, AngloGold announced that it was investigating the possibility of exploiting its Western Ultra Deep Levels (WUDLS) lease area down to 5000 m below surface, and that the possibility existed that two or more new ultra-deep mega shafts could be commissioned. This triggered off a spate of renewed interest in ultra-deep mining, and in addition to a 3D surface seismic survey being conducted over the whole

area, a medium term ultra-deep drilling programme was commenced as well as several conceptual feasibility studies for mining at these depths.

There are at least three potentials for new ultra-deep mining projects in South Africa, in addition to the three existing ultra-deep projects, namely Mponeng, Moab Khutsong and Driefontein Deep. In order to fully evaluate the technological challenges of mining at these depths, the industry embarked upon a collaborative research programme called Deepmine. The participating parties are AngloGold, Gold Fields Limited, Durban Roodepoort Deep Limited, CSIR Miningtek, the University of the Witwatersrand, the NRF, and Department of Trade and Industry (through their THRIP Programme), the Chamber of Mines and the National Union of Mineworkers, as well as the various leading contract consulting engineering organizations in South Africa. A R60 million three-year research programme was set up, and the project is already two years down the track. There are 15 broad technology 'elements' which are being researched, principal amongst which is access development at great depth. This includes rock mass behaviour in tunnels at 5000 m, rock mass behaviour of tunnels in sequential grid-type mining layouts, support requirements, and shotcrete logistics—in fact all of the issues raised in this paper.

While no definitive answers are as yet forthcoming, at least these issues have been 'legitimized', and there is now a broad industry focus on coming up with solutions to these problems.

Whereas, two years ago, the majority of opinions relating to critical technologies involved in ultra deep level mining focused on rope technology, refrigeration, seismicity and new stoping technologies, now at least it is realized that the ability to design, excavate and SUPPORT tunnels at ultra depths is as important as all the rest.

Conclusions

Hopefully I have managed to give you an insight into what tunnelling at ultra depths is all about. In my opinion the tunnelling aspect of our total gold mining endeavour has not received the amount of engineering input or focus that it has deserved in the past. To back this statement up, just witness dozens of kilometres of poorly supported and often poorly constructed tunnels in our gold mines.

South Africa still has huge reserves of unmined gold at great depths, and if ultra-deep mining is to become a reality this century, then one of the technologies that we are going to have to master is tunnelling at ultra depths.

It is ironical that in coming up with an alternative to longwall mining, which while it is wholly unsuitable for stoping in a geologically disturbed environment, is nevertheless very friendly towards tunnelling, the new stoping solution, namely sequential grid-type mining, has gone and put the focus back on tunnelling.

If our tunnels are going to do this new mining method justice at ultra depths, then they have to be properly designed, and excavated, constructed, and *supported* as never before.

I have indicated that the support has to cope with some severe stress changes, and that the most appropriate material available today is most definitely steel fibre (or polypropylene) reinforced shotcrete (S.F.R.S.). What is absolutely critical and fundamental is that these tunnels have to be fully supported at the development stage, and this HAS to be taken account of in the planning, costing, and scheduling of large access development programmes.

The major unresolved problem at this stage is the logistics of bulk material supply to widely dispersed shotcrete machines in remote locations, and perhaps we could solicit your advice and help in this area?

Will we be seeing tunnels at depths of greater than 4000 m in the foreseeable future? I think it will depend more on economics than technology—in the meanwhile we have to focus on the tunnel networks that we already have and those that are on the 'drawing board' between 3000 and 3500 m in the next 5 years and ensure that they are correctly designed, excavated and supported.

Mining at 4000 m is going to be problematic enough in terms of seismicity and cooling. What future mine operators do not need is a collapsing tunnel network; indeed this would spell the end of mining at depth in this country.

It is up to the mining engineers and rock engineers to get on top of the problem now, and in most cases I think it is true to say that we are adequately focusing on the problem. Perhaps we will be able to update you on developments in this fascinating technology area at the next International Tunnelling Conference, but in the meantime some advice from your profession would be welcomed! ◆