

## Preface

This thesis looks at how vertical shafts can be constructed in unstable soil and rock. It is intended that it expands the scope of shaft construction by integrating many fields of expertise and looking at how we can combine our experience.

Because I have an Australian background my search for a research project began there, to build contacts and experience in the Australian environment. The thesis first got off the ground in november 2003 when Dr. Bamford of Melbourne University responded with the potential of projects approaching the field of mining engineering. As the thesis progressed, it became apparent that Dr. Bamford would always be extremely helpful anytime progress threatened to slow.

Through Dr. Bamford the Melbourne based company Australian Mining Consultants (AMC) were involved, where Max Lee and Warren Peck proposed the wall-support problem for raise-boring. Throughout the project Warren was a considerable help, ensuring consistent meetings and generously supplying a lot of helpful data. Max was often out in the field, but because of this, his involvement always guaranteed plenty of practical out-in-the-field problems and solutions.

In the Netherlands Bert Everts and professor van Tol were very supportive of the overseas project, even though it did not always coincide with the research they are normally involved in. They assisted in gaining financial support from the Kivi (The Royal Institution of Engineers in the Netherlands) and in keeping me on track in the final stretch of the project. Dominique Ngan-Tillard, who was always very busy, nevertheless always managed to make time for me. With her knowledge of rock mechanics she was an important bridge between the overseas and local part of my research.

This research has shown that pre-reinforcement, blind hole drilling and remote excavation can all be viable alternatives to conventional drilling and blasting. I hope that, as a result of my work, other students may investigate these alternatives in more detail. More importantly, I hope that smart and responsible mining companies will then be inclined to consider these alternatives.

My thanks go out to all those that have helped me with this work.



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## Introduction

Getting access to underground area's is a useful construction activity for many human activities. Each year we use over 500 megatons of metals in our everyday life, which has all been mined from pits and underground ore deposits sometimes as deep as 3000m. To gain access to these deep deposits requires an efficient method of construction of vertical shafts to get there, to transport men and equipment, to carry fresh air and to carry the ore out.

Besides mining we also use shafts to transport water through damsites, for transportation purposes through tunnels in urban areas and to store chemical and radioactive waste. Research into shaft construction has always been limited but is now becoming of increasing importance. Because ore bodies are becoming depleted, shafts are being constructed ever deeper and in ever more challenging geologies. Secondly, unsafe practices that endanger the lives of men working in shafts have become unacceptable.

This research looks into ways of constructing vertical shafts in area's with soft and weak overburden that have been uneconomical previously. The focus is on ways to reinforce soft soils and soft and fractured rock. Without further treatment such geologies normally cause collapse of the shaft.

The research looks at construction methods within the confines of increased safety demands, low cost and varying geology and hydrology.

During the research, no single obvious solution became apparent for reinforcing weak geologies. However it became clear that there are a great number of different geologies which can each be tackled with specifically tailored construction methods.

The result of this research is an insight and methodology for determining how to best construct shafts in weak overburden. A decision schematic now allows mining and construction companies to take informed decisions at an early stage. Expert experience, examples and literature have been used to generate design criteria and quick-and-easy models.

Although it should be noted that detailed research and local experience is always necessary when designing and constructing shafts, this report should reduce risks and help decide on optimal shaft construction methods early on, prior to detailed design.

## Document Structure

This report is built up in a number of research stages.

In the first chapter, an analysis of the raiseboring method is given. The problems and limits of current practice are analyzed and the aim of the research is set. The different types of shafts are identified along with their demands on dimensions and stability.

Then the various methods of vertical shaft construction are researched. Current methods, innovations and methods from other fields are investigated. This was done under guidance of Australian Mining Consultants and Melbourne University. During this period in Australia an examples database was started, and many experts were consulted in regard to their experience with shaft construction methods.

In chapter three, the wide array of methods is assessed. To be able to do this, the geological conditions that affect shaft construction are analysed. With these constraints in hand, the methods are evaluated and three are identified for detailed research.

Chapter four describes methods of excavating relatively shallow shafts with continuous cutting machines.

Chapter five details Blind Hole Drilling which is a method derived from oil-well type drilling. A site visit was made in the Springvale shaft thanks to Zeni Drilling.

Chapter six looks into forms of pre-reinforcement. These are methods where lining or reinforcement is constructed prior to excavation, such as grouting and diaphragm walls. This research was continued in the Netherlands where the knowledge of deep foundations and geotechnical modeling is extensive.

In Chapter seven shaft stability is discussed, and also the way in which shaft stability is affected by the different construction methods. Empirical and analytical methods are demonstrated so they can be used to compare methods.

The concluding chapter presents a decision model for determining the best construction method in varying geologies. Alongside this, recommendations for further research are presented. Furthermore the experts consulted and the examples database are shown in the appendices.

The structure of the report is also given schematically in Figure 1.

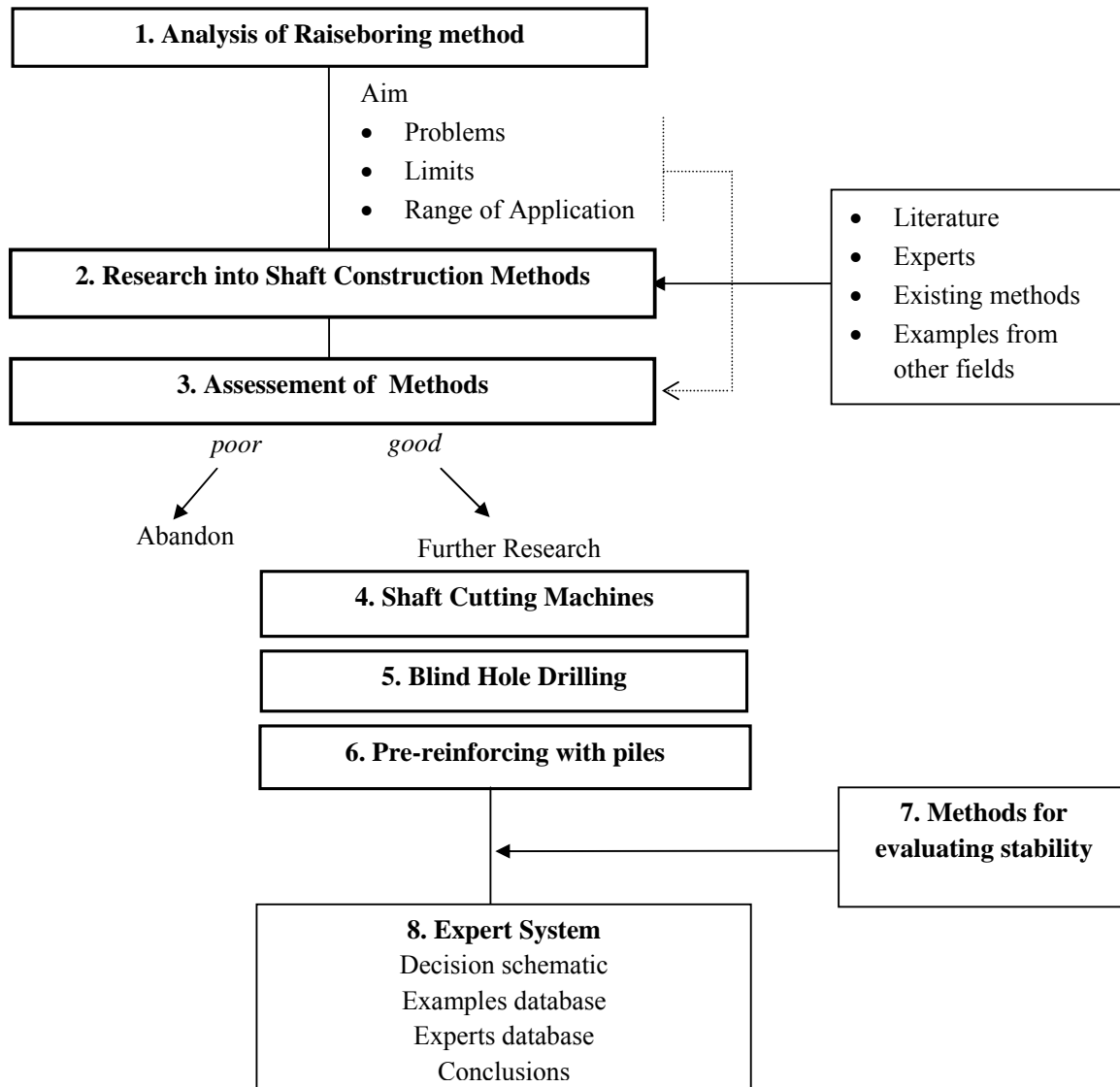


Figure 1 - Overview of the report

## Abstract

Minesites require ventilation shafts and ore passes to gain access to resources. As ore becomes depleted, methods for constructing deeper and cheaper vertical shafts are required. Also, increasing safety demands mean the risk of having workers down shafts is becoming unacceptable.

Raiseboring is a common method used to create ventilation and ore shafts for secondary mine openings. Lengths usually range from 200-800m, with diameters up to 7m. The raiseboring process works by boring a pilot hole to an existing horizontal shaft, where a reamer is installed. This reamer is pulled back up to the surface creating the shaft. The method is efficient because clippings fall down the shaft and can be left there or easily collected. More importantly there are no men down the shaft.

In layers of soft soils or highly fractured rock, the raiseboring method becomes unsuitable.

The weathered rock caves into the hole, jamming and possibly damaging the reamer,

sometimes even causing collapse of the entire shaft. This thesis looks into cost-effective and safe methods of constructing ventilation shafts through weak rock.

Analyzing the potential methods has resulted in an impression of the suitability of each method in different conditions. Three areas have been selected for further research.

- ▶ Blind-hole drilling, with the shaft filled to the top with mud to stabilize the walls is a safe, innovative method. However the method can be restricted in its application because of large transportation and setup costs, limited thrust and problems with existing mine openings.
- ▶ Remote shaft cutting machine's (similar to road-headers) can be dropped into the shaft, or a similar microtunneling machine or a boom-mounted cutter. A wide range of lining methods can be applied to line the shaft as drilling progresses, of which the most suited are remote shotcreting, floating in a lining and caisson sinking. This low-investment method may be suitable for traversing the weak overburden, leaving the remainder of the shaft to be raisebored, but the method is not suited to deep layers of weak rock.
- ▶ At first glance grouting of a ring of mini-piles, or localised grouting in weak layers, is a method with high potential as it enables raiseboring in most situations. However previous cases have shown the method to be ineffective, with collapses both South African and Australian mineshafts. Problem areas are i) inaccurate measurement and positioning of grout; ii) dispersion of grout due to groundwater flow; iii) grout not getting into small clay-filled joints and escaping into wide fractures.

The thesis concludes with a method diagram to assist mining companies in selecting suitable construction methods at an early stage.

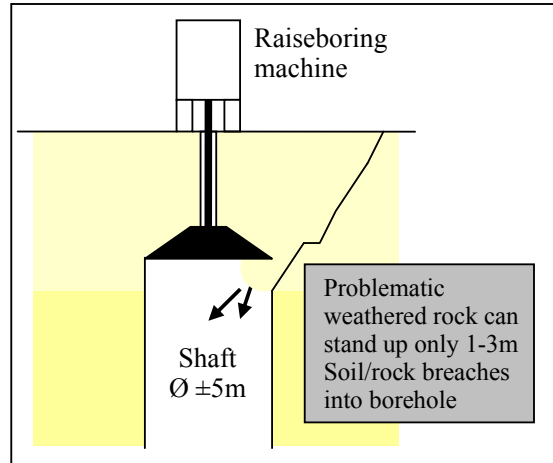


Figure 2 - The problem of wall instability encountered in soft soil/rock due to fractures and weathering, during raiseboring.

# 1. Analysis of the raiseboring method

## Introduction

This chapter explains the kinds of shaft being constructed. It introduces us to mining engineering and traditional methods of constructing ventilation shafts and ore passes. The purpose, dimensions and engineering demands of these shafts are discussed. This illustrates the problems shaft designers encounter, and specifically explains the problem of raiseboring through weak overburden. Later on the other shafts such as penstocks, tunnel access shafts, waste disposal shafts, foundation shafts and others are discussed, and how they relate to the raisebored shafts in mining engineering.

## History

### Elements of a mine

Mines are used to access and recover ore bodies which are made into minerals. Australia is a leading country in the field of mining, recovering large amounts of gold, copper, zinc, iron and aluminium.

There are two main types of ore access, open pit (or surface mining) and underground mining. Open pit mines are used where ore is near the surface. Underground mines are used to gain access to deep ore bodies, or ore bodies where the surface mining operation has depleted the ore reserves near the surface.

Ore bodies with different properties, are mined in different ways. The development method used depends on many factors: host rock strength, ore strength, ore grade, thickness and dipping angle of ore bodies, etc. In longwall or stope and pillar mining large areas of ore are mined out underground, leaving walls or pillars

to support the overhang. In block caving, chunks of the ore body are collapsed into underground areas using controlled blasting. The fragmented ore tumbles into the shafts where it can be hauled out. Cut and fill stoping is used in near-vertical ore-bodies that are susceptible to collapse. It is mined out in layers and backfilled to support the overhanging rock, before moving to the next level.

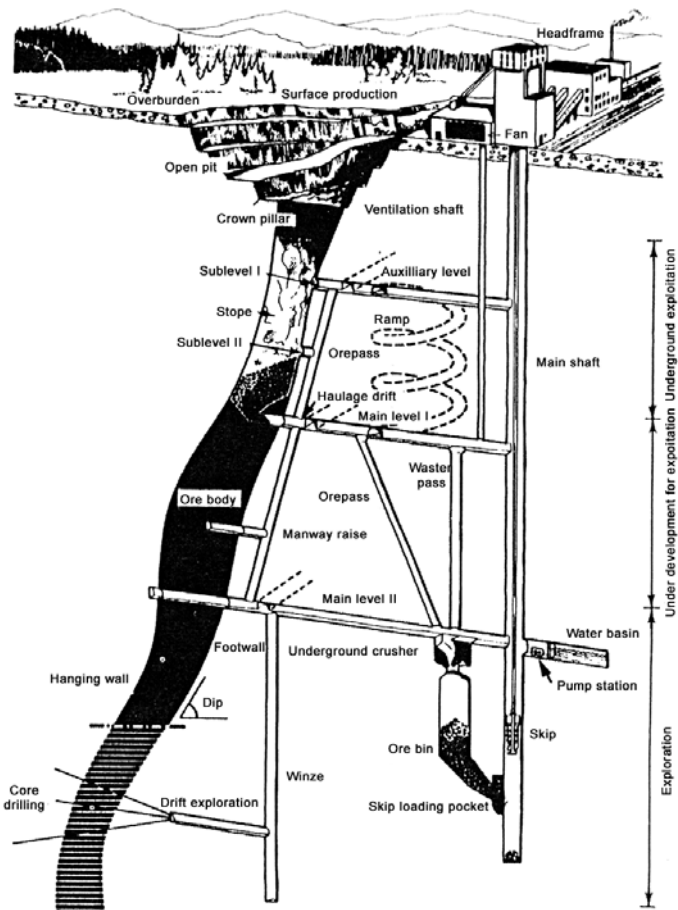


Figure 3 – Picture of typical mine development and its' elements [Hartman & Mutmanky 2002]

Whichever method is used, underground mining requires vertical shafts. These shafts can have many purposes. The primary shaft is usually large (6-12m diameter) and is used to get workers and equipment into and out of the mine, for ore haulage and for utilities like electricity and water.

Generally the bottom level of the mine has some sort of ore transport system that brings the ore to the primary shaft where it can be lifted to the surface. This is called the haulage level. By building 3-8m diameter vertical shafts to this haulage level, ore can fall naturally down towards it and transported further. These shafts are called *ore passes*.

Because of the heat from the earth's core, deep underground mines can become very hot. This heat, combined with moisture, makes working conditions underground very harsh. To allow a workforce to function effectively, cold and dry air should be circulated through the mine. To this end *ventilation shafts* are constructed to the surface with big blowers to pump the air. This also helps to remove hazardous dust or even hazardous gasses from the drilling and blasting of the ore bodies. Ventilation shafts and ore passes should have a round, smooth surface to reduce wall friction.

Sometimes extra secondary openings are constructed as a mine develops, because it becomes uneconomical to carry the ore all the way to the primary haulage shaft. A second haulage shaft is constructed near to new ore bodies.

Because of the need for access openings, ore passes and ventilation shafts, a safe and economical method of vertical shaft construction is a vital part of mine development.

### Raiseboring & shaft sinking

Up to the 1950's the conventional way of constructing shafts was by drilling and blasting. A drilling jumbo drills holes around eight metres long into the rock mass which are then loaded with explosives. With a mucking bucket the rock is hauled out and wire mesh, rockbolting and steel rings installed to stabilize the walls. This method is slow and cumbersome because all the

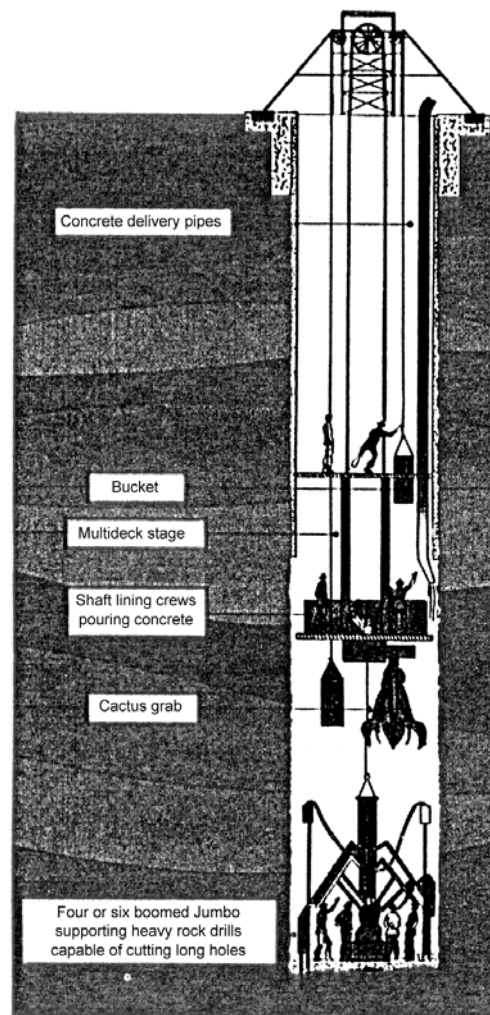


Figure 4 – Drilling and blasting a shaft

workers and equipment had to be hauled out of the hole before each blast. Conventional drilling and blasting is still the most common method of shaft sinking used to date, although work is now carried out from separate blasting and lining platforms.

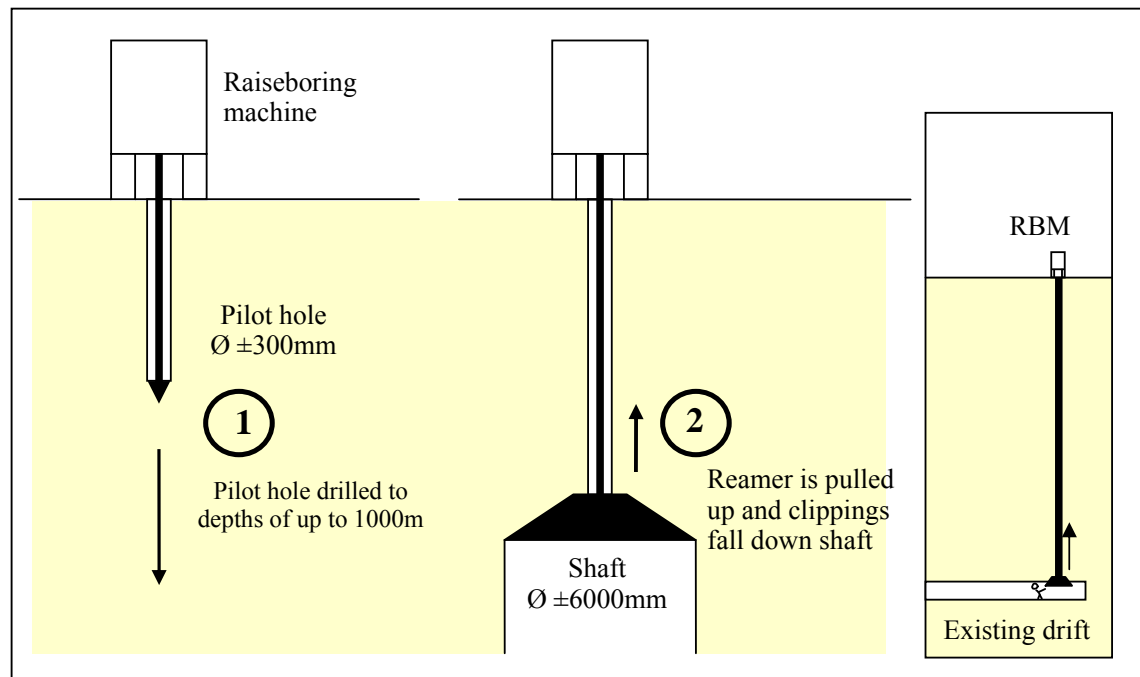


Figure 5 – Overview of the raiseboring process.

Looking to optimize this process, mining engineers went in search of continuous machines to speed up shaft sinking. This is where shaft boring and drilling came into practice. Shaft boring machines were constructed, but these had problems in removing the cuttings. The tailings would clutter and thereby damage the cutting head and haulage couldn't keep up with drilling. Also maintaining verticality with a boring machine was an issue.

Later on the V-mole was designed which had the cuttings fall down a pilot-hole and used a sloped cutting head to transport them away from the cutters. Because of the pilot-hole guiding it, the V-mole was also easier to keep on the vertical. However the problem still remained of needing shaft access underground to remove the cuttings. This led to the adaptation of drilling rigs from the oil industry. In the beginning these rigs were limited in the torque and pressure they could apply to the cutting face, and thus diameters were initially only small. This method is known as blind hole drilling or shaft drilling.

Alongside the development of shaft boring machines, engineers had another growing concern, which was mine safety. Looking for ways to get mine-workers out of dangerous shafts, raiseboring was invented and developed into a successful technique between 1960 and 1970.

Raiseboring uses a small diameter drill rod, around 200-300mm, to drill a pilot hole down to the required depth of the shaft which can be drilled up to around 1200m. The raiseboring technique

assumes there is already existing shaft access at the bottom of the shaft. Once the pilot hole has been drilled to the desired depth, a reamer of up to 6m diameter is attached to the drill rod. The reamer is then pulled back up to the surface, creating a round shaft. The pilot hole is used to let the clippings fall down the shaft by means of gravity, where ore can be collected and other rock can be used as backfill in old mine cavities.

The raiseboring technique has some major advantages compared to traditional shaft sinking methods.

- *Safety.* There are never any men down the shaft (except to fit the reamer).
- *Speed.* Because it is continuous and because muck automatically falls down the shaft, speeds of up to 30m/day can be achieved.
- *Smooth.* Because no blasting is used, the shaft walls are very smooth. A smoother shaft is more stable, and has less wall friction, making it ideal for ventilation shafts.
- *Versatile.* A raiseboring machine does not go down the shaft and can be easily re-used for many shafts. Compared to a shaft boring machine a raiseboring machine is much more versatile, making it a more economical investment. Raiseboring machines can drill under angles, with low headings and can be easily adapted to drill upwards from a drift (called boxhole drilling or downreaming).



*Figure 6 - Sign near ventilation shafts in outback Australia. It shows one of the safety issues with vertical shafts. It is also dangerous to work in shafts because of the chance of rockfall from overhead*

Mainly because of the advantage in safety, raiseboring has become a popular method used around the world. However there are some restrictions to it's application which will be discussed in the next section.

## **Geological Conditions**

Australia has a very specific geology which is largely determined by the absence of a glacial period in it's history. This means the bedrock is commonly covered by a thick layer of overburden which has been built up over as long as five million years. Deep weathering is common in the rock, leaving highly fractured, deeply weathered zones. It is common for these most unstable zones to be just above the bedrock as this is where most of the leaching and weathering through groundwater flow has taken place. From an engineering point of view this leads to a difficult situation where the most unstable layers are the hardest to get to.

In South Africa karstic (limestone) zones are common. Although overburden layers are not necessarily as old, this leads to the same sort of situation where weathered zones (even entire cavities) can occur at deep locations underground.

In practice it is not very practical to look at the geology of such large regions, as each site always has its individual geology. However it is useful to understand such large scale differences in geology. Take for example a tunnel access shaft to be constructed in urban areas. Typical of urban areas, such as the Netherlands, is the close proximity of rivers and the coast. This means alluvial and fluvial deposits cover any igneous or metamorphic rock. The behaviour of this geology is determined by soils and clays which consist of individual particles low cohesion and high porosity compared to rock. Also water levels can be much higher than in remote mining locations. It should be clear that this location requires an entirely different engineering approach.

## AMC Consultants

Max Lee and Warren Peck of AMC Consultants Pty Ltd have supervised this thesis, helping out with advice and supplying case examples where possible. AMC is well known in Australia for providing a broad range of Mining Engineering, Geotechnical, Geological and Corporate consulting services to the exploration, mining and financial services industries.

AMC has an international customer base and the scope of their work includes engineering, ore reserves, feasibility studies, due diligence project reviews, valuation of companies and projects, technical research and advice to management. AMC maintains a policy of independence from exploration and mining interests and complete confidentiality of client information. Extensive records of mining costs, performances and productivities are maintained as a basis for engineering, due diligence and feasibility studies.

AMC agreed to support this research thesis looking at stability problems encountered during the raiseboring of shafts. AMC invited me to use a civil engineering approach, applying any experience from foundation engineering, tunnelling and off-shore around the world that might seem useful.

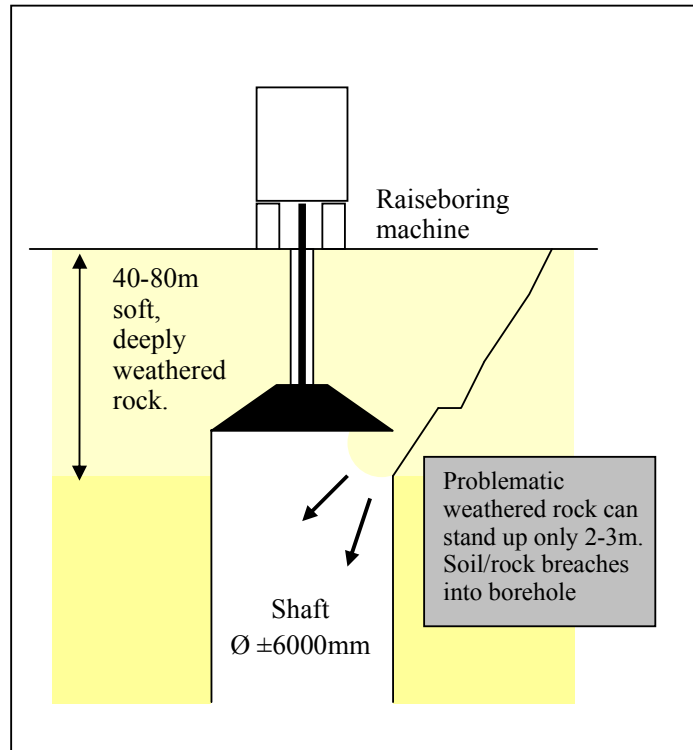


Figure 7 - The problem of wall instability that is encountered in soft soil/rock due to fracturing and weakness of the strata. This is a typical Australian situation, but similar circumstances exist in Scandinavia, South Africa and China.

## Aim

During the construction of raiseboring shafts in Australia, problems have been encountered because of the thick layer of overburden. Because there is no possible access to the shaft beneath the reamer, it is not possible to immediately construct a lining. When the reamer passes through the weathered zone, both the back of rock above the raiseborer, as well as the walls, become unstable and slip into the reaming zone. The instability is due to either low strength of the overburden, extensive jointing or both.

This causes many problems:

- Overbreak along the shaft wall, which will later require grouting and rockbolting.
- Jamming and potential destruction of the reaming head.
- Breakage of the drill rods and loss of the reaming head.
- Deformations at the surface and even entire collapse of the shaft.

This thesis will look at solving the problem of wall and back instability during raiseboring.

### **Thesis aim:**

**Find a cost-effective and safe method for construction of raisebored shafts through low strength and/or highly-fractured overburden.**

During exploration of methods that are currently in use around the world it will become clear that raiseboring may not be the single solution for construction vertical shafts. The scope of research will include other methods that may be more effective than raiseboring.

In the following section the *problems* any construction method should overcome will be discussed – any new methods or adaptations should overcome these problems.

Besides the stability of the walls, there are other *limits* which currently apply to current raiseboring practice; if the range of these restrictions can also be widened, new shafts may become feasible along the way.

## Problems

### Safety

Safety is an important issue in mining. *Figure 8* from the Mine Safety and Health Administration of the United States shows how fatalities in mining have continuously been reduced. Australian mining shows a similar trend with less than ten fatalities a year, and is quickly pushing to the forefront of mining safety.

Unfortunately vertical shafts are one of the most dangerous places of a minesite.

This can best be illustrated by the simple words of an experienced geologist :

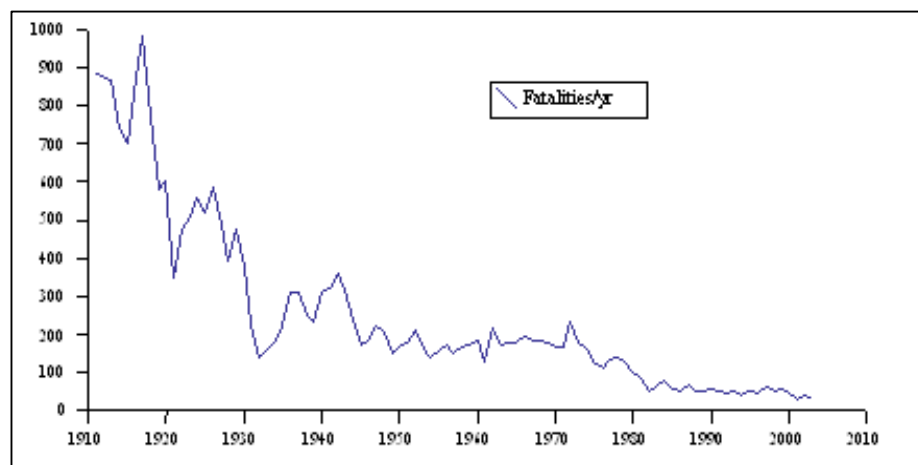
- ▶ People fall in them
- ▶ Tools and rocks fall down them, on top of the people in them.

The great advantage of the raiseboring method is it's high level of safety.

During raiseboring the only time men are actually in the shaft is for changing the reamer or bits on the reamer. This mine access is always planned carefully, and prevented altogether whenever possible (for example by using extra long life bits that prevent having to change the reamer during the raise).

Any devised construction alternative will ideally prevent any need to have mineworkers in the shafts, as with current raiseboring practice. This is referred to as *remote* construction.

Also a mechanical drilling method, that does not make use of blasting, is preferred. This is because there is no sudden impact and because the excavation is smoother and thus inherently more stable.



*Figure 8 - Fatalities in Metal and Non-metal mining in the U.S. [Courtesy MSHA]*

### Cost

The construction of the vertical shaft must be cheap. Civil engineering practice is generally aimed at long-term structures for urban zones; mining engineering however, has a more remote, low-cost and

temporary character. This means elaborate civil engineering solutions quickly become too expensive for mining. On the other hand the remoteness of mining locations means excessive deformations are rarely a problem, unlike in civil engineering practice.

Low cost is a vital key to a successful construction method.

Generally this means using low-cost machines that are re-usable and easy to set up. Shaft boring machines and V-moles, as we will see later, are typically high-investment machines usually not suited to simple shafts in remote locations.

In the majority of cases, high construction costs are a consequence of :

- ▶ high capital investments with long periods till payback
- ▶ the large amount of labour involved

Therefore an automated, continuous process with a high development rate is essential to cutting costs. In all potential solutions the penetration rate forms a key indicator of the total shaft cost.

### Wall and back instability

Raiseboring has been applied successfully around the world. The problems with raiseboring occur mainly in the soft and fractured overburden. The walls collapse as the reamer traverses the fractured area's. Sections of rock outside the shaft diameter that are connected by weak fracture planes can cave into the shaft, called overbreak. This is very common in drilling and blasting operations, but can also occur where the reamer travels from fresh to soft rock.

The collapse of big blocks can cause the raiseboring machine to jam potentially resulting in loss of the raiseboring machine, or even collapse of the entire shaft.



*Figure 9 - Looking down what was intended as a round ventilation shaft. Overbreak has occurred along two intersecting fracture planes.*

Not only the walls, but also the back (the overburden above the reamer, also referred to as crest or crown) can become unstable. This can sometimes be prevented by maintaining constant pressure on the back by keeping the reamer close to the back.

There are generally two reasons for instabilities: The first is the presence of incohesive and weak material like running sands, clays and deeply weathered soft rock. The other is instability due to intensive jointing and fracturing, sometimes made worse by water pressure or soft filling (such as clay gouge) in the joints.

These instability problems should be addressed. Barton's Q-system [90. Barton 1974] will be used incorporating stress reduction factor (SRS) [91. Kirsten 1984] can be used to test stability of the back (or crest) and walls. Several adaptations for vertical shafts in raise boring [89. McCracken 1996] will be adopted.

## Current limits

### Non-entry method

The shaft under the raiseborer cannot be accessed, because of the instable walls and back overhanging the shaft. In some areas, where the rock has some stand-up-time, the raiseborer is quickly pulled to the surface. Even then no workmen can access the shaft because it is unstable. In this case the shaft is first lined by using a remote fibrecreting machine dropped into the shaft. Because estimating time-dependant behaviour is a very unpredictable task, remote fibrecreting can be a dangerous exercise if the stand-up time is critical.

A method of construction that prevents the necessity for having men in the shaft, like raiseboring, greatly increase it's level of safety.

### Limited Diameter

The maximum diameter that can be drilled in one pass is determined mainly by the drilling torque and the face pressure that can be applied to the reaming head. Torque and pressure are in turn limited by the bearing capacity of the drill rods. Because reaming is directed upwards, the weight of the reamer and drill rods works adversely, limiting raiseboring diameters to a maximum of around 7m. Such dimensions would be done in two or even three stages.

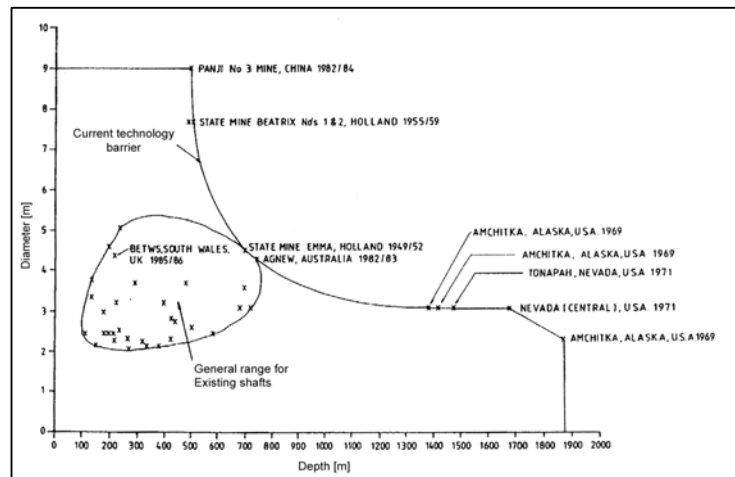


Figure 10 - Diameter versus depth for existing drilled shafts [Bell 1988]

There are some cases where it useful to create shafts with larger dimensions such as when shafts are used as ore-passes or access shafts. Generally 3-4m is a comfortable diameter for most ventilation shafts, but with greater depths larger diameter ventilation shafts will be needed. South African mines at depths over 1000m already require ventilation shafts of 6 ½ m diameter.

### Bottom-end access

To attach the reamer to the drill rods at the bottom of the shaft, there must be an existing drift to get to the foot of the shaft. This, in combination with the restricted diameter, is why raiseboring is generally used for ventilation shafts or ore-passes, rather than primary mine openings. Although for the purposes

of this study, underground access is assumed, shaft sinking methods from the surface would have added value over raiseboring

Table 1 - Overview of problems and limits in shaft construction

<b>Main problems in shaft construction</b>
Safety
Cost
Unstable overburden
<b>Limits on shaft construction</b>
Methods that do not require entry into the shaft
Increased shaft diameter
The need to have bottom-end access to the shaft
Construction in area's with low groundwater table
Construction in area's with high water inflows
Speed of muck removal
Drilling versatility

## Groundwater

A ventilation shaft should generally be kept relatively dry. In most situations in Australia, the water-table is generally very low (-50m or a few meters above bedrock) and it is also highly saline. On one hand this means construction of the shaft may be easier; limited flows can easily be pumped from the shaft. On the other hand it rules out some construction methods such as ground freezing. Dry rock cannot be frozen, and high flow rates which inhibit freezing result from raising the water table.

Also high flow rates are encountered around many bedrock zones because of pumping activities around existing mines or aquifers. In this case flow rates may be so high that it is not possible to pump the shaft dry. In such cases it would be useful to find a construction method that also limits the flow of water into the shaft. Ventilation shafts should be kept especially dry because a moist shaft supplies humid air that greatly affects the climate in the shafts.

It should also be noted that high water inflows through joints greatly affect the stability of the rock mass. In general it would be useful to find construction alternatives that can not only be used with a low groundwater table, but also in unfavourable conditions like high groundwater flow rates or a high water heads.

## Muck removal

Raiseboring uses gravity to remove the drill cuttings from the shaft. Once down the bottom of the shaft, the conventional mining equipment (used for mining the ore) can be used to remove the muck. This is a common and efficient practice for raiseboring, however in some alternate methods muck removal is often the single factor limiting progress.

## **Drilling versatility**

Raiseboring allows accurate drilling up to around 45 degrees, depending on how easily the muck passes through the shaft, and it allows drilling from within a shaft with limited headroom. A raiseboring machine can be used many times with different reaming heads in varying diameters and geologies. Any alternate methods should attempt to maintain this versatile nature of raiseboring.

## Range of application

### Mine ventilation and ore passes

To assess the different methods, the typical case AMC and other mining companies in Australia are interested in, will be described below. This is a common “weak-overburden” shaft that might be required for mining in Australia. A typical ventilation shaft would require a diameter of around three metres, however increasing depths of mining require increasingly large ventilation shafts.

Also ore-passes, although less common, would require larger diameters over 5m. Open cut or conventional drill and blast are generally used on shallow shafts up to 100m. Most shafts built today are up to 500m length, with problems of high temperature and long haulage distances for deeper shafts. Although uncommon, depths up to 1000m are considered because of the need to access deepening ore-bodies.

It is hard to describe overburden because of the multitude of rock conditions that can be encountered. In Australian minesites the thickness of the overburden generally ranges between 30 to 100m, with problem areas consisting of highly weathered sandstones and mudstones, slates and shales, extremely weathered graniorites, etc. Also several layers of quartzite veining are taken into account as it is not uncommon for hard, abrasive layers to intercept weaker ones causing problems with cutter or drill bit wear.

In Australia because of existing mine-workings the groundwater table is generally very low. Existing mine activity usually implies water is already being pumped leading to high groundwater flow rates. Also the groundwater is typically highly saline which affects freezing and grouting characteristics.

The range of situations in mining, with the most typical dimensions in bold, are given on the left side of *Figure 11*. Ventilation shafts and ore passes are not the only application for vertical shafts. Other applications will also be considered in the scope of this project. However differing applications also have different requirements.

Primary shafts for mine access are similar to ventilation shafts for mining, but much larger in diameter. They cannot be raisebored because there is no bottom-end access to the shaft, and alternative methods are required.

### Tunnel access shafts

Access and ventilation shafts for civil tunnels are another increasingly important application. Several recent accidents with explosions and fire in tunnels in Europe have led to an increased importance of emergency exits from enclosed spaces. Also tunnels are becoming both deeper and longer, requiring longer more complicated access shafts.

Tunnel access shafts may be considered for raiseboring because they fulfill the important criterion of bottom-end access. On the other hand permeability and stability criteria are far more stringent.

Because of the long life of tunnels and the large number of people that use them, they should be much less susceptible to leakage, damage and collapse, also in the long term.

Except for mountain-passes, tunnels are generally be built in densely populated urban areas. This means surrounding structures can easily be damaged by deformations, leading to tight limits for surface deformation. Also it is common for urban areas to have developed in alluvial or coastal deposits, leading to a sedimentary lithology consisting of clay, peat and sand rather than rock. In this case the water table is usually near the surface and pumping is limited or prohibited completely. This is a typical situation in the Netherlands.

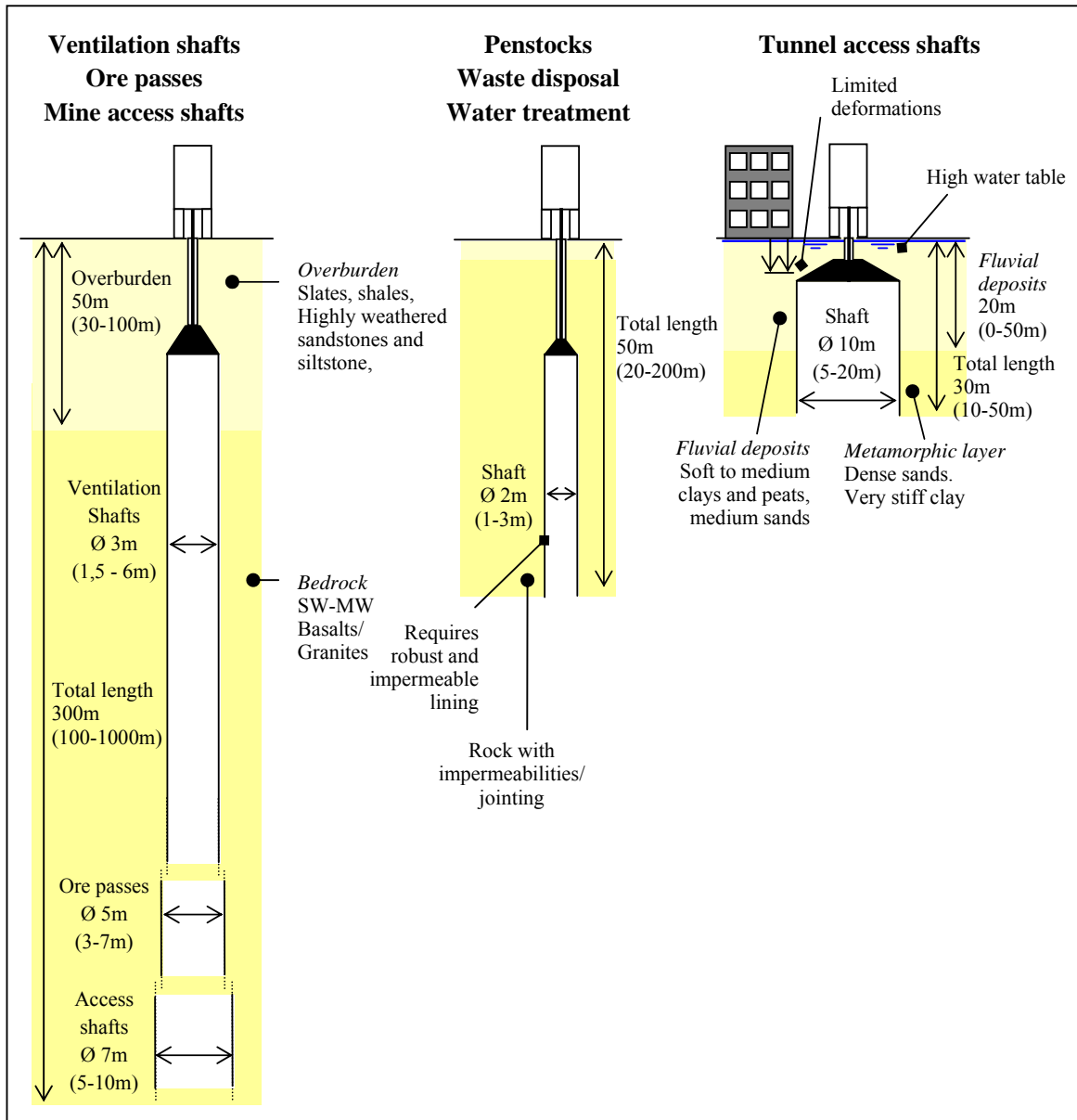


Figure 11 - Typical shaft dimensions and geological conditions for different shaft types. (Typical minimum and maximum dimensions are shown in brackets)

The dimensions of tunnel access shafts also differ from mineshafts. From a cost perspective a tunnel will be constructed as close to the surface as possible, leading to shaft lengths of 50 metres at most, but more commonly around 20 metres. The diameter required for safely evacuating commuters in a tunnel, or allowing access for emergency workers is generally much greater than for mineshafts, ranging from anywhere between 5-20 metres. Tunnel access shafts that are longer than they are deep have wall support systems based on resistance of the toe of the wall (such as sheet piles) hence these shafts will not be discussed in this thesis. TBM entry and exit shafts will not be discussed because of the length required to fit the machine is much greater than the depth. The specifics of the tunnel access shafts that will be discussed are shown on the right in *Figure 11*.

## **Other applications**

Penstocks are shafts used for discharging water through dams. Mostly a turbine will be constructed in the shaft for generating hydro-electric power, but penstocks also exist simply for redistribution of water. Penstocks are generally around two metres in diameter and between 20-200m long, depending on the distance the water should travel. Again raiseboring is a useful alternative as bottom-end access is available (at the bottom side of the dam) and because a smooth, round shaft is created, reducing friction. Penstocks should always be lined because they should be impermeable and they should be able to withstand the high water pressures.

Similar to penstocks are wastewater treatment shafts and chemical and radioactive waste disposal plants. For these shafts a safe, impermeable lining is vital. Also sufficient depth is important for the filtration of wastewater in the case of treatment shafts, and to prevent chemical or radioactive waste from affecting surface soil and groundwater in waste disposal shafts. Penstocks, wastewater and waste disposal shafts are also shown in *Figure 11*.

A few very specific shafts have been constructed for special needs. For example to access the underground Superconducting Super Collider in Texas. Shafts were constructed up to around 80m depth in both small and large diameters (up to 20m).

Shafts that will not be included in the scope of this research are water wells, sewer shafts and shafts for extracting geothermal power. These shafts are generally small in diameter (and remain unlined) and are drilled with efficient technologies driven by the oil industry.

Some foundations for very large civil engineering jobs such as coastal bridges and off-shore platforms also use shaft drilling technology. Although drilling methods are sometimes similar, the purpose is entirely different. Foundation shafts are designed solely to transfer immense vertical and horizontal stresses to the subsurface and not for gaining access to deep locations. These shafts will not be considered in this study.

Table 2 – Types of shaft that will be facilitated in this study, including typical shaft dimensions

Shaft type	Main demands	Diam.	Depths	Scope of work
<b>Mining ventilation</b>	Dry, deep, smooth, cheap	3 (1,5-6)	300 (50-1500)	Primary scope
<b>Mining ore passes</b>	Dry, deep, smooth, cheap	5 (3-7)	300 (50-1500)	Secondary scope
<b>Mining access shafts</b>	Dry, deep, smooth, primary access	7 (5-10)	300 (50-1500)	Secondary scope
<b>Penstocks</b>	Narrow, smooth, impervious	2 (1-3)	50 (20-200)	Secondary scope
<b>Chemical/ radioactive waste dumps</b>	Deep, totally impervious	2 (1-3)	100 (20-300)	Secondary scope
<b>Water-treatment shafts</b>	Impervious, deep	2 (1-3)	50 (20-100)	Secondary scope
<b>Tunnel access shafts</b>	Shallow, large, impervious, safe, little deformations	10 (5-20)	20 (10-50)	Secondary scope
<b>Access to supercollider</b>	Impervious, safe	7 (5-10)	50 (40-80)	Secondary scope
<b>Geothermal heat storage</b>	Impervious, deep, narrow	0.8 (0.5-1)	40 (20-200)	Secondary scope
<b>Gas and water pipelines</b>	Horizontal, little deformations, safe, impervious	1.2 (1-3)	(5-5000)	Outside scope: Horizontal drilling is well developed.
<b>Piles for off-shore Piles for large bridges</b>	Bearing of loads	1.4 (0.6-2)	30 (10-60)	Outside scope: Load-bearing has different mechanics
<b>Water pits</b>	Very narrow, pervious, cheap	0.3 (0.1-1)	30 (8-350)	Outside scope: Tiny diameter has different mechanics

## 2.Methods of shaft construction

### Introduction

This chapter will look at potential ways of constructing vertical shafts through soft overburden. Some methods have been commonly used, some are still being developed and others are just concepts and ideas from other fields. Generally there are three possible approaches allowing a shaft to be sunk through highly weathered overburden:

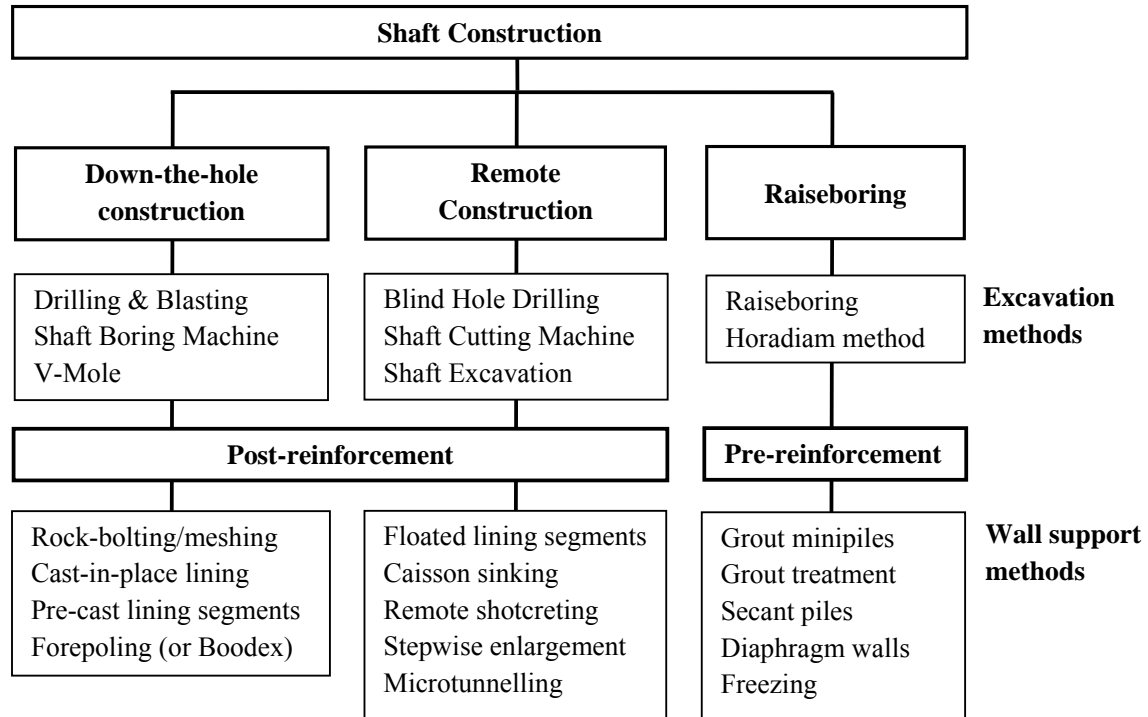


Figure 12 - Overview of construction methods grouped by location and direction of the construction activities.

## Down-the-hole shaft sinking methods

### Conventional drilling and blasting

In conventional drilling and blasting, a shaft is constructed by drilling holes and filling them with explosives. The holes are installed in patterns and the explosives carefully detonated in a specified order, to maximize blasting performance. Using this method, drilling and blasting can sink around 5-10 metres in one blast.

Because of the discontinuous manual processes of drilling and also of mucking out the shaft, this is very labour-intensive, unsafe and has high running costs. However it is still commonly used and is often still the most viable alternative for shafts up to 100m in length. A second working platform is utilised for immediately lining the shaft with rockbolting and mesh, shotcrete and/or a cast in place lining. Nevertheless drilling and blasting is not very well suited to soft overburden because the blast can easily

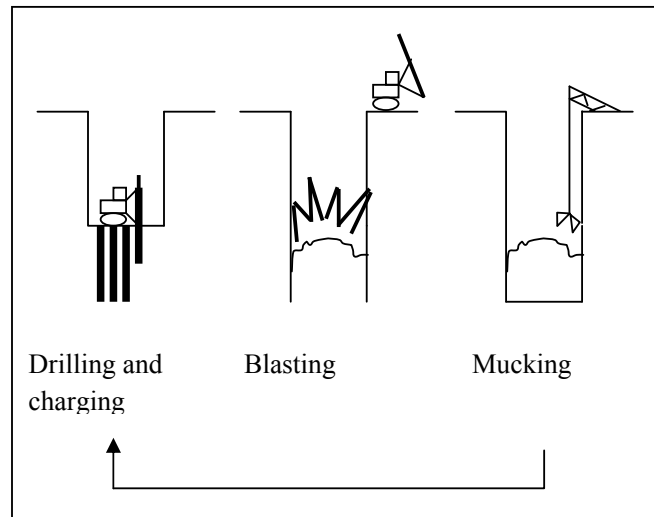


Figure 13 – Shaft sinking through conventional drilling and blasting

cause overbreak or collapse of parts of the shaft. The advantage is there are low setup costs and problems with stability can be dealt with as the shaft progresses. This method is especially useful for access and hoisting shafts because the hoisting equipment for production can also be used during construction.

Table 3 - Shaft sinking methods: Drilling and Blasting

<b>Drilling and Blasting</b>	
<b>Advantages</b>	+ cheap and quick setup + suited to most ground conditions (in combination with a second working platform for lining the shaft)
<b>Disadvantages</b>	- unsafe for mine workers - costly and time-consuming process - overbreak is common
<b>Examples</b>	VR-3/VR-4 pres-sink, Callie, AUS (Newmont) White County Coal, USA
<b>Range of application</b>	Remote locations, short shafts/presinks (<100m)
<b>Key Aspects</b>	Personnel safety: Quality headframe, safety around the shaft opening and sound geotechnical stability analysis.
<b>Alternative applications</b>	With ground-freezing through soft strata.

## Shaft-boring machine with mucking

In the search for continuous mechanical drilling methods, the shaft boring machine was developed akin to tunnel boring machines for horizontal excavation. The problem with this method, is mucking out cuttings from the bottom of the shaft. Usually this would require some skip-hoisting, bucket-hoisting or clam-shell-grab equipment, which generally impairs the progress of the shaft boring machine and requires mine workers down the hole to load the buckets.

An SBM is a costly machine not suited for drilling short shafts. Furthermore it is weighed down by high research and development budgets. During the 1970's vast budgets went into shaft boring machines with little result. Generally blind hole drilling, i.e. drilling from the surface and removing cuttings with drilling fluids, has surpassed shaft boring.

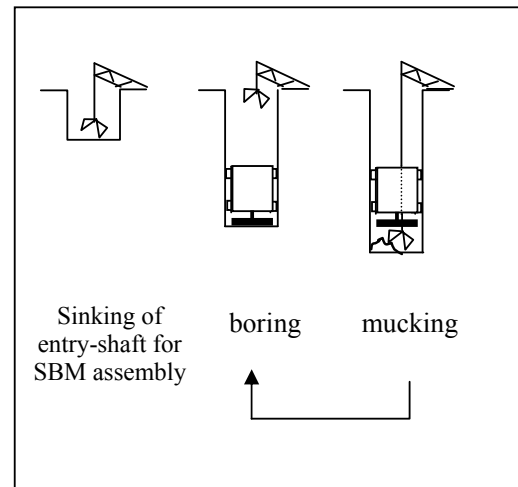


Figure 14 – Shaft sinking with a shaft boring machine and mucking

Nowadays some automated machines exist for small diameters, called microtunneling machines. These also have extremely high development costs, but may become lucrative where many shafts are to be drilled. These systems have been developed only for small diameters, but they can perform in soft strata and high water pressures due to them having a pressurised closed front.

BorPak is an alternative shaft boring machine with partial front excavation, like a roadheader. It is designed specifically for raise-drilling in narrow locations at a diameter of 1500mm and uses packers to support itself on the shaft wall.

Table 4 - Shaft sinking methods: Shaft Boring Machine

<b>Shaft Boring Machine (with mucking)</b>	
<b>Advantages</b>	+ semi-continuous operation + suited to nearly all ground conditions, large diameters and great depths
<b>Disadvantages</b>	- huge investment and setup costs - workmen in the shaft - restricted constant diameter
<b>Examples</b>	
<b>Range of application</b>	Long shafts (>200m) and large diameters Where costs of transport and installation are low
<b>Key Aspects Adaptations</b>	Cost of setup, Speed of cuttings removal, shaft damage from grippers Microtunneling BorPak raise drilling machine

## V-mole with pilot-hole

The mining equipment company Wirth from Germany has developed the most successful V-mole system. The V-mole is an improvement on the concept of the shaft boring machine. Before boring, a pilot-hole is drilled, to assist in both cuttings removal and guiding the machine along the correct path. The V-mole uses grippers to hold on to the side of the shaft while boring downwards by rotary crushing.

The V-mole is a costly machine not suited for drilling short shafts

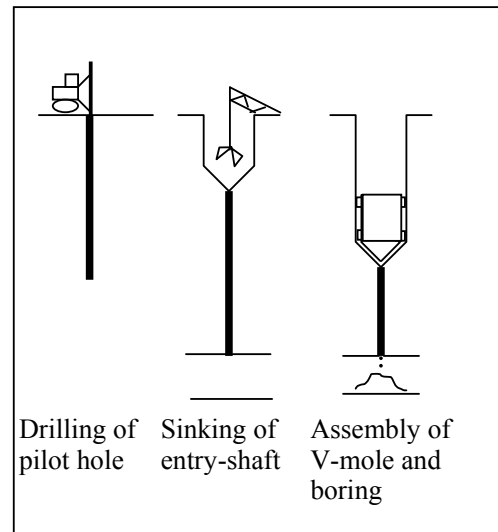


Figure 15 – Shaft sinking with a V-mole where

Table 5 - Shaft sinking methods: V-mole with pilot-hole

<b>V-Mole with pilot-hole</b>	
<b>Advantages</b>	+ continuous operation + suited to nearly all ground conditions and to great depths
<b>Disadvantages</b>	- huge investment and setup costs - workmen in the shaft. - restricted constant diameter
<b>Examples</b>	Lummerschied shaft, GERMANY (Wirth)
<b>Range of application</b>	Long shafts (>200m) and large diameters Where costs of transport and installation are low, and liabilities for workers in shafts are high (Europe) Suited to enlargement of existing shafts
<b>Key Aspects</b>	Cost of setup, bottom-end access for mucking

## Down-the-hole lining methods

### Rock bolting and meshing

The easiest way to line a shaft is with rock-bolting and meshing. A wire mesh is fastened to the walls with evenly spaced rock bolts. For vertical shafts ring shaped beams called ribs are usually also added to support increasing horizontal stresses as the shaft moves down.

Rock bolting is a commonly used, cheap method. The rock-bolts increase normal stresses on joints so that shear failure along joints becomes more difficult. However it has some drawbacks [*Spearing, 2002*]. It is hard to automate, making it labor-intensive. Also it is relatively unsafe as it requires about 2 men down the hole working on unstable walls. The unrolling and handling of mesh can be difficult when working in close proximity to a boring face. Also this method is not watertight, meaning it does not prevent water inflows nor does it prevent weathering of the rock beneath the mesh. Often rock bolts and mesh are used as a basis for shotcreting, however this is risky because the placement of the mesh in the shotcrete determines how well it will function. Water in-flow during shotcreting severely reduces the quality of shotcrete. Also the mesh in the middle of the shotcrete may not contribute to its' strength, whereas mesh near to the surface may be subject to corrosion.

### Cast-in-place lining

It is possible to cast concrete rings as the shaft sink progresses. This is commonly done in combination with a V-mole or shaft boring machine. Generally temporary rock bolts and mesh are still required close to the cutting head. Then, on a second floor of the shaft boring machine, an L-shaped casing is positioned which is then filled from a hose transporting concrete from a surface plant. This method provides a smooth, watertight and permanent lining for the shaft. The casing can be reinforced to cope with horizontal stresses (i.e. ring-shaped reinforcement) making the casing elements more economical, and in this case the reinforcement is well protected by the concrete. Some attention should be given to connecting the elements with rubber profiles to prevent water inflows.

Unfortunately this method is discontinuous, with many men down the hole. The safety of the workmen is usually fair because they generally work under the cover of the shaft boring machine cage. Also the robustness of the lining system means there is practically no chance of rock-fall or collapse from above. The first metres of lining are the most unsafe in their application.

This method has been used a number of times in Europe, in combination with an SBM or V-mole. The Lummerschied shaft [*Haas & Schneider, 1991*] in west Germany was safely enlarged to a diameter of 8,2m.

### Forepoling or Boodex method

The Italian ground treatment manufacturer Soilmec has successfully used the forepoling method in rock for the stabilization of tunnels [*Martin(ed.), 1990*]. It has come into common practice for tunnelling, also given the name Boodex by Atlas Copco.

In the case of Soilmec, the method uses Tubex technology to drill a ring of piles about 12 metres long at a slight incline around the tunnel face. The ring forms an umbrella to support the next nine metres of shaft excavation, before a new ring of piles was installed. The method is slow because of the many piles that need to be consecutively driven, resulting in only 15-20 m a week. However it does form a safe barrier ahead of the excavation process for workers to operate more safely.

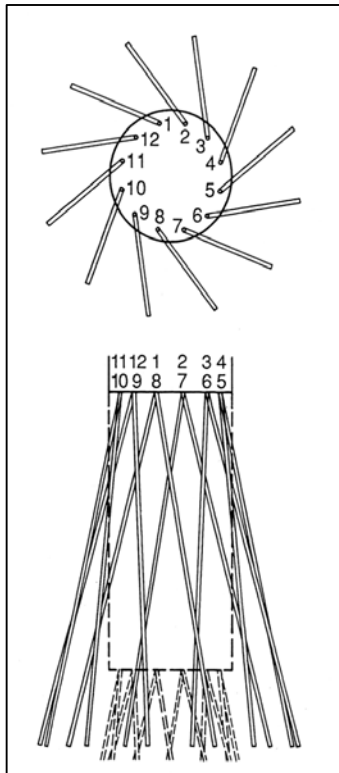


Figure 17 – Typical drill patterns used for forepoling ahead of the face in a vertical shaft.

The method described above is typical for tunnelling, but has also been used vertically for shaft drilling. The limited length of piles means the forepoling or Boodex machine has to be used from within the shaft along with conventional drilling and blasting or mechanical excavation for the removing rock and soil.



Figure 16 – Tunnelling example of forepoling in fractured rock in Greece [courtesy of the Geogineer Website, D. Zekkos]

## Pre-cast lining segments

Shafts up to 4.5m are being blind-hole-drilled more and more often around the world, with pre-cast lining positioned during or after workings. For limited diameters a large steel pile is often used because it is stiff and smooth and can easily be lowered or driven into the ground. Concrete can then be poured behind the walls to create the lining. It is common to insert the steel pile during drilling in clay soils which tend to collapse, but also have low friction making pile driving easy.

In sands, mudstone and sandstone, steel, pre-stressed concrete or composite liners with a smaller diameter than the shaft are lowered after drilling out the hole.

The space behind the piles is then filled with grout to ensure a close fit with the surrounding soils.

[105. Hamburger 1991]



Figure 18 - Composite pre-cast liners ready for floating into a mud-filled shaft.

## Remote shaft sinking methods

### Blind Hole Drilling

It is also possible, instead of having a V-mole or boring machine down the hole, to apply the drilling method used for oil-drilling, on a larger scale. Here a rotary cutting head is dropped into the shaft on the end of a drill string. The large diameter drill-string is used to apply surface pressure and torque to press and rotate the cutting head into the rock. The differences with boring and V-moling are that no workmen are sent down the hole and that the torque is applied from the surface through drill rods.

Usually shaft walls are stabilized by filling it to the rim with a bentonite mud or polymer-mud. Cuttings removal is achieved by pumping drilling mud through the drill pipes with air pumped in through an airline. Upon completion a shaft lining (usually composite, 200mm thick concrete with an outer steel skin) is then dropped down in 3m segments, being welded together as it progresses. The space between the outer skin and the rock face is then concreted up to the surface, and the shaft pumped clean.

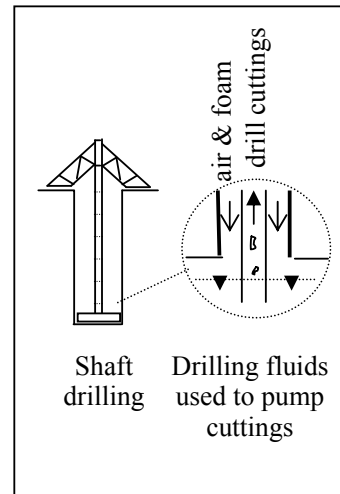


Figure 19 – Large diameter blind hole drilling.

A small overpressure is always used, whereby excess fluid slowly flows into fissures and porous rocks. If excessive flows are encountered, a lost-circulation material is added, such as shredded paper, woodchips or other cellulose material, effectively blocking the mud inflows. However, this method would not be possible in the vicinity of large cavities such as old mine caverns. [M. Zeni, Ardent Underground, 2003]

The diameter of the shaft is limited, partly by the amount of torque that can be applied through the drill string, but mainly by the amount of load that can be applied to the drilling face. This is determined by the weight of the cutting head and drill rods; often dead weights are added, around 200 tonnes for 4m diameter shafts, allowing a load of around 450 tonnes on the cutter head. This increased weight in turn makes the headframe and equipment heavier and more expensive.

Given a 4m diameter shaft, speeds of around 10m/day are achieved in soft, weathered and layered strata. For a hard rock case, for example basalt of 250-300Mpa UCS, 2-3m/day would be the limit, using a single multi-purpose cutter-head (i.e. for soft and hard rock). [M. Zeni, Ardent Underground, 2003]

An alternative method of shaft drilling in rocks that can remain stable without drilling muds can be performed with a pilot-hole for cuttings removal. Lining the shaft can be solved by lowering a remote fibrecreting machine into the hole. However, this method of dry-hole drilling has the disadvantage that the cutter head must be cumbersome lowered down to and raised up from the bottom of the hole every 2-3 metres. On the other hand, this permits application of the exact amount of fibrecrete necessary to hold up specific rock layers and retain water. Building on the concepts of the Shelob

system, a spinning disk to apply shotcrete, developments by a company called Jetcrete have produced impressive results. [L. Newnham, R.O.C., 2003]

Table 6 - Shaft sinking methods: Blind Hole Drilling

<b>Blind Hole Drilling</b>	
<b>Advantages</b>	+ works in nearly all ground conditions up to great depths + safe construction from the surface + underground mine workings are unaffected
<b>Disadvantages</b>	- high setup costs - limited access to the bottom of the hole in case of problems. - potentially high environmental impact
<b>Examples</b>	Springvale, Nsw., AUS (Arden Underground) North Goonyella, Qld., AUS (Arden Underground) Henty shaft, Tas., AUS (Arden Underground) Dendrobium shaft, Nsw, AUS (BHP Billiton) -various- [105. Hamburger] (Wirth/R.U.C.)
<b>Range of application</b>	Medium to long shafts (d>60m) Unstable soils, fractured and weathered rock, in aquifers
<b>Key Aspects</b>	Fluid mix: use correct additives to ensure stability and optimal cuttings transport. Controlled drilling: Prevent system down-time caused by cutter damage; prevent deflection through hard, dipping veins
<b>Adaptations</b>	Additives for increased thixotropy to support running sands and soft soils, and still maintain cuttings transport. Clay-binding additives for stopping swell from reactive clays. Fibrous additives for blocking sudden leaks into fissures and openings. Dry-hole drilling with shotcrete for use with existing pilot-holes and in water-sensitive strata. Low-clearance setup for use in caverns with limited headroom. Fishing tools developed for problems with jammed rocks and equipment. Dry-rock drilling with pilot hole and fibrecreting

## The Shaft-cutting machine (SCM) or Excavation

A simplified cutting and excavation machine, called a Shaft Cutting Machine has been developed by Alpine of North America. The machine is designed like a road-header, with a rotary disc cutting device mounted on a hydraulic boom. It is ideally suited for short shafts in soft to medium hard rock. A machinist can move the boom around the bottom of the shaft, cutting one side, while a second mucking arm puts the clippings into a hoisting bucket. The machine is small enough to move around the bottom shafts down to 4m diameter, allowing it to excavate the alternate side to where it is standing.

For depths up to 25m it is also possible to mount the cutting heads on a hydraulic boom mounted at the surface of the shaft or on a surface excavator. Alternatively the machine can be mounted on the lining



Figure 22 - Boom type excavator used to build a tunnel entry shaft in Abu-Dhabi

Raiser, moving down the shaft in stages. Because of the low cost and ease of implementation, this machine is well suited to constructing a short shaft through the weathered overburden.

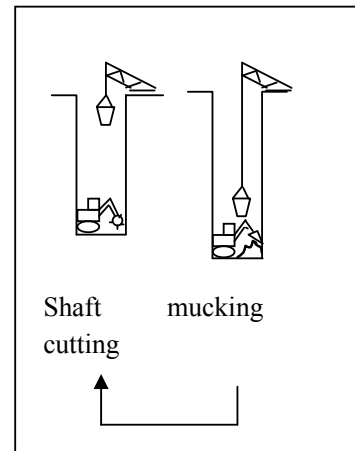


Figure 20 – Shaft sinking with a shaft cutting machine (SCM) down the shaft and mucking.

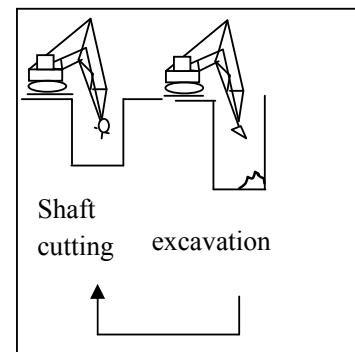


Figure 21 – Shaft sinking from the surface by excavation with a crane or boom.

Table 7 - Shaft sinking methods: shaft excavation and shaft cutting machines

<b>Shaft Cutting Machine</b>	
<b>Advantages</b>	+ semi-continuous operation + quick and effective
<b>Disadvantages</b>	- restricted depth and rock strength - potentially workmen are required in the shaft for excavation, cuttings loading and haulage
<b>Examples</b>	Supercollider, USA (Atlas Excavation Inc, USA) CANADA (Montala) Tas, AUS. (Mancala)
<b>Range of application</b>	Short shafts or pre-sinks (d<25m) Soft soil/rock <4 UCS
<b>Key Aspects</b>	Speed of mucking
<b>Adaptations</b>	With (hydro)fraise, higher rock strength can be excavated Excavation mounted on the lining (Alimak-style) with excavation/lining stages From the shaft bottom with a road-header type excavator

## Remote lining methods

### Floated pre-cast lining segments

Shafts up to 4.5m have been commonly drilled around the world with pre-cast lining positioned during or after workings. A large diameter steel pile is often used because it is strong and smooth and can easily be lowered or driven into the ground. Concrete can then be poured behind the walls to create the lining. It is common to insert the steel pile during drilling in clay soils which tend to collapse, but also have low friction making pile driving easy.



*Figure 23 - Composite pre-cast liners ready for floating into a mud-filled shaft.*

In sands, mudstone and sandstone, steel, pre-stressed concrete or composite liners with a smaller diameter than the shaft are lowered after drilling out the hole. The space behind the piles is then filled with grout to ensure a close fit with the surrounding soils. [105. Hamburger 1991]

### Caisson sinking

Wall elements that are smaller than the shaft diameter can be dropped into the shaft as it progresses, or upon completion. However, this means the shaft must be supported by mesh or drilling fluids during construction. As an alternative, it may be possible in the future, to push down a lining as work progresses, in combination with shaft excavation, and only lubricate behind the shaft wall.

Wall elements are added from the top avoiding the need for any worker's down the shaft, and providing easy access to the work. A slipform lining can be used, allowing a continuous pour of concrete, or pre-cast elements can be added piece by piece. Horizontal rings of reinforcement can easily be installed to withstand horizontal pressures. Because the horizontal pressures increase as the shaft goes down, the amount of reinforcement can be scaled to the expected loads.

However, as the hole deepens, wall friction will continuously increase, until the casing will not slide down any further. A raisebore-style machine with an anchored foundation plate should be used to jack the lining downwards. Even so, the friction at greater depth will determine the potential of this method. By undercutting the shaft, the toe friction



*Figure 24 - Jack-down lining performed by Marin through soft clays. Pipes used for lubrication and grouting can be seen running along the outside of the lining*

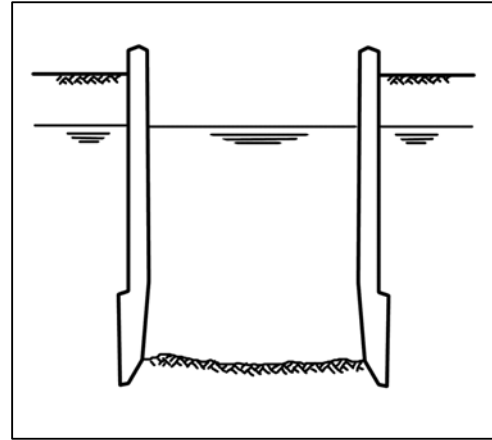
can be overcome, and by excavating a slightly larger diameter than the final lining, the contact friction along the outside of the lining can also be reduced. In rocky geologies the excavation will cause some relaxation of the overburden and this may push against the lining with considerable pressures. This is the main problem involved in jacking the lining.

To solve this, some additional measures may be applied:

- ▶ Use of mud or drilling fluid to lubricate between the shaft wall and rock.
- ▶ Use of a series of steel cables that are unrolled from the bottom of the shaft as it proceeds downwards.  
*[van Dijk, Almeraris & Rice, 2001]*
- ▶ Use of waterjets to decrease effective stress, lubricate the wall and push aside any obstructions.

In soils the additional problem arises of a blow-out into the shaft bottom or high water inflows through water bearing strata. Some form of closed shield needs to be devised to prevent this.

Caisson style linings have been used in the Netherlands in soft clays with a mud-filled hole. Horizontal box-jacking has been used successfully in soft soils with stress-reduction cables, for some years in England and for the Boston Central Artery/Tunnel Project. However, this was for expensive large-scale civil engineering projects and in this case the surrounding soils were first frozen. *[137. Puller 2003]*



*Figure 25 - Wall lining through sinking of a caisson - open front excavation*

## Remote shotcreting

The method of spraying pumpable concrete onto walls as reinforcement is becoming more controllable. Fibrecrete offers a system where mesh is no longer required as reinforcement – this function is replaced by fibreglass in the shotcrete.

The application is also being improved. In the 1990's a system of remote shotcreting, i.e. with an automatic machine was developed, at first under the name of the Shelob system. [7. *Mason & Bishop 1993*]

This method has been developed in recent years for civil tunneling purposes. Currently it is possible to line shafts remotely, using video camera's to check the result, as was done in the Dendrobium shaft in Australia.

Advantages are the flexibility, that there is no need for workmen down the hole, and that lining thickness can be adjusted as needed.

The problems this method encounters is the amount of rebound of shotcrete. It is difficult to get shotcrete to stick to the walls in sufficient thickness. More than one pass may be needed where strong support is needed. Also it is hard to combine the messy shotcreting process concurrently with drilling where the drill pipes and drilling head get in the way. This results in a discontinuous process where shotcreting and drill head are lowered and raised alternately.

Also area's where water flows or bleeds from the surface into the shaft, are hard to shotcrete adequately.

Research is promising in the application of superskins, which consist of a sprayable polymer that can have adequate strength at only 3-5mm thickness. [58. *Spearing2002*]

Figure 26 - Detail of fibrecrete nozzle

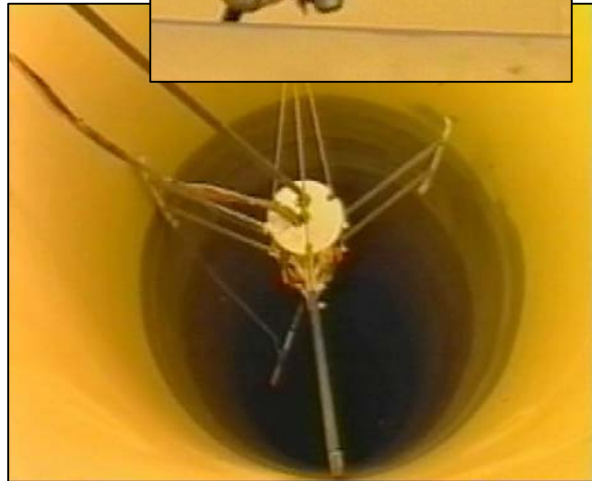


Figure 27 - Remote fibrecreting machine with three stabilizers and the nozzle pointing to seven o'clock, as it is lowered into a shaft

## Raiseboring methods

The raiseboring method requires drilling of a small diameter pilot hole to the required depth. In the second stage a reamer is attached and drawn back to the surface. Because it is not possible to apply any wall support beneath the reamer, raiseboring requires special adaptations in unstable overburden.

The group of remote lining operations that can be carried out from the surface before drilling starts will be referred to as pre-reinforcement. In many cases, such as freezing, a more permanent lining may also be needed.

Raiseboring can only be carried out through unstable overburden, if pre-reinforcement is applied or if another method is used to create a pre-sink through the weathered portion of the raise. Alternatively the more risky horadial method may be used.

## Horadial method

The Horadial method is a specific method that is used in Western Australia where the top layer consists of silcrete. This soil type is partially cemented and thereby very stable compared to layers beneath it.

The method works by first drilling a small pilot hole and using a raiseboring machine to ream it out to the maximum stable diameter. This usually means the hole is drilled out to the full diameter through stable rock, and that drilling is stopped for the instable areas near the surface. For this area, one of two methods may be applied:

An *Alimak* climber is installed from below. This machine can climb up to the crest from below along a steel monorail that is installed as work progresses. It is a very dangerous method because workmen in the Alimak are always working beneath an open rock face. As work progresses rock bolts and mesh are applied to stabilise the shaft. Because of the pilot hole there is space for rock to expand on blasting – this makes the blasting process quick and less destructive.

The slightly safer method is to perform *stepwise-benching* from above. Workers are lowered into the shaft on a working platform and drill and blast holes into the areas of the shaft that need to be enlarged. Again the expansion space of the pilot hole makes blasting light and easy. After blasting workers are again lowered into the shaft to apply mesh and rock-bolting or shotcrete.

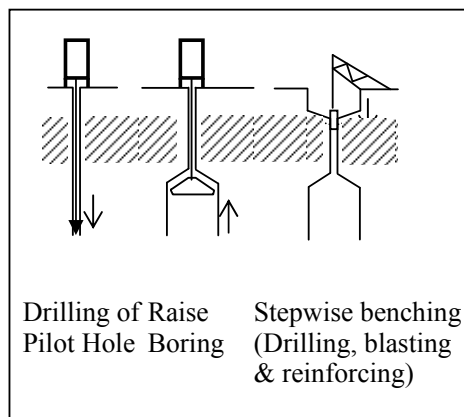


Figure 29 - Horadial method  
(with stepwise benching)

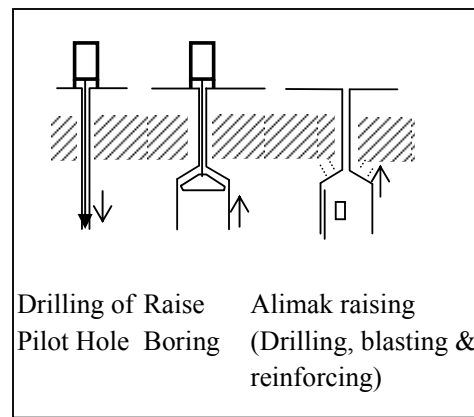


Figure 28 - Horadial method  
(with Alimak raising)

The Horadiam method creates an unsafe scenario for workmen for the last portion of the shaft, and also provides a rougher final shaft. Nevertheless this method is popular in Western Australia because raiseboring can be applied efficiently through most of the shaft and the unstable area's tackled conventionally. Also shafts can easily be made larger in diameter than with simply raiseboring.

In Stawell a similar method was used where a small, stable hole was grouted after construction. In this way, grout penetrates around the hole and thereby stabilises it.

In stages the hole was enlarged and grouted again, until the final diameter was achieved.

Unfortunately both these methods are limited to area's where the soil or rock has some stability (the small diameters are stable) and some standup time (the time it takes to apply mesh, rock-bolting and/or shotcrete after each blast)

Table 8 - Horadiam method

<b>Horadiam method</b>	
<b>Advantages</b>	+ low investment and setup costs
<b>Disadvantages</b>	- dangerous blasting operations for workmen
<b>Examples</b>	Leinster, WA., AUS (Coffey Geosciences)
<b>Range of application</b>	Short shafts or pre-sinks (d<75m) Rock with some standup time (days)
<b>Key Aspects</b>	Experienced workmen for benching operations
<b>Adaptations</b>	Using an Alimak-raiser from the bottom Using stepwise benching from the top

## Pre-reinforcement for Raiseboring

### Grout treatment

The most problematic unstable areas in overburden are commonly encountered near the bedrock (hard rock base). Continuous ground water flow and movement of rock layers results in abundant fracturing and weathering at this location.

Some features can be recognised as especially threatening to shaft stability:

- ▶ joints filled with poorly graded materials,
- ▶ clay gouge and other soft or soluble materials in the joints,
- ▶ open joints,
- ▶ smooth, slickensized joints,
- ▶ high water pressures
- ▶ high residual stresses

In areas where joint planes threaten shaft stability and where water flowing into the shaft is a problem, shafts may be treated with pressurised grout.

Grouting is traditionally performed from inside the shaft in combination with conventional shaft sinking. To get workmen out of the shaft, it is also possible to grout from the surface. Rotary-percussive drills are used to get to the required depth where packers or tubes-a-manchette are used to inject grout at high pressure.

The aim of this grouting is to:

- ▶ Decrease permeability and thus stop water flows
- ▶ Increase normal stress on joint planes, thereby increasing shear strength.
- ▶ Increase cohesion on joint surfaces by replacing soft materials and forming a chemical bond with the rock surface.

Grouting in this manner has certainly seen some failures. Two documented cases in South Africa and Tanzania encountered sudden rushes of water which could not be stopped, alongside many other cases of shaft collapse in Australia. On the other hand, carefully planned, well-controlled grouting can result in successfully making shafts stable and watertight, such as the case in the Longos Gold mine in the Phillipines.

Grouting has some fundamental problems that commonly lead to its failure. Firstly it is difficult to get grout into the correct spot: the location of weaknesses is not exactly known, deflections occur during drilling, deflections are measured inaccurately, and the flow path and quantity of the grout injected is not known. Commonly areas with high groundwater flow rates disperse ('wash') grout so it does not harden properly, and displace it from where it should be.

Not unimportantly it is hard to estimate the effect grouting has had on shaft stability.

Table 9 - Pre-reinforcement: Grout treatment

<b>Grout Mini-piles</b>	
<b>Advantages</b>	+ allows raiseboring + quick and effective
<b>Disadvantages</b>	- limited depth - questionable effect on stability - no-way-back method
<b>Examples</b>	Longos Gold Mine, Paracale, PHILIPPINES (Multi-urethanes) Freestate, S.A. (Rodio)
<b>Range of application</b>	Fractured and weathered rock, with unfilled or open joints Area's with low-moderate groundwater flow rates
<b>Key Aspects</b>	Drilling accuracy: good initial survey, calibrated surveying tools Good grout penetration: suitable joints, quality control Limiting grout wash: avoid high-pressure aquifers, groundwater flows
<b>Adaptations</b>	Navi-drill can be used for more accurate drilling Grout types: cement, ultrafine cement, chemical grouts. polyurethanes Reducing flow: fast-setting grouts, hot bitumen, water relief holes

## Grout mini-piles

A different form of grouting is where a concentric ring of mini-piles is constructed around the shaft perimeter. This method is suited to areas where the rock stability is determined by jointing rather than weathering. The grout columns intersect potential shear planes and the reinforcement keeps the planes together. It is not intended that grout penetrates the joints to any considerable depth, so it is simply poured into the bottom of the hole.

This method has been applied successfully in Golden Grove in Western Australia, however in the Callie mine, drilling accuracy was questionable hence the shaft was sunk conventionally and not raisebored.

Table 10 - Pre-reinforcement: Grout Mini-piles

<b>Grout Mini-piles</b>	
<b>Advantages</b>	+ allows raiseboring + quick and effective
<b>Disadvantages</b>	- limited depth - questionable effect on stability - no-way-back method
<b>Examples</b>	Callie, AUS Golden Grove, AUS (Bachy)
<b>Range of application</b>	Fractured but not soft rock Area's with low groundwater flow rates
<b>Key Aspects</b>	Piling Accuracy: good initial survey, calibrated surveying tools Avoid reamer damage: User armoured grouts, not steel drill rods
<b>Adaptations</b>	Navi-drill can be used for more accurate drilling Fibreglass armoured grouts instead of reinforcement

## Secant piles

Down to limited depths, interconnecting columns can close groundwater flows and stop soft clays and running sands from collapsing. They can be constructed through jet-grouting or auger drilling a circular pile wall.

Auger drilling is possible up to about 25m because greater depths jam the auger and may also lead to such deflections that the secant piles no longer overlap. Rock strengths up to approximately 2MPa can be tackled using the auger drill. Piles can be supported with fluid or a casing and filled with concrete or mix-in-place additives.

Oscillating “Cassagrande” type piles can reach depths of roughly 35 metres where a hydrofracture is used for stiff clays, soft rock and boulders. To be able to drill secant piles, bentonite fluid should be used instead of casing, which means the method approaches that of diaphragm walls.

Table 11 - Pre-reinforcement: Secant piles

<b>Secant piles and diaphragm walls</b>	
<b>Advantages</b>	+ allows raise boring + quick and effective in soft soil
<b>Disadvantages</b>	- restricted depth
<b>Examples</b>	Cannington, AUS (BHP Billiton – Bachy)
<b>Range of application</b>	Auger drilled secant piles: soft, boulder-free ground of up to 1-2MPa and to depths of 22m. Casagrande piles: Soft ground to weak rock to depths of 25m
<b>Key Aspects</b>	Connectivity of secant piles (drilling accuracy)
<b>Adaptations</b>	augers drill inside a casing to prevent borehole collapse two augers can be connected to achieve greater depths in soft clays

## Diaphragm walls

Diaphragm walls are constructed by digging rectangular trenches under support of bentonite fluid using a large mucking crane or hydrofraise. In the case of shaft sinking the diaphragm walls are constructed before raiseboring in several segments around the perimeter of the proposed shaft. Often round casagrande piles are first excavated at the segment intersection to function as guides for the excavation process.

The method is only useful for large diameters, because otherwise the volume of drilling mud is greater than for simply blind hole boring. A simple volume criterion can be used to see if a slurry trench can be useful, for example assuming a thickness of 0.8m of the diaphragm wall and a distance of 0.8m outside the shaft perimeter, a diaphragm wall uses less bentonite fluid at diameters of about 5m or greater. [137. Puller 2003]

It should also be noted that diaphragm walls form the danger of blow-out when constructed near to existing mine workings, or areas with large underground cavities.

Table 12 - Pre-reinforcement: Diaphragm walls

<b>Diaphragm walls</b>	
<b>Advantages</b>	+ allows raise boring + final wall support
<b>Disadvantages</b>	- costly equipment - prone to discontinuity in excavation
<b>Examples</b>	Eastern Harbour Crossing access, HONG KONG (Soletanche-Bachy) Speckholzerheide mineshaft, HOLLAND
<b>Range of application</b>	Soft clays, sands and soft rock to depths of approx 60m. Diameters > approx. 5m
<b>Key Aspects</b>	Continuity of excavation Trenching accuracy
<b>Adaptations</b>	Additives in case of intersecting water flows

## Freezing

Instead of creating a grout curtain wall, an freezing provides an alternative method to harden the ground. This is common practice in Germany, North America and Canada. The primary factor affecting ground freezing is the speed of groundwater flow. Other factors are water temperature and salinity of the groundwater. Groundwater flows are usually limited in greenfield sites, but existing mine developments usually have some form of groundwater pumping in effect. Because of the heat transport that accompanies groundwater flow, it will cost extra time to freeze the groundwater, and it may even be impossible to create a complete ice curtain.

The problem with groundwater flow is increased if the groundwater table is very low. To create a frozen curtain wall at low depths, the groundwater table should be raised. Unfortunately the raising of

the groundwater table implies groundwater flows away from the shaft, making freezing difficult. The flow rate may be limited in soil strata because of the large amount of pore space – partial saturation will be enough to strengthen the soil. In fractured rocks full saturation will be required, and pumping will induce high flow velocities, making freezing impossible.

The accuracy needed for freezing is lower than for grouting, because the ice wall spreads around the drill pipes. Accuracies of 1,5 %, achievable by good drilling contractors, are sufficient for around 50m depth. For depths greater than 100m, steerable Navi-drilling technologies are used to achieve the desired accuracy.

Installation of piles around a 4m diameter shaft to 100m depth with approximately still groundwater would take around 10-15 weeks for freezing, plus 5-10 additional weeks required for raiseboring and permanent lining. [Freezwall Inc., 2004]

The freezing operation can reduce the effectiveness of raiseboring as soft soils become hard because of the ice formation. This results in low penetration rates and excessive cutter wear. Frozen clays resulted in 50% greater torque required than through shales and gypsum. Ice formation along the walls of the pilot hole can inhibit the movement of the drill rods within the pilot hole. Warm air blown through the annulus to melt the ice along this surface along with scraping off by rotating and reaming the drill strings can prevent this buildup, but slows the drilling process. [87. Walsh 1991]

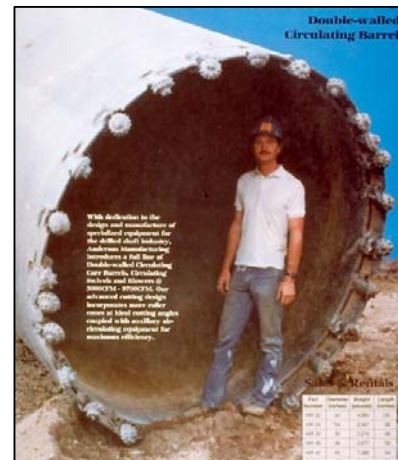


Figure 30 - Calyx drill

## Calyx drill

For small shaft diameters up to 3 metres, double-walled core-drills or ‘calyx’-drills have been developed and used that are even suited to medium-hard rock. These use mud flushing through the annulus and mud between the shaft and the wall for added lubrication. The drill excavates a hollow core leaving much the same result as with blind hole drilling, but with significantly less energy.

Only one company is known to date that produces this size core-drill.



Figure 31 – retrieved segment of core from calyx drill



### 3. Assessment of methods

#### Varying geologies

At first it was assumed a solution was necessary to extend the possibilities of raiseboring through instable overburden. However, on examining this method, a fundamental problem with raiseboring presents itself: the shaft is constructed *bottom-up*. This severely limits the potential of raiseboring.

Firstly, only shafts with bottom-end access can be constructed. This is not always available, for example when creating primary access shafts or when a tunnel or adit is not ready in time for the shaft. However this is not the biggest issue that is raised by bottom-up construction.

More importantly, it makes many construction methods used to stabilise the shaft impossible. When progressing downwards, drilling muds, shaft lining, mesh and bolting, fibrecreting and so forth can be used. Bottom-up construction doesn't allow access to the shaft to apply any of these methods. This is why, when looking at constructing shafts through unstable overburden, the scope has been expanded to allow for *top-down* construction.

*Table 13 - Local and economic factors that influence the shaft design method.*

<b>Local and Economic factors</b>	<b>Influence on design</b>
<b>Availability of equipment and experienced contractors</b>	- design choices
<b>Required speed of construction</b>	- capital expenses / mine planning
<b>Remoteness of location</b>	- creates high transport costs for large equipment
<b>Acceptance of groundwater pollution</b>	- is chemical grouting acceptable? - what drilling muds and additives are acceptable?
<b>Level of acceptance of risk-taking</b>	- is having men down the hole acceptable? - what safe stable span is accepted? - what amount of geotech. research is undertaken? - will a top-down or bottom-up approach be used?
<b>Legislation</b>	- are men allowed down the hole? - are men allowed to replace reamers? - what are the liabilities for accidents?

It would be a severe shortfall if blind drilling and mechanical excavation methods were excluded from the possible set of solutions simply because they are not raiseboring. It should be made clear that many different methods are plausible, but that it depends on many factors, which solution is optimal. While looking at the methods used the factors that determine if a method is effective, have been noted. These factors are shown in *Table 13*. Where possible, tests are indicated which may be used to quantify them.

Besides conditions implied by design or geology, some conditions are enforced by local and economic factors. These may be implied by government, by the availability of equipment and the attitude of mining companies and contractors. They are listed in *Table 14*.

Table 14 – (Hydro)geological and design parameters that influence shaft construction

PARAMETER	SYMBOL	UNIT	TEST	NOTES ON TESTING
<b>Geological conditions</b>				
<i>Rock Drillability</i>				
-Unc. Compressive Strength	UCS	MPa	Triaxial	
-Abrasion Value	AV	-	Abrasion test	[119 Barton: p15]
-Siever's J-Value	SJ	-	Siever's miniature drill test	[119 Barton: p15]
-Drilling Rate Index	DRI	-		Related to UCS/Abrasion
<i>Rock penetrability</i>				
-Sand density or clay plasticity	$D_r$ / PI	kN/m	CPT/SPT	
-Presence of rock/gravel/boulders				
<i>Rock/soil stability</i>				
-Degree of weathering		[I-V]	Core samples/ Age	[78 Goodman]
-Unc. Compressive Strength	UCS	MPa	Triaxial	
-Cohesion [soils]	c	MPa	Triaxial	
-Tensile strength [rock]	q;u	MPa	Simple shear / triaxial	
- Soil/rock elasticity	E	MPa	Triaxial, Seismic velocity	
<i>Rock fracturing</i>				
-Number of joints	J;n	-	Core samples, Seismic velocity/amp	[90: Barton] Q-System
-Joint roughness	J;r	-		[89:A.McCracken & Stacey]
-Joint alteration i.e. filling	J;a	-		
-Dip angle of shear zones/ in situ stresses/ intersecting joint sets	SRF	-		[110: Logan & O'Toole]
-Depth of weak layers/overburden		m		
-Sensitivity to alteration				
<i>Rock stress state</i>				
- primary stresses and directions	$\sigma_1, \sigma_3$	MPa	CCBO Overcoring, Hydraulic fracturing	[138. Obara et.al.]
<b>Hydraulic conditions</b>				
Height of water table	h	M	wireline in borehole	
Presence of aquifers and hydraulic head in aquifers			Core samples, thermal capacity	
Permeability	C;v	Lugeon	Packer test	
Flow rate due to pumping/aquifers	q	m/s	2 borings with tracer	
Salinity of groundwater		ppm	borehole sample	
<b>Design parameters</b>				
Diameter	D	m		
Total depth	d	m		
Shaft smoothness	$\Delta D$	mm		Accepted size of overbreak (i.e. for laminar flow)
Shaft inclination and azimuth		degrees		
Access to bottom of shaft		[y/n]		
Possible alternate locations				

## Workers in shafts

The initiative to this work was the demand for a safe method of shaft construction through unstable geologies. Of all safety aspects, there is a single key issue in shaft construction that outways all other safety measures: The amount of time workmen are active inside the shaft.

For this reason any method that still requires workmen down the shaft is a poor one.

The methods discussed in the previous chapter are first assessed according to the amount of work that is necessary in the shaft. Methods with a low or moderate safety will be abandoned, as shown in *Table 15*.

Shaft excavation will be reviewed in more detail in chapter 4, as it forms an alternative to constructing short pre-sinks without heavy equipment, where shafts are not long enough to install a complete blind hole drilling rig. Also the development of remote controlled equipment means there may be room for further development in this area in the future.

Blind Hole Drilling will be researched in further detail in chapter 5, because it appears to be able to tackle nearly any geology effectively, yet it is one of the safest methods available.

Grout treatment and grout minipiles will be elaborated further in chapter 6. Grouting can be a very cheap method, especially when used on localised targets. Also the understanding of the effect of grouting is still poorly understood, leaving room for improvement and a desire for a better knowledge base.

Table 15 – Level of safety of each construction method.

Method	Work done in the shaft	Safety
<b>Down-the-hole shaft sinking methods</b>		
Conventional drilling and blasting	Drilling, blasting, mucking & reinforcement.	Low.
V-mole with pilot-hole	Maintenance, reinforcement	Moderate
Shaft-boring machine	Maintenance, reinforcement, mucking	Moderate
<b>Down-the-hole lining methods</b>		
Rock-bolting & meshing	Rock-bolting & meshing	Low
Cast-in-place lining	Lining.	Moderate
Precast lining elements	Lining.	Moderate
Forepoling/Boodex	Forepoling and final lining.	Mod. high
<b>Remote shaft sinking methods</b>		
Blind Hole Drilling	Lining only. ( <i>see lining methods</i> )	Very high
Shaft Excavation (from top)	Lining only. ( <i>see lining methods</i> )	Very high
<b>Remote shaft lining methods</b>		
Floated pre-cast lining	None.	Very high.
Caisson lining	Excavation beneath lining shoe.	Very high.
Remote shotcreting	None.	Very high
<b>Raiseboring</b>		
Horadial – stepwise benching	Some drilling, blasting, mucking & reinforcement. (from above) Raiseborer maintenance.	Low (for unstable areas)
Horadial – alimak raising	Some drilling, blasting, mucking & reinforcement. (from below) Raiseborer maintenance.	Very low (for unstable areas)
<b>Raiseboring with pre-reinforcement</b>		
Grout treatment & Grout minipiles	Raiseborer maintenance. Final lining & watertighting.	Mod. high
Secant piles	Raiseborer maintenance.	Mod High
Diaphragm walls	Raiseborer maintenance.	High
Freezing	Raiseborer maintenance. Final lining.	High
Calyx drill	Raiseborer maintenance. Final lining.	High

## 4. Shaft Cutting Machines

Shaft cutting in this context refers to removing soil and rock material from the surface rather than raiseboring. The methods that can be used will be discussed below.

### Excavation mechanisms

#### Augering

Augering refers to removal of soft plastic soils by applying torque to a helical blade, as shown in Figure 32. The amount of torque that is necessary depends on the depth and diameter of the shaft. For small diameters and limited depths this is a very competitive technique. Diameters up to 500 mm are common, however diameters of approx. 2 m diameter are possible by more elaborate rigs. In the Cannington area in Australia augers have also been used to hollow out a 6 m diameter shaft pre-sink where smaller cores were removed from the greater circle. The maximum depth is about 22 m.

Augering is limited to low soil strength., although it can be combined by a diamond drill bit at the tip to break moderately sized boulders. An obstruction may cause an auger to fail if it's diameter is larger than a third of the diameter of the auger.

#### Excavation

Excavation of the shaft can be performed by full-face mechanisms such as a microtunnelling machine or a V-mole. However, these systems have proven to be inflexible and costly, and are being replaced by non full-face machines.

Atlas Excavations has performed extensive shaft sinking with a small, down-the-hole excavation machine which has fittings for shovel, bucket tooth or hydraulic hammer. This makes the machine extremely versatile. Such machines were used, for example, for excavation of about thirty shafts for the Super Collider in the U.S. Unfortunately this machine requires a controller, which makes it relatively unsafe for shaft sinking. As developments in underground mining are going at the moment, this equipment will be controllable by computers from the surface within the next decade, and this may be a promising alternative to the heavy equipment required for blind hole drilling.



Figure 32 - Excavation of a shaft with a large diameter auger.

Shaft Sinkers inc. of India have developed a boom operated excavator for remote excavation of shafts. This has the added advantage that the shaft can be excavated wet in area's with a high water table. For

depths of up to 30 m it is reasonable to consider a boom operated excavator, but legislation limits the length of the boom to 22 m in some countries. In sandy soils wet excavation is an especially efficient method.

An alternative to surface excavation in areas with a high water head is down-hole excavation under pneumatic pressure. This method, where a caisson is sunk gradually as excavation proceeds from inside, has serious health-and-safety hazards. The pneumatic system requires decompression of all personnel working at the bottom of the shaft. Hence this method is rarely used nowadays.

In all cases either an airline or fluid flushing can be used to get the soil to the surface. The question remains how to support the shaft wall in combination with a shaft cutting machine that excavates top-down.

## Caisson-style lining

### Skin friction

The top-down approach allows access to the shaft wall for applying support. It would be economical and safe if it would be possible to insert prefabricated rings into the soil from the surface. This will be referred to as caisson-style lining.

For soft plastic soils, it is most common to use steel lining elements which are pressed in to the soil hydraulically. IHC Calland has the largest available equipment designed for off-shore construction purposes. They have pushed steel tubes of up to 5 m diameter at least 20 m deep into soft marine soils.

In sands smaller diameters are possible, however as the relative density increases it becomes more difficult to get the lining to penetrate. In sands it is common to use vibratory equipment which locally liquefies the sand next to the steel lining. The following problems lead to jamming of pipes when pushing them in to the ground :

- Excessive skin friction as the length, diameter and soil density increases
- Ovalisation of the lining
- Elastic deformation of the lining as length increases. This makes it harder to vibrate or ram the lining any further.

Determining the penetrability of sands is beyond the scope of this study, however extensive knowledge is available from pile foundation engineering. A dynamic pile driving analysis could be performed to determine if a casing could be driven into stiff sands.

Also it is generally accepted that the friction along a pile shaft is related to the in-situ vertical effective stress and the friction angle between the lining and the soil as follows :

$$\tau = \sigma_{v0} \tan \delta \approx \sigma_{v0} \tan \frac{2}{3} \phi$$

The total resistance to skin friction can be derived by a simple summation of the area of the lining. The following measures can be taken to reduce the shaft friction and thereby increase the depth attainable by driving a lining :

- ▶ Greasing the lining to reduce skin friction.
- ▶ Use of an oversized tip to excavate slightly larger than the diameter of the lining and reduce soil pressure on the lining.
- ▶ Pumping lubricating fluids along the outside of the lining.
- ▶ Use of thicker steel to reduce ovalization and increase the blow that can be applied to the shaft bottom.
- ▶ Excavate during driving and in combination with a down-the-hole hammer

Because skin friction generally determines the penetrability rather than the tip resistance, linings are similarly made of concrete. Caisson style shafts are common up to approximately 20 m depth and 5 m diameter.

## **Conclusion**

Caisson-style sinking is a suitable alternative where soft soils and sands occur, along with high phreatic levels. Dredging or “wet excavation” from a boom is a safe and economical way to get to depths about 20 m. At greater depths, boom-length and skin friction start to restrict further progress.

The skin friction resistance and drivability of shaft elements can easily be analysed by analogous tools designed for pile foundations.

## 5. Blind hole drilling

### Introduction

This chapter will discuss the method of blind hole drilling (BHD) sometimes also referred to as blind hole boring. This method is derived from reverse circulation drilling (or RC-drilling) which has been used extensively in mining and oil-drilling to get core samples from layers of rock far beneath the surface.

In the 1980's several companies developed BHD equipment, but there are two main companies serving the majority of large

diameter shafts (>3m). Wirth of Germany spent a lot of its efforts on a down the hole type boring machine. The V-mole, which uses a pilot hole to remove cuttings downwards, was a success, but a similar machine which was to be its successor, which had the cuttings lifted first by a muck hoist and later hydraulically, was abandoned [17. Keeble, 1990]. Wirth decided to adopt a blind hole drilling machine positioned on the surface of the shaft.



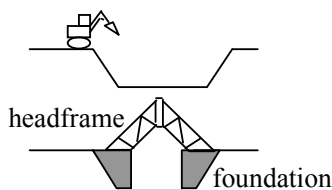
Figure 33 - Headframe for shaft drilling

Ardent Underground from North America, previously known as Zeni, is expanding around the world. Because of the use of drilling mud that can support the shaft walls, they are doing very well in Australia where thick layers of instable overburden are common.

## Description

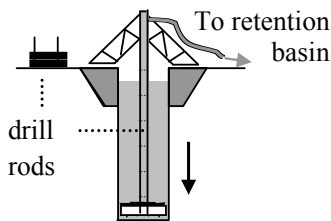
Blind hole drilling uses a cutter head similar to those used in raiseboring that is rotated from the surface by drill rods. The hole is filled to the rim with drilling fluid, which can have clay or polymer additives to make it cohesive and heavy so it will support the shaft wall. The fluid is also used to transport rock cuttings from the bottom of the shaft, through the inside of the drill-rods.

The following steps are required to construct a shaft by the BHD method:



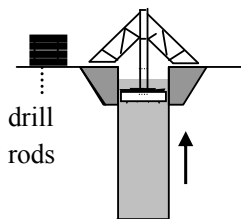
1. Excavation of a 3-5m deep presink, and construction of a concrete foundation.

2. Setup of headframe and mud-plant.

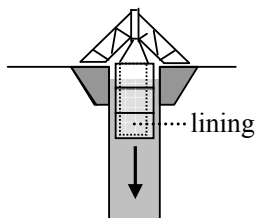


3. Start of drilling. The presink is filled with mud and the cutter lowered into the shaft.

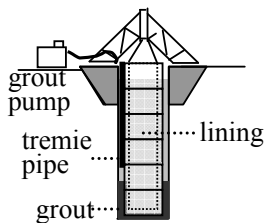
Drilling progresses and every 11m a new drill rod is attached. Cuttings are pumped to the surface and transported to a retention basin, where they are left to settle.



4. Upon reaching the required depth, the cutter head is lifted from the shaft by raising and disconnecting each of the drill rods.



5. A composite lining is lowered into the shaft. The 3m segments are welded together as they go down the shaft.



6. Small diameter drill rods are lowered down the outside of the lining and grout is pumped in from the bottom up. The shaft is pumped clean and the headframe and equipment are removed.

A significant depth is necessary (>100m) to make the method economical because the transport and setup of the headframe can take up to four weeks, including creating a concrete foundation on-site.

Either a power swivel or a rotary table is used to power the drill rods.

A high degree of accuracy is required, both for the successful construction of the shaft as for

it's final use. Especially access and haulage shafts need to be exactly vertical for lift cables

to function effectively. The cutter head is kept on course by 200-400 tonne weights near the cutter. Due to the pendulum effect the cutter should always follow an exactly vertical path.

Strong, dipping veins like quartzite tend to cause the cutterhead to lose track. In this case drilling should be slowed, or the cutter head can be lifted slightly and lowered again to get it back on track. Accuracies of 0.25% are attainable by well controlled drilling. By drilling a small-diameter pilot-hole and using a leading pointer higher accuracies up to 0.1% have been achieved. Such a hole should be filled with a gel-grout to avoid loss of the drilling fluids. [17 Keeble, 1990]



Figure 34 - Composite lining elements which will be welded together as they are floated into the shaft.



Figure 35 - Drill pipes and the airline-nozzle [left] which is lowered through the pipes.

## Cuttings Removal

The transportation of rock cut from the surface is done by reverse circulation drilling. This means drilling fluid from outside the shaft is pumped up through the inside of the drill string. Generally a thin airline is lowered down inside of the shaft with a nozzle at the bottom. Wirth either uses a double walled drill string, where air is pumped down the annulus between the outer and inner wall, or an airline fastened to the outside of the drillpipe which has a special connection at each flange. This air

Figure 36 - Detail of drill-pipe flanges and connection bolts. To transmit the drill torque and carry the weight of pipes and cutterhead they are thick and are made from high-grade steel.



is pumped into the inner pipe reducing the density of the fluid. This creates a flow which is able to carry pieces of rock up the pipe, some just smaller than the inner diameter of the drill pipe (up to 340mm).

At the top the fluids are collected in a retention basin, where cuttings are left to settle and drilling fluids can be pumped off the top and reused. Reverse circulation was invented because the upward flow in the inner pipe can carry cuttings better than the outer pipe (traditional forward circulation). The inner cross section is small compared to the cross-section outside the pipe, resulting in high flow speeds. This is necessary in big hole drilling where the diameters are so great that forward circulation is impossible. Also chunks of rock tend not to jam easily because the diameter of the inner drill pipe is relatively large being round (rather than when the annulus was used).

The air that is pumped inside the drill pipe lowers the density and thereby reduces the head. This is why water or drilling fluid is required right up to the top of the shaft. The weight of the drilling fluid drives the upward flow through the drill pipe. This is an important restriction because it means water, under high pressures, must always be used.

Some rocks may dissolve or react with water, resulting in significant loss of strength. As well as this, the washing of clay and minerals from fractures combined with high pore pressure can make fractures turn into instable shear planes.

Another danger of the pressure of the drilling mud, is the risk of blow-out into nearby cavities. Area's with washed out cavities or existing mine openings may not be able to withstand the high pressures of the mud. The shaft walls may suddenly burst into these openings rapidly flushing the fluid away. This will stop the drilling progress, damage the shaft wall and potentially cause the rest of the shaft to collapse. More importantly it will endanger people's lives if they are present in the adjacent mine openings.



*Figure 37 - Settling ponds for drilling mud*

## Lining

The lining segments, each about 3m high, are generally pre-cast on site. The linings consist of a 20-30mm steel outer ring with a layer of 100-200mm thick concrete poured inside. A thin ring is welded to the outside of each segment to allow it to be lifted mechanically.

The lining is dropped down into the mud, with a plug at the bottom that is filled to the top with concrete. This weight is necessary to stop the lining segments from floating in the drilling mud. As the lining is floated in, each segmented is welded onto the previous one. A space of 100-200mm is required between the shaft and the lining to stop it from jamming. It is very important for the success of this stage that the shaft has been drilled as close to vertical as possible.

When the lining reaches the bottom, common drill rods around 72mm used for core-drilling are lowered between the annulus behind the lining. The lining is carefully grouted from the bottom up, creating a solid connection between the lining and the rock. The mud cannot be emptied until the grout has hardened because fluids behind the lining compromise its strength, potentially causing it to buckle. When the grout hardens it ensures stresses are transferred to the stiff rim of the lining through arching. [70. Hunt, 2003]

For some deep shafts, where rock strength increases at greater depths, the drilling can be done in stages. This way costly and thick drilling muds can be exchanged for water for the deeper section. Because water is lighter and more viscous than muds, it makes cuttings removal easier. Also it lowers the pressures at the bottom of deep shafts - reducing the chance of a blow-out. To be able to lower the lining in the second stage, and grout behind it, the second section of the shaft must be drilled at a smaller diameter than the inside diameter of the first.

Alternately blind hole drilling can be done without drilling fluids. In this case a pilot hole must be drilled or raise bored, to allow for removal of the cuttings. This is not common practice.

The speed of drilling is generally limited by the weight at the cutting head. Pressure cannot be applied to the cutting surface from above because this would cause the drill string to flex and the cutting head would deviate from its' vertical course. To achieve large diameters above 5m the shaft would be drilled in more than one pass. A reamer would be used to enlarge the hole to the ultimate diameter of up to 7m.

It should be noted that floated in lining only becomes strong once it is grouted up at the back – this transfers the horizontal pressures to the outsides through shear, unlike with fluids [Hunt et.al. 1995, *Casing collapse at the CT-8*].

## Cost

The cost of blind hole drilling is generally twice the cost of raise boring. The main costs of blind hole drilling is the setup of the drilling equipment, can take up to 30 truckloads and four weeks. Once drilling starts, costs per meter are only 20-30% higher than raise boring [Zeni 2004]. For remote locations such as those in the Northern and Western deserts of Australia, pre-reinforcement options tend to outweigh the high cost of setup. Despite the extra costs, there are many reasons why blind hole drilling can still be the preferred method.

Firstly the liabilities of BHD are lower; for raise boring a reaming head must be positioned from the bottom of the shaft, which is a very dangerous position to work from. For long shafts through hard rock, the cutters become worn and damaged and must be changed, again putting workmen at risk.

In situations where soils or rock are unstable, raise boring requires a pre-sink. This pre-sink can be done to about 20-30m below the surface by an excavation arm, but below this a working platform with a protective cage is required. If the rock is hard, drilling and blasting is used, which is a dangerous and cumbersome operation. This is where blind hole drilling starts getting an edge.

Often it is easy for mine planners to be able to have a shaft ready to go as underground workings reach it. With raise boring the underground opening always has to be excavated first, and the cuttings removed as the shaft is constructed. This can have significant economic disadvantages compared to blind hole drilling.

Alternatively it is possible to combine raise boring and blind hole drilling. This way the unstable shaft can be drilled by the more expensive blind hole drilling, and raise boring can be done for the remainder of the shaft. This poses some difficulties.

It should be noted that it is not possible to raise bore first, then blind hole drill. The pilot hole will lose the drilling muds, and as the blind hole drilling approaches the raise bored hole, the drilling muds will suddenly be breach into the opening, causing shaft collapse.

The hole will have to be blind hole drilled first, then raise bored. This is possible, but three problems arise during the raise boring:

- ▶ Additional stabilizers are required because the drill strings are not supported by the pilot hole at the top of the shaft. Although the drill strings are in tension, they may deflect because of the torsion that is applied.
- ▶ The foundation of the raiseboring machine is more complex. The shaft beneath the raise boring machine means it is hard to transfer the vertical load to the ground beneath. Beams across the hole are required which divert the load to a large area foundation.
- ▶ The beams that cross the hole need to support very large vertical loads from the raise boring machine. Because of this they may deflect up to 20mm, which means control of the raise boring head becomes very difficult.

Eventually the costs of setup of both the blind hole drilling and raise boring machine may not outweigh the costs of simply blind hole drilling all the way, but combinations of raiseboring and a short pre-sink should always be considered in area's of weak overburden.

## Limitations

With a common drill pipe diameter of 20", depths of 700-800m can be drilled, depending on rock conditions. A smaller setup with 12" rods can reach 600m (and up to 3,5m diameter) rock conditions permitting. At great depths drill strings start to get 1-2 rotations of 'windup'. This is elastic deformation of the drill pipe between the top where torque is applied and the resistance on the cutter head at the bottom. Because rock is never completely homogenous, this can cause sudden spinning followed by sticking of the cutter head, as the deformation travels up the shaft. The only solution for this problem is a larger diameter drillpipe with better quality steel combined with heavier equipment.

Depth is hardly limited by the drilling fluids as it is usually possible to simply pump more air down the nozzle. The increasing weight of the drill pipes is a bigger problem; it requires stronger drill pipe with thicker flanges (or better quality steel) and larger equipment.

Diameter is still limited in blind hole drilling. Because the weight is supplied through gravity and not through tension in the drill strings like in raiseboring, the thrust is limited, and thereby also the diameter. A two-phase sink head or "sumped cutterhead" can be considered where thrust is a problem,

but these are still being developed for shaft drilling. An untried solution may be to place an anchor at the end of a pilot hole, which can be tensioned and thereby apply thrust to the cutterhead.

Blind hole drilling applies large pressures to the surroundings. In the neighbourhood of cavities and existing mine openings this can form the danger of a blow-out. Generally a 20-30m barrier between the shaft and neighbouring openings is considered quite substantial to support the fluid stresses (up to 30Mpa for very deep shafts). For soft coal seams which may be weaker and have high stresses, up to 50m may be required to support the standing head.

Uncemented sands, unstable weak rock and large water inflows are supported by the drilling mud. In these cases bentonite is added which makes the mixture thixotropic and supports the shaft walls. This must be balanced against keeping the drilling fluids viscous enough to easily transport the cuttings.

Some karstic limestones and similar rocks dissolve in the drilling mud and cause the walls to break and dissolve. This can be solved by adding bentonite or polyacrilonite to the drilling mud which makes the fluid thixotropic. This means it forms a solid “cake” around the outside of the fluid which keeps the fluid together and stops it dissolving the walls. To prevent washing soluble clays potassium chloride ions can be added (at around 20,000 p.p.m.). These form a molecular bond with the clays, effectively hardening them. A simple test where core samples are dissolved in buckets of water with various concentrations is sufficient to find out how much additive to use to stop solution of the clays. The potassium chloride can cause some environmental problems where the chlorides cannot be disposed of safely. Here a more expensive alternative is used (at about 10 p.p.m).

Areas of uncemented sand in combination with reactive clays can form a problem. This is because bentonite is used to make a thixotropic solution which forms a “cake” and stabilizes the sand. Bentonite consists mainly of smectite which is a reactive clay. This added clay prevents the addition of potassium chloride, the additive that is used to prevent the solution of the reactive clays.

Open fractures can allow the drilling muds to escape. This is a problem that can be solved by using “sure-seal” or other cellulose products, which are added to the drilling mud. Typical products such as paper clippings or wood chips tend to get carried into the fractures by the high flow rates, where it swells and blocks the hole.

Alternatively a ring of grout columns has been drilled to reduce the permeability of fractures, for example in cases where shafts have been constructed near water catchment area's. The penetration of drilling muds into the groundwater and surface retention basins can form an unacceptable environmental hazard, restricting the use of blind hole drilling. Drilling with polymers or dry-drilling combined with remote shotcreting may be an alternative in this case.

In Chapter 8 the rules for shaft drilling will be assessed and compared to other construction methods.

Table 16 - Blind Hole Drilling guidelines [Zeni 2004, Weber]

<b>Blind Hole Drilling, guidelines</b>
<p>For shallow depths up to 100m consider alternative methods, cheaper in setup.                      Suited to depths up to 500m at diameter of 3,5m with 12” drillpipe.                      Suited to depths up to 700m at diameter of 3,5m with high-strength steel 20” drillpipe.                      For diameters of 5m and over drill in two or more passes</p>
<p>Remote locations: consider alternative methods</p>
<p>Proximity to existing openings (evaluate fluid pressures and rock strength)</p> <ul style="list-style-type: none"> <li>▶ medium strength rock: 20-30m</li> <li>▶ soft coals seams: 50m</li> </ul>
<p>Unstable shaft: Use thixotropic solution with bentonite clays.</p>
<p>Danger of fluid escaping into cavities: cellulose mud-additives on-site (sure-seal, wood-chips, etc)</p>
<p>Expansive clays in fractures: Add potassium chloride ions to drilling mud to bind clays.</p>
<p>Environmentally sensitive areas: Pre-grout perimeter to reduce permeability, use polymer muds.</p>

## 6. Pre-reinforcing with piles

### Introduction

One of the most efficient methods of drilling is raiseboring. Raise boring has some major advantages compared to other methods of drilling. It is a fast, continuous process with no need for mucking out the hole. The machine is relatively small and easy to setup. Machines can be used with different sized reaming heads and under different angles making them very flexible. One major limitation on raise-boring is the need to have access to the bottom of the shaft to fit the reaming head, but this is usually common in mining and tunnelling applications.

The other limitation to raiseboring is that there is no access to the shaft to apply any form of reinforcement. This means that any unstable rock and soil must be reinforced from the surface before raiseboring begins. Two commonly used methods are grouting and freezing.

This chapter looks at potential ways of constructing pre-reinforcement. The methods of drilling and inserting grout are discussed, along with the potential of these methods in different geologies. Alongside the different drilling methods, grout can also be applied differently. It may be poured into the drill hole or it may be pressurised into joints and weakness areas. Also it may be reinforced with steel rods or fibreglass. Ways for maintaining the accuracy of drilling are also reviewed.

Some problems that occur during grouting are assessed such as the problem of grout flow, grout wash and the penetration of grout in narrow and clay-filled joints. Also there is some reflection on the way grouting can increase stability.

## Drilling methods

### Secant Piles

Secant piles are commonly drilled with an auger, which is a corkscrew shaped drill that transports cuttings to the surface by rotation. In very soft rock, augers can be used with a drill bit at the tip. The problem with augers is the limited torque that can be applied to the auger to overcome friction. In soft clays augering works very well, but sands already start to become problem. As depth increases so does the friction on the auger, reducing penetration rates until finally the auger refuses to penetrate any further.

Table 17 - Secant pile guidelines [134. Herrenknecht AG.]

Secant piles, guidelines
Depth up to 22m, in soft soils <2MPa Depth up to 44m, in very soft soils <1MPa, where connectivity of piles is not crucial to stability
Maximum obstacle size (boulders etc..) $D < \frac{1}{3} D_A$ for auger diameters $D_A < 300mm$
Maximum obstacle size (boulders etc..) $D < \frac{1}{4} D_A$ for auger diameters $300mm < D_A < 800mm$

Another important vulnerability of an auger is where boulders and solid obstacles occur, which also jam the auger. As a guideline, drillers can use augers up to a depth of 22m for soil and rock strengths up to 2MPa. By connecting two augers together, a depth of up to 44m may be possible in rock and soils less than 1MPa.

This is obviously an uncommon geology especially in mineshafts as it is generally only encountered in alluvial deposits or extremely weathered zones (e.g. karst). Generally any boulders cause problems blocking the auger, as well as great depths because the friction increases with depth. If unstable clays are encountered a casing can be used to support the shaft, which is driven by a vibrating block at the same time as the auger drilling. In areas with only a few boulders, it may be viable to use jet-grouting.

### Jet grouting

Although more expensive, jet-grouting has less problems with higher strength sands and gravel. Jet-grouting is suited to porous soils where the particles can be moved by a pressurised jet of air and water. Areas with a large amount of large boulders should not be grouted as the boulders can stop penetration of cement in their 'shadow'.

Jet grouting is not very common in mining engineering because it is expensive, inappropriate to rocky conditions, and error-prone at large depths.

## Rotary percussive DTH-drilling

The most suitable form of drilling for drilling grout holes, and the most common method used today, is rotary-percussive down-the-hole hammer drilling.

Simply rotary drilling implies you are pushing a diamond cutting head into the ground along with a rotating action. This is usually used in conjunction with a diamond core barrel which allows core samples to be pumped up through the inside of the pipe to allow for geological analysis.

Rotary-percussive drilling, however, uses some form of percussive hammer along with the rotation which greatly increases drilling speeds. It is easiest to place the hammer in the headframe and drive the pipes from the top. However as the depth increases, the shockwave from the hammer needs to pass through more and more drill rods. The drill rods exhibit elastic behaviour and dampen the blows. For greater depths a down-the-hole hammer is used. Diesel hammers are common, but are being replaced by hydraulic systems which are fed by a hydraulic pump at the surface.

An example of a machine specially designed for drilling pre-grouting holes has recently been introduced by Indau of Finland. The newly developed machine, costing €450,000, which can drill piles at 2-3m/hr in soft rock and 1-1½ m/hr in hard rock using a tri-cone bit at 381mm diameter (diam range 171-381mm). One man can work the machine and both setup and take-down takes a team of two men one day. A 50m length pile requires two stabilizers at 1% deflection, monitored by a Swedish Reflex AB down-the-hole camera. A 100m length would require three stabilizers at 1% accuracy. Air flushing can be used for clays, gypsum and other solubles. Indau uses armoured concrete rather than steel reinforcement to prevent damage during raiseboring: otherwise large deflections that may occur during drilling and placement of the pre-reinforcement will cause the reaming head to run into solid steel. [88. Roger Nylund, 2004]

Table 18 - Rotary percussive DTH-hammer drilling guidelines [88. Roger Nylund, 2004]

<b>Rotary percussive down-the-hole hammer drilling, guidelines</b>
Depth up to hundreds of metres
Diameters 90-400mm
Accuracy dependant of drilling contractor and quality of survey: 0,5 % - 2%

## MUD-support

For drilling in any soft soil or rock, some form of drilling fluid or 'mud' is used. The fluid cools the drill bits, transports tailings back to the surface and, if necessary, supports the walls of the hole. When extra stability of the hole is required, montmorillonite clays (bentonite) are added making the mix thick, but reducing cuttings transport. Another important function of the clays is to form a filter cake on the surface.

Often water flushing is adequate for small holes, except in soft or reactive clays and karstic geologies that contain soluble rocks like gypsum and limestone. Also, situations where the in-situ stress is high in one direction, and low in the other may require more than just water support, to prevent borehole breakout.

## Dry-rock-drilling

For reactive clays, gypsum and some limestones dry flushing can be used with air to support the walls. Powermole or its Italian equivalent Technolgie Avanzate use this method on a regular basis, mainly for directional drilling of pipelines (The PM903 system is used).

<b>Dry-rock drilling, guidelines</b>
Applied in geologies that react adversely to water-based drilling fluids: <ul style="list-style-type: none"> <li>▶ expansive smectite clays, common in deeply weathered rocks (often granites) in acidic environments</li> <li>▶ semi-expansive illite clays or mica's, common in weathered rocks (often sandstones, shale) in basic environments</li> <li>▶ rocks susceptible to solution: carbonaceous rocks (limestones), chalk, marl, mudstones, gypsum, anhydrite, rock salts</li> </ul>
Diameters 90-200mm

## Odex

Odex is a form of drilling with an eccentric drill bit, specifically tailored to drill through overburden. Where ordinary drilling uses a casing only for the first few metres and uses drilling fluids to support the hole, Odex uses a casing all the way down to the bedrock.

Odex is an eccentric bit that folds out of the casing by rotation, cutting a path just outside the diameter of the casing. Because overburden can contain blocky and weathered rock that can jam the bit, the Odex drill bit also has top bits that can drill backwards. When the rotation on the Odex bit is reversed, it collapses so it can fit inside the casing and be lifted to the surface. This also allows the drill bit to be exchanged for a hard-rock bit which allows drilling to proceed easily into the bedrock.

Table 19 – Odex drilling guidelines [62. Verfel 1989]

<b>Odex drilling, guidelines</b>
Depth up to 72m for 140mm diameter holes Depth up to +/- 100m with a telescopic arrangement
Diameters 90-240mm

Odex also uses a down-the-hole hammer, which has been improved in a new system called DEPS where the thrust and percussive action of the hammer is passed on to the drill bits more effectively, greatly increasing drilling speeds [123. Atlas Copco 2004].

## **Abrasive water-jet-cutting**

In the interest of selective mining and mining through very hard rocks, significant research has been done into cutting with water jets or jet-kerfing. Generally water-jet cutting has insufficient cutting speed to be effective for large diameter shafts in soft rock.

Besides speed, the costs of water and abrasives used and the cost of replacing the water nozzles is far too high. [117. Vijay 1992]

The use of water-jets in combination with drilling is quite useful as it removes tailings effectively. However both drilling and cuttings transport through water-jets are highly complex mechanisms – description of these phenomena and how they collaborate requires extensive research. The development of integrated drilling systems is being led by the exploration sector of the oil-industry. [121. National Academy of Sciences 1994]

<b>Abrasive water-jet cutting/kerfing, guidelines</b>
<i>Not suited to pre-reinforcement.</i>

## Drilling Accuracy

### Measuring and correcting deflections

A vital part of successful grouting is getting the grout into the area's that need reinforcing. This not only means accurately surveying grouting operations, it also means drilling accurate geotechnical investigation holes.

Firstly, this means grouting should be performed as close to the target as possible, such as from completed mine activities close to the shaft. However, having workmen down the shaft is a problem, so drilling grout holes from the surface is preferred. Also this is more economical as it is difficult to get large equipment into the shaft.

Accurate grouting is also necessary if raiseboring is to be performed after drilling. An ventilation shaft in north-western Australia could not be raisebored because reinforced grout piles had deflected inside the shaft

perimeter, which would have caused the reamer to jam. Fibreglass reinforcement is a more expensive alternative which prevents this problem.

From several examples have shown that the selection of the drilling contractor and surveyor plays a vital role in the succes of grouting operations. Several tools can be used to measure deflection of boreholes, one better than the other.

- ▶ Timed mechanical tools that lock a gimbaled compass on angular scales.
- ▶ Tools taking a timed photograph of the graticule on a floating ball.
- ▶ Tools that measure (changes in) magnetic field, magnetic azimuth and acceleration in three directions, in a single shot.
- ▶ Tools that measure (changes in) magnetic field, magnetic azimuth and acceleration in three directions, at intermediate points down the hole.

Timed mechanical tools, which are becoming outdated, are tedious and inaccurate. It relies on the drilling operator to run a stopwatch and ensure correct positioning of the tool down the hole at exactly the right moment.

Timed single shot photographic tools are still tedious, but more reliable because correct positioning of the tool down the hole can be checked on the photo. This eliminates the danger of incorrect centering of the tool in the borehole.

More advanced tools are now available, that measure magnetic field in three components. Disruptions of the earth's magnetic field occur frequently in rocks with a high metal content, and result in incorrect

azimuth measurement. These disruptions can be detected by measuring changes in magnetic strength and dip, allowing incorrect readings to be ignored. Also it helps detect drilling tools that are

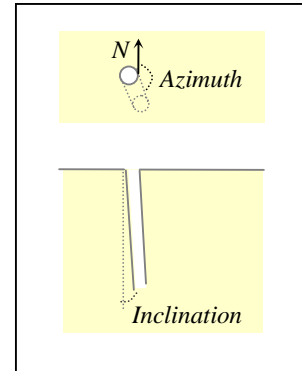


Figure 38 – Measuring borehole deviation: azimuth and inclination.

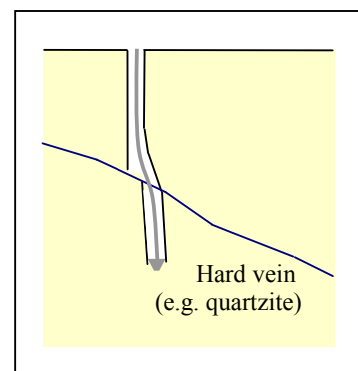


Figure 39 - Deflection caused by hard, dipping layers known as 'rat-holing'

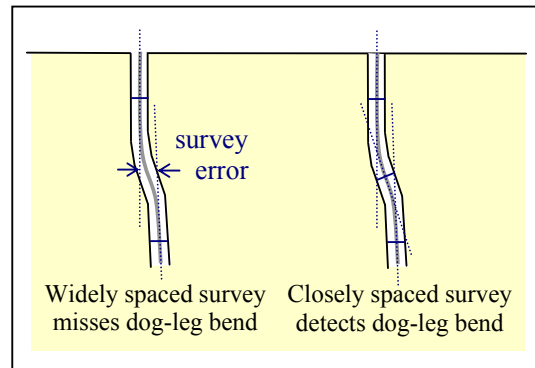
disrupting magnetic readings. This can be solved by moving the measuring tool away from drilling equipment using non-magnetic aluminium extension pipes.

Such modern tools also contain three-component accelerometers rather than a graticule, which provides for more accurate readings. Also it helps prevent error introduced by movement of the tool during measurement. To provide more continuous operation, these tools may be used with a wireline, to directly connect the measuring tool to the surface. This works well in conjunction with a Navidrill or similar steerable drill that can then quickly adjust it's direction with the help of a dogleg bend.

Reflex of Sweden also produce a multi-shot tool called Maxibor, which allows for quick measurement as the tool travels down the hole. Rather than a single shot, Maxibor takes measurements up to as little as 3m between, which is possible because it only takes a few seconds to create an image. The system should also be rotated between measurements to average calibration mistakes in all directions.

One area of concern is where hard layers such as quartzite veins intersect the borehole at an angle. This is a typical location for deflections to occur due to the phenomenon of 'rat-holing' where the drill bit is pushed away from it's target, as shown in

*Figure 39.* Drilling should be performed with less pressure on the bit when traversing these layers, along with extra measurements so that deflections can be quickly corrected.



*Figure 40 - Improved accuracy through multi-shot survey*

Common problems in measuring drilling accuracy are listed in *Table 20*. Calibration and initial survey of equipment are by far the most common sources of borehole deflection. [139, 140. *Reflex instrument AB*]

Table 20 - Guidelines for troubleshooting drilling accuracy problems. Solid bullets indicate survey systems that are susceptible to errors.

<b>Problem</b>	<b>Solution</b>	<b>Mechanical gimbaled compass (Pajari Prod S)</b>	<b>Photograph of graticule (Icefield MI-3)</b>	<b>Electronic Single-shot ( Reflex EasyShot)</b>	<b>Electronic Multi-shot (Reflex MaxiBor)</b>
<b>Poor survey of initial inclination</b>	<b>Employ reliable surveyors, Check calibration of survey equipment, Check verticality of drilling mast, Check for surface magnetic disturbance</b>	●	●	●	●
Poor centering of the down-the-hole tool in the hole.	Use 2-3 stabilisers. Check with photo.	●	○	●	○
Poor tool calibration	Calibrate away from magnetic disturbance (equipment/metalliferous deposits)	●	●	●	●
Missing deflections because of distance between measurement (See Figure 40)	Decrease distance between shots	●	●	●	○
Cumulation of tool error in readings	Rotate tool between readings	n/a	n/a	n/a	●
Drilling equipment upsets magnetic readings	Extend distance between survey tool and drill rods with up to 8m of aluminium rods	●	●	○	○
Metalliferous deposits upset magnetic readings	Ignore azimuth readings in metalliferous zones	●	●	○	○
‘Rat-holing’	Reduce pressure on the bit	●	●	●	●
<b>Approximate error :</b>		2%	2%	1%	,3%

## The grouting process

### The purpose of grouting

Grouting generally has a positive effect on the stability and impermeability of a fractured rock zone.

The purpose of grouting can be split into :

- ▶ Increasing normal stress across joint planes and thereby increasing joint shear strength
- ▶ Increasing cohesion of joint planes, through removal of infill material and cementation or binding of the joint surfaces
- ▶ Blocking pore and fracture space to inhibit water flow. Water decreases stability by reducing normal stress on joints and also by weathering material in joints or the joint surface. Besides for stability purposes, large amounts of water will render a shaft useless.
- ▶ Connecting joint planes by hydrofracturing followed by grouting of the joints.
- ▶ Encapsulation for shear reinforcement rods or armouring.

The most crucial function of grouting is the increase of normal stress across the joint, and secondly the reduction of permeability.

### Quality of grouting

To determine whether grouting will be effective, the factors that influence the result should be identified. It is important to get grout sufficiently far into joints and pores.

The distance grout can penetrate is determined by:

- ▶ joint thickness, joint roughness and joint filling (clays gouge, etc)
- ▶ initial normal pressure on the joint
- ▶ stiffness of the rock surrounding the joint. Stiff rock can prevent fractures from opening. On the other hand 'hydrojacking' may allow opening of joints and further penetration.
- ▶ 'filtration' effects achieved by cement particles blocking holes
- ▶ thickness of the grout mix (expressed by a Bingham fluid with viscosity and cohesion)
- ▶ grout choosing the path of least resistance, instead of going into all cracks.
- ▶ grouting pressure
- ▶ reduction of grouting pressure due to hydrofracturing

The strength of the bond is dictated by:

- ▶ Shrinkage called "slump" due to high water ratio's, resulting in pore space
- ▶ Dry powdery grout because of inadequate water .  
Inadequate water occurs where :
  - the grout is too thick
  - The grout flow slows along the pore walls where friction is highest
  - Absorption of water by 'dry' rock
- ▶ Additives like bentonite or superplasticizer (e.g. Intraplast) that weaken the grout
- ▶ Dissolution of grouts due to groundwater wash.
- ▶ Weathering after grouting due to in-situ water flows
- ▶ Hydrofracturing causing new fractures

Accurate grout-control is needed for succesful grouting. Lugeon tests are a reliable way of testing the permeability, and thereby the succesful penetration of grouting. During grouting accurate control is necessary. [93. Lombardi 2003]

Firstly the grout mix should be closely monitored. Batches should be checked for proper mixing and should not be too thin or too thick, in the form of measuring the Marsh flow time and the bleed. Also samples should be kept and cured for triaxial testing to ensure the required strength is attained, taking proper care to store the grouts in the same conditions (temperature and moisture) as where the grout is injected. If insufficient strength is attained, water-cement ratio's may need to be adjusted, or the amount of additives like superplasticizer or bentonite reduced.

Not only the mix, but also the grouting proces should be accurately controlled. It is recommended that holes that may be clogged with clay, debris or drilling mud be flushed first with water. Also this wets fracture surfaces making sure there is sufficient moisture for hydration of the cement. As grout pipes may become clogged, it should be possible to flush them with water when necessary. In case of flushing or if grouts do not meet quality standards, it should be possible te defer the flow of grout into some sort of sump pit.

The flow rate and total amount of grout pumped should be monitored, as well as the grouting pressure required. In case of large grout takes, the grout mix may be temporarily thickened to stop it continuously disappearing into large fissures. When grout take starts to decrease, it should be readily possible to lower the discharge of the grout pump accordingly, to prevent excessive grouting pressures causing fracturing. Grout lines should be kept as short as possible so adjustments can be made quickly. A return line allows deferring of poor grout and relaxation of pressures when necessary. It may also be economical to defer a portion of grout into the next grout hole.

Finally, packer tests to determine the Lugeon value are the most practicable method of checking grouting was succesful.

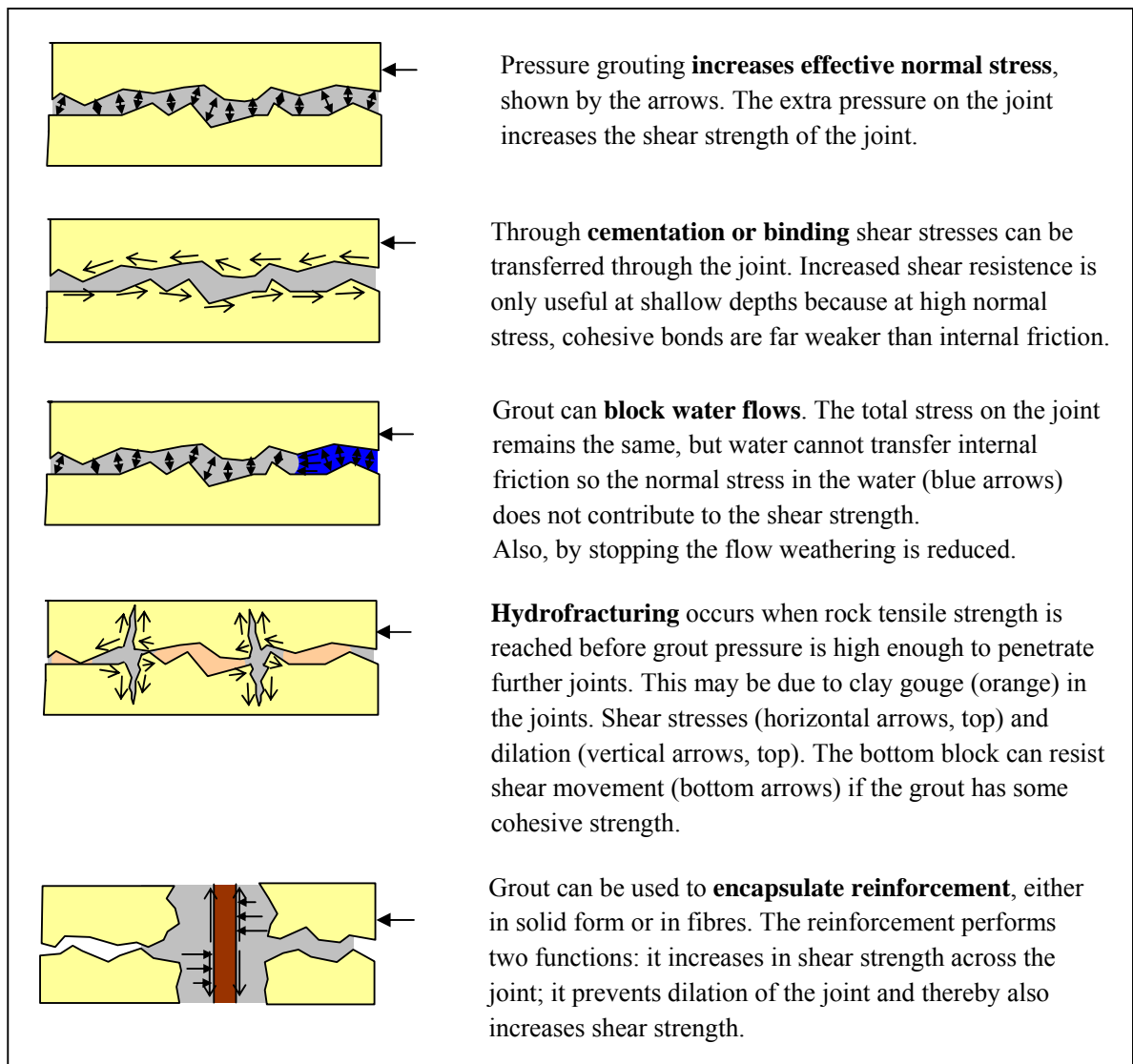


Figure 41 – Mechanisms of grouting for increasing stability

## Grouting and groundwater

### Grout flow

It is important to get grout on target. Poor grouting can occur where grout flows away from the target because grout flows along aquifers. It is common to use a packer test, however this only determines the permeability, and thus only the potential for water movement. In sites where there is a potential for fast flow of water, for example in minesites that pump groundwater, or where large open fractures are common, additional testing is advisable.

*Crosshole radar tomography* is a method of finding flow rates where three holes are drilled in a triangular pattern. The first hole is used to inject a tracer. The second and third holes are used to transmit and receive radar signals that pick up the tracer. The time it takes for the tracer to pass through the second and third holes is a measurement of the speed of flow along that flow path.

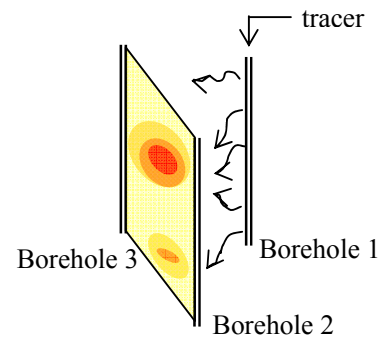


Figure 42 - Crosshole radar tomography to find flow paths

Radar tomography, although more expensive than a packer test, is suited to shafts that are being grouted because the holes used for grouting can first be used for the tomographic survey. A thorough understanding of water and grout flow can be attained by using the software package NAPSAC to perform hydrogeological modelling [143. *Serco Assurance – NAPSAC*].

Because there is little to no control of grouting down the hole, contractors should have a good idea what conditions to expect before attempting any grouting operation. A 4m diameter ventilation shaft in Tanzania was excavated in weathered rock down to 75m. It suddenly breached and collapsed when a water zone was encountered, however there was no indication of any water zone in the core samples, because the core failed to intersect this body. In areas where pockets of water are likely to occur, *thermal imaging* is a useful tool to detect bodies of water in the rock mass.

If high water flow rates are to be expected, grout relief holes should be drilled. By pumping away water through relief holes, grout has a better chance of setting without being carried by water.

### Grout wash

Water flow has another effect on grouts, especially on cement grout. Water flushes the cement particles, reducing the final strength, called grout wash. This occurs mainly during grouting while the mix is hardening, but also in hardened grout where flow paths have not been completely blocked. In the Stawell mine in south-eastern Australia, it is assumed the breaching of pressurized aquifers caused strong water inflows that washed grout and later caused the shaft to collapse.

This problem is exceedingly difficult in the cross zone from weathered rock into bedrock. Close to the hard rock zone, rocks are increasingly saturated and weathered, sometimes leading even to running sands at the cross zone. Grout not only takes the path of least resistance, but can also be washed by

strong water flows across the bedrock. The Freestate mine 75 km SW of Johannesburg at 2.4m diameter had high water inflows through dolerite layers. It was preconsolidated by a local grouting company, but collapsed on excavation of the cross zone. All grouting efforts had been washed by water flowing across the bedrock.

Some additives like quick hardeners can shorten the hardening time and reduce excessive grout wash. The addition of bentonite can keep the mix stable, controlling bleed, but this also weakens the hardened grout. Bentonite works ineffectively for seawater inflows or other highly saline groundwater.

An alternative to quick-hardeners is the use of separate holes to concurrently inject sodium silicate. Fast-gelling of the grout can be achieved because of the instant hardening when the two components meet; this limits grout dilution and transport of grout away from the targeted areas.

### Hot bitumen grouting

For permeation grouting hot bitumen is recently being used with a lot of success, pumped through insulated drill-pipes. This effectively stops groundwater flows because it hardens the quickest where it is cooled most, i.e. where the flows are rapid. Because of the relatively high slump of bitumen, it may need grouting afterwards to connect and fill the voids.

The reason hot bitumen works so effectively is that it cannot be flushed by water. When bitumen is poured into fractured zones containing water, the outsides are immediately cooled by the water, creating an impenetrable skin. Because bitumen is also a good insulator, this skin remains thin and can be constantly melted from the inside by the hot bitumen, so that it extends as far as possible into the joints. The hot bitumen is very viscous and has been known to seal apertures as small as 0,1mm. Generally there is no refusal unlike 'cloggy' cement grouts, with examples where bitumen traveled over 100m.

For shaft stability the danger of hot bitumen should be noted, which is the strong slump that occurs after setting, leaving joints slightly open. There is no bonding between rock surfaces as it occurs with cement, so bitumen must rely totally on internal friction. In soft rock asphalt will contribute only slightly to increased shear strength because it is so elastic. In very brittle rock the elasticity of the asphalt may be advantageous because it prevents progressive failure of shear surfaces, as shown in *Fout! Verwijzingsbron niet gevonden.*

For the purpose of stabilising shafts, bitumen should be combined with cement grouting for added stability and durability. In one case aquifers were sealed so effectively, the rock mass failed repeatedly under the built up water pressures. From this point of view asphalt grouting should be performed some distance outside the shaft perimeter, and cement grouting within.

Road-bitumens should not be used for grouting as they are poor in quality. Rather high solidification temperature bitumens should be used because they become harder. Bitumen is batched in heated and

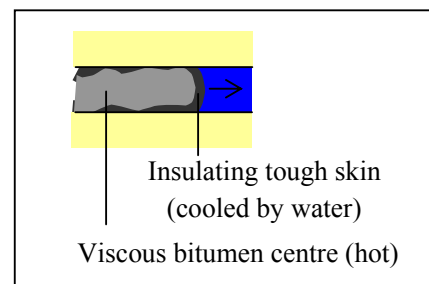


Figure 43 - Penetration of hot bitumen in water-filled joints.

insulated bulk containers with a temperature booster at the facility, capable of maintaining a high temperature (180-225 deg Celcius). Pipes should be preheated with hot oil and much care should be taken when handling the hot material..

[132. Naudts & Hooey]

## Grouting and joints

### Small joints

Small joints are difficult to treat, because it is difficult for grout to penetrate into them. Cementitious grouts are less successful in treating small joints because it is a colloidal mixture. Small cement and clay particles may not remain in suspension and form a filter around the grout that is penetrating the joint. These small particles get in the way of others trying to penetrate the joint, with the result that only water penetrates the joint. This mechanism is termed bleed.

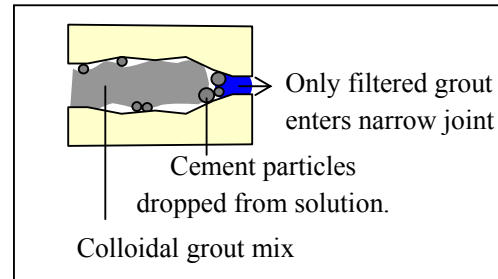


Figure 44 - Grout bleed

There are several approaches to getting the grout to carry cement particles into narrow joints:

- ▶ The particles are made smaller, e.g. ultrafine cements.
- ▶ Superplasticizers are employed to disperse the colloids better. Particles drop from the solution less easily.
- ▶ The pressure is increased, in order to widen the joint.
- ▶ Use of polyurethane or silicate grout, or hot bitumen, which does not contain suspended particles.

Superplasticizers have a secondary effect – the reduction in viscosity reduces wall friction on the grout. The pressure at the front of the grout remains higher, causing joints to open further and grout to be pushed deeper into the joint. The most highly jointed zones are often the deeply weathered zones just above the bedrock. Fortunately high-pressures can be applied to these zones because of the significant ground cover (1-2MPa).

Poly-urethane grouts have proven effective because they have viscosity less than water and penetrate well because of the high pressures applied due to the foaming action.

An example of effective grouting is Paracale in the Philippines where advanced grouting with both local Portland cements as well as by water-activated polyurethane resins took place. High water flows were limited by heavy localised pumping through 'relief'-holes. In earlier attempts in Paracale, grouting had been ineffective before because of typical errors in quality control:

- ▶ grout holes had not been flushed clean of drilling debris and mud infillings
- ▶ lack of control because there was no hydrofracture pressure testing done
- ▶ grouting occurred in one pass rather than controlled stage-down grouting
- ▶ grouting pressures were too high (7-14 MPa) for the weak, highly fractured ground conditions, which eventually caused a blow-out of the shaft bottom.

[124. Ayugat et.al 1998]

## Filled joints

Infill material can significantly reduce the shear strength of discontinuities. Soft materials such as clay act as a lubricant between shear surfaces. Swelling clays are especially dangerous because they absorb water and push apart joint surfaces so that nearly all internal friction is lost.

Theoretically clays can be washed from joints, but only at slow velocities of around 0.1 cm/s, and at high pressures. Unfortunately clay usually fills the smaller joints, which, when washed, have higher flow rates. Also hydrofracturing often limits the pressures that can be applied remove the joint filling. *[Verfel 1989 Rock Grouting & Diaphragm Wall Construction]*

Treatment of clay fillings with cement, chemicals or bacteria that produce carbonates to improve bonding is difficult. Penetration of joint filling with whatever particle can be in the order of weeks to years.

Recent research in the Netherlands is looking at treatment of clay layers through electro-osmosis. The aim in this case is to accelerate consolidation of clay layers and to create low strength foundations. Through this method water is extracted from the clay and strengthened by drying. Because of the complexity of clays and the remoteness of grouting it is hard to say if joint infill could be treated successfully by electro-osmosis.

At the very least clays that are to be treated should satisfy the following conditions:

- ▶ Predominantly expansive forms of 2:1 clays such as smectites (e.g. montmorillonite) and poor illite clays (e.g. vermicullite) that are sufficiently saturated. These are formed mostly from sandstones and shales in high pH areas (where  $K^+$  and  $Al^{+3}$  cations are abundant).
  - ▶ Groundwater flows should be near zero, otherwise the driving current will be insufficient to counteract flow.
  - ▶ Host rock needs to be non-porous. Porous rocks fill with water and have a high conductivity.
- Electro-osmosis is worth further investigation as it may provide a solution to clay-filled joints that cannot be grouted in any way. At the moment electro-osmosis is too uncontrollable to use effectively.

## Hydrofracturing

Grout loss can also occur because hydrofracturing and hydrojacking opens extensive new flow paths. It is important to conduct a hydrofracturing test, where water is pumped into the borehole through a packer under increasing pressure. The maximum grouting (hydrofracturing) pressure can be found by a sudden surge in water take, often accompanied by pressure drop.

There can also be a positive effect by hydrofracturing, although this is questionable. Hydrofracturing creates new joints and thus also new weakness planes. It is common for hydrofracturing to occur in vertical planes normal to the borehole wall. This means planes that dip towards the shaft are intersected, which is a useful mechanism if it is hard to strengthen these joints directly. On the other hand hydrofracture planes usually form parallel to the major principle stress, which is the exact direction that a joint is most unstable. However, in weak rock where grout bonds are relatively strong

compared to rock strength, and where grouting is inhibited by clay gouge or extremely narrow joints, this may be the only way to get grout to intercept fractures.

## **Cavities and large fractures**

For large cavities, sudden pressure drop can occur, with excessive grout losses. To solve this problem at first the grout is first thickened so that large fissures which may contribute to instability are filled with cement. If grout loss persists, it is likely that a cavity has been encountered, and cellulose material should be added to the grout, such as paper pulp or woodchips. This material clogs the joints that lead to the cavities and prevents further losses.

Some surveying may be necessary to ensure that an aquifer has not been encountered which is washing the grout. In this case polyurethanes or hot bitumen should be used to reduce the flows, before proceeding with ordinary grouting.

## **Conclusion**

Grouting can be used to increase internal friction between joint surfaces. Other important effects of grouting are blocking of water flow and increased cohesion.

There are abundant examples of shaft collapse after poor grouting operations. However, if grouting is better understood, it forms a valuable, economical tool for reinforcement of shafts. The three most common causes of collapse are:

- ▶ Inaccurate positioning of grout
- ▶ High groundwater flow
- ▶ Poor penetration of grout

In this chapter we have seen that there are solutions for most of the problems that are encountered during grouting. Accurate survey of grout holes and quality control of grouting operations is fundamental. Grout wash can be tackled with appropriate countermeasures, such as the use of hot bitumen grouting and pressure relief holes.

Poor penetration is more difficult to counteract, although reinforced minipiles that intersect joints are an alternative. Grouting should not be applied when joints are blocked with infill material, and water pressures also threaten shaft stability.

At the end of this chapter, a series of guidelines is given to ensure successful grouting.

Table 21 - Rules to ensure effective grouting

<b>Effective grouting rules</b>
▶ Establish that grouting will stabilise the shaft (See <i>Chapter 7 – Shaft Stability</i> )
▶ Ensure accurate positioning of grout holes (See <i>Table 20</i> )
▶ Monitor and correct the quality of grouting (See <i>Table 22</i> )
▶ Detect and prevent problems with grout flow and grout wash (See <i>Table 23</i> )
▶ Detect and prevent problems with grout penetration (See)
▶ Determine whether to grout above or below hydrofracturing pressure. (See <i>Table 25</i> )
▶ Do not attempt grouting where joints are blocked by soft infill material and water pressures also threaten shaft stability. Consider freezing instead.

Table 22 – Ensuring the quality of grouting

<b>Grouting setup</b>
▶ Keep grout lines as short as possible to lower reaction times.
▶ Include a return line so grout pressures can be relaxed and grout deferred from the hole
▶ Include taps at the hole to defer grout to other holes or to the return line, in case of problems.
▶ Grouting should occur in stages with a packer or tube-a-manchette.
▶ Start a grout batch with water, to wet all rock surfaces and to attempt to push away joint fillings
▶ Quickly increase grout thickness, to prevent open fractures from filling with water instead of grout.
<b>Grout quality control</b>
▶ Perform packer tests to determine Lugeon values before and after grouting.
▶ Continuously check grout quality.
▶ Check for proper mixing (lumps) and correct water cement ratios.
▶ Beware of excessive water as it causes grout slump and insufficient strength
▶ Beware of excessive cement as it causes poor penetration, cement filtration and poor bonding.
▶ Beware of using bentonite, super-plasticizers and quick hardeners, as it often results in significant loss of grout strength.
▶ Monitor grout viscosity by using a Marsch funnel
▶ Monitor grout bleed to warn for an instable mix.
▶ Take samples for triaxial testing. Keep these stored in similar temperature/humidity conditions as the grout that is pumped underground.

Table 23 - Detecting and preventing problems with grout flow and grout wash

<p><b>Detecting grout flow problems</b></p> <ul style="list-style-type: none"> <li>▶ Detect grout flow problems with a packer test. High permeabilities and nearby pumping activities indicate high risk of grout flowing from it's target.</li> <li>▶ When in doubt, pockets of water should be detected by <i>thermal imaging</i> from the borehole.</li> <li>▶ When in doubt, high water flow rates and paths should be accurately detected by <i>crosshole radio tomography</i>. Modelling is possible with a tools such as NAPSAC.</li> <li>▶ When losing grout into large cavities, thicken the grout and employ cellulose material.</li> </ul>
<p><b>Preventing grout flow problems</b></p> <ul style="list-style-type: none"> <li>▶ Low groundwater flow-rates can be stopped by adding quick-hardeners to the grout.</li> <li>▶ Moderate groundwater flow-rates can be stopped by using two-component silicates from separate boreholes.</li> <li>▶ Moderate to High groundwater flow-rates should be stopped by pre-grouting with polyurethane or hot bitumen.</li> <li>▶ High groundwater flow-rates should be reduced by drilling water-relief holes before grouting.</li> </ul>
<p><b>Hot bitumen grouting guidelines</b></p> <ul style="list-style-type: none"> <li>▶ Take adequate safety precautions for handling high temperature materials.</li> <li>▶ Beware of road bitumens. Use high solidification temperature bitumens.</li> <li>▶ Guarantee bitumen temperature: <ul style="list-style-type: none"> <li>▶ Use insulated, heated bulk containers</li> <li>▶ Have a temperature booster on-site</li> <li>▶ Use insulated drillpipes preheated with hot oil.</li> </ul> </li> <li>▶ Beware of slump and low durability. For stability, combine with cement grouting. Apply hot bitumen some distance outside the shaft perimeter as water pressure may build.</li> </ul>
<p><b>Open fissures and large cavities</b></p> <ul style="list-style-type: none"> <li>▶ Open fissures can be recognised by large grout losses, and should be filled by thickening the grout mix.</li> <li>▶ Large cavities will continue to lose grout, and should be blocked by adding cellulose material to the grout mix. Cavities may also be backfilled seperately with sand and gravel mixes.</li> <li>▶ Continuous grout loss should be treated suspiciously, it may indicate an aquifer is washing the grout. Detect aquifers by drilling extra core samples, using thermal imaging and/or radar tomography.</li> </ul>

Table 24 – Guidelines for grout penetration

<b>Grout penetration</b>
<ul style="list-style-type: none"> <li>▶ Grout selection:                             <ul style="list-style-type: none"> <li>▶ Joints &gt; 1 mm with normal portland cements</li> <li>▶ Joints &gt; 0.1 mm with ultrafine cement grouts</li> <li>▶ Joints &lt; 0.1 mm with polyurethane/silicate grouts</li> <li>▶ For wide and unfilled joints where water wash is a problem, use hot bitumen</li> <li>▶ For narrow and filled joints where water wash is a problem, use polyurethane foams</li> </ul> </li> </ul>
▶ Grout at a small incline ( $\pm 20^\circ$ ) if vertical joints are closely spaced and need grouting.
▶ Generally grouting should occur at maximum pressure, but below hydrofracturing pressure

Table 25 - Application of hydrofracturing

<b>When to allow hydrofracturing [93. Lombardi 2003]</b>
▶ Hydrofracturing generally creates extra weakness planes vertical and normal to the borehole
<ul style="list-style-type: none"> <li>▶ Apply hydrofracturing if weak planes dip toward the shaft and cannot be penetrated by grout because they are extremely narrow or filled with clay gouge.</li> <li>▶ Only apply hydrofracturing if the strength of the cement bond is high compared to the in-situ stresses. This usually means at shallow depths only.</li> </ul>
▶ Determine hydrofracture pressure with a packer by increasing pressure until sudden water loss occurs accompanied by pressure drop.

## **7.Stability of shafts**

**Instability problems**

**Empirical methods for assessing shaft stability**

**The Q-System**

**Adaptations for raisebored shafts**



## **Analytical methods for assessing shaft stability**

### **Shaft in isotropic horizontal stress field (Lamé's Problem)**

## Shaft in anisotropic horizontal stress field (Kirsch Solution)





**Wedge Analysis**

**Block Theory**

## Application to shafts



## Limit Equilibrium Analysis

## Joint stability

## Joint Orientation

## Joint Roughness

## Joint filling

## Conclusions



## 8.Results

### Introduction

## Reviewed methods











## Guidelines for use

## Conclusion



## Recommendations for further research



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## Glossary

<b><i>Big hole drilling or Blind hole Drilling</i></b>	Drilling of shafts from the surface through drill pipes. Cuttings are flushed through the pipes with air or drilling fluids.
<b><i>Boring</i></b>	Excavation of a shaft, tunnel or hole by a machine with a rotating cutting head. This boring machine is located at the excavation front in contrast to <i>drilling</i> where thrust and rotation are applied by the headframe on the surface.
<b><i>Clippings</i></b>	Rock and rubble that has been cut loose from a rock face by cutters or drill bits. Also known as <i>cuttings</i> or <i>tailings</i> .
<b><i>Cuttings</i></b>	Rock and rubble that has been cut loose from a rock face by cutters or drill bits. Also known as <i>clippings</i> or <i>tailings</i> .
<b><i>Drilling</i></b>	Excavation of a circular hole through soil or rock with a drill bit that is powered from the surface. This may be through a rotating drill string or a drill pipe supplying hydraulic pressure. The method differs from <i>boring</i> in that pressure and rotation are applied from a headframe on the surface, whereas boring supplies rotation and thrust from a boring machine within the hole or shaft.
<b><i>Fracture</i></b>	A general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fracture includes cracks, joints, and faults.
<b><i>Joint</i></b>	A fracture or parting that cuts through and abruptly interrupts the physical continuity of a rock mass.
<b><i>Muck</i></b>	A mixture of drilling fluids and rock cuttings
<b><i>Mucking</i></b>	Transporting rock cuttings to the surface, for example with a muck bucket.
<b><i>Mud</i></b>	Water with additives which is used to support holes or rock faces, and often serves a double purpose as drilling fluid. Most drilling muds are bentonites (a heavy mixture of water with montmerillonite clays that stick together forming a 'cake').
<b><i>Overburden</i></b>	The layer of soil and/or rock overlaying the bedrock of the Earth's crust. Depending on the geologic history this layer may be only a few metres or more than a hundred metres thick. It can consist of fresh or weathered metamorphic rocks or sediments such as sand and clay. Overburden is sometimes referred to as the <i>rheology</i> .
<b><i>Pre-reinforcement</i></b>	Refers to stabilizing a shaft before excavation. For example ground freezing, grouting around the perimeter of the shaft and diaphragm walls are methods of pre-reinforcement.
<b><i>Tailings</i></b>	Rock and rubble that has been cut loose from a rock face by cutters or drill bits. Also known as <i>cuttings</i> or <i>clippings</i>
<b><i>Shotcreting</i></b>	Spraying of a very plastic (fluid) form of concrete onto a surface through a nozzle. In this way thin concrete linings of around 200mm are constructed.
<b><i>Fibrecreting</i></b>	<i>Shotcreting</i> using a special mix that contains fibres that withstand tension and buckling.
<b><i>Grout</i></b>	A concrete-like mix which is so fluid that it can be pumped into the ground to fill voids and pores.

<b><i>Stepwise benching</i></b>	A top-down approach for drilling and blasting rock in steps of a few metres at a time. A 'bench' is a stable rock face that has room to expand horizontally, and is thereby easy to blast.
<b><i>Alimak raising</i></b>	A (rather hazardous) bottom-up approach for drilling and blasting rock in steps of a few metres at a time. An Alimak climber crawls into a shaft from beneath, along a steel monorail that is installed as work progresses.
<b><i>Fault</i></b>	A fracture or parting that cuts through and abruptly interrupts the physical continuity of a rock mass. In contrast with a joint, there has always been some displacement (throw and heave, or slip) between fault planes.



## Appendix A – Database of Shaft Construction Examples

Contractor	Mining company	Location	(Inner) Outer Diam. [m]	Phreatic level / Overburden type	Overburden depth [m]	Total Depth [m]	Drilling method	Stabilis. method	Final lining
AMC / Wellnavinc	Newmont	Callie, N.T., AUS	4.5	Soft to hard rock with narrow clay-filled jointing. Dry down to approx 70m. weathering. Some hard quartzite veining.	120		raiseboring (in the end: conventional shaft sinking)	minipiling	remote fibrecreting
AMC / Bachy Soletanche	Cannington Mine	Cannington, Qld, AUS	3	Running sands to deeply weathered rock, dry	60	500	raiseboring	jet-grouting. Also augering of walls to 30m depth and augering out of inside 6m diameter	remote shotcreting
Ardent / Abergeldie	BP Billiton	North Qoonyella, Qld, AUS	3.15	weath+fresh basalt, sand, clays	110		b.h.drilling	bentonite drilling fluids + steel	grouted up final liner (steel?)
Ardent / Abergeldie		Springvale, Nsw, AUS	(4.3) 4.7	1 auqifer ex.weath.sandstone, sand	67	367	b.h.drilling	polymer mud + steel	composite concrete
Coffey Geosciences	WMC Resources Limited	Leinster, W.a., AUS	(2.4 pilot) 7.0	auqifer at 100m depth (Packer tests: 20 lgs) 10m silcrete, 28m mafic clays, 15m dist.weath.amphibolite, 2m mafic clays, 8m dist.weath.amphibolite	48/76	805	presink to 48, raiseboring 2.4m diam, b.h.post-sink to 80m Horadiam on rest of shaft.	small diameter raise. Post-sink with fibrecreting. concrete lined presink, fibrecrete/bolts through 38-76m. Alternatives presented: (1)Blind shaft to 57m, support as you go down (2) 1m diameter pilot with downbenching	

<b>Contractor</b>	<b>Mining company</b>	<b>Location</b>	<b>(Inner) Outer Diam.</b>	<b>Phreatic level / Overburden type</b>		<b>Overburden depth</b>	<b>Total Depth</b>	<b>Drilling method</b>	<b>Stabilis. method</b>	<b>Final lining</b>
	Crinum Colliery	Bowen Coalfield, Qld, AUS							Cage of reinforcement	
	North Selby Coalfield	Yorkshire, UK					>400		Ground freezing	
		Bendigo, Nsw, AUS	2.4			60		raiseboring	Extra grouted cable dowels, because drilling was needed anyway to check for existing mine workings	Notes: One hole deviated into the raise, but was reamed succesfully.
Frontier Kemper Construction	White County Coal	Illinois, U.S.	4.8	Two fast flowing aquifers	Moderate to hard rock, alternated by running sands.	42	257	b.h.drilling	temporary lining 10mm thickness steel can and drilling mud	composite lining 102 2.46m tall x 3.86m o.d. x 210mm thick composite concrete segments
Frontier Kemper Construction	White County Coal	Illinois, U.S.						raiseboring	freezing	ring and shotcrete
	Potash mining (some Uranium)	Saskatchewan, CA	6m		Blairmore Formation which had high-pressure sand aquifers		900-1100	conventional d&b / excavation and hoisting	freezing & tubing, cement grouting	

<b>Contractor</b>	<b>Mining company</b>	<b>Location</b>	<b>(Inner) Outer Diam.</b>	<b>Phreatic level / Overburden type</b>	<b>Overburden depth</b>	<b>Total Depth</b>	<b>Drilling method</b>	<b>Stabilis. method</b>	<b>Final lining</b>
Lake Mead Intake No. 2, access shaft	Lake Mead Constructors, subcontractor: Zeni	Las Vegas, Nevada	6,5-10m	mostly below water table soil, weathered rock in first metres	??	70+	??	grouting	reinforced cast-in-place concrete
Longos Mine mainshaft	United Paragon Mining Corp.	Paracale, Camarines Norte, Philippines		water surge on top of diorite zone at -257m, with water inflows of 500GPM  granidiorite, quartz diorite intrusives. Water inrush occurred 5m above mafic-granidiorite contact. This zone was 1m thick ultrafine mafic hybrid zone overlain by 1,5m thick sands where most water flow occurred. Ultramafics were sealed with quartz-calcite fillings whereas granidiorites were open, interconnected, water-bearing fissures.	257m	500	conventional d&b / excavation and hoisting	cement and polyurethane grouting, water relief holes  cast-in-place concrete  Notes: Abandoned in 1984 with water inflows > 850 GPM, Fixed with intensive down-the-shaft grouting, polyurethane grouting and intense monitoring	
Stawell minesite	Stawell Gold / WMI			Along stawell fault, wonga and mine schist, high horizontal stress conditions (reverse fault) Host rock is psammo-pelitic rocks i.e. sedimentary fine-grained rock like mudstone, clayey sandstone. Also lodes in shear system strike 330-340 deg, dipping 50-80 deg SW	76m	403	pilot hole: was drilled to just above transition zone and grouted there. Then the shaft was redrilled (grouted outer diameter 66cm, inner diameter 38cm diamond cored) Simultaneous dewatering hole was drilled.		

<b>Contractor</b>	<b>Mining company</b>	<b>Location</b>	<b>(Inner) Outer Diam.</b>	<b>Phreatic level / Overburden type</b>	<b>Overburden depth</b>	<b>Total Depth</b>	<b>Drilling method</b>	<b>Stabilis. method</b>	<b>Final lining</b>
Middelbult and Bosjesspruit mines (3 shafts)	Sasol Mining's (RUC)		7,1m	Shaft 1: Sandstones and siltstones <100 MPa Shaft 2: some dolerite areas with 1,4m blocks and a few serpentine (dissolves in air) filled zones	10m	90 & 173	Raiseboring; Concrete shaft placed to 10m depth for weak overburden - Then percussion holes drilled, grouted and reinforced to 5m beneath dolerite depth. (250mm diameter, 0,5m from shaft and 0,5m between centres) - Also cable doweling (24 x 89mm diameters) on a 1,2m grid.		some flash shotcrete to stabilise serpentine layers within 55 days of reaming. Notes: Biggest raisebored shaft in the world
Dendrobium Mine	BHP Billiton	Dendrobium Mine, NSW, Australia			60m		pre-grouting, drilling and remote shotcreting		some polyurethane remote post-grouting
	Soletanche-Bachy	Eastern Harbour Crossing, Honk Kong			+/- 40m		hydrofraise	Diaphragm walls	
		Speckholzerheide, Holland	4,6m		72m		hydrofraise	Diaphragm walls	
	Freezewall	Anonymous example	4m	Shaft freezing with insulated pipes	100m				Anonymous cost estimation example. US\$600.000 installation plus US\$20.000 p.w.

## Appendix B – List of experts consulted

Name	Company	Location	Subject
Warren Peck	Australian Mining Consultants	Melbourne, Australia	Ventilation shafts, pre-grouting techniques, remote shotcreting
Max Lee	Australian Mining Consultants	Melbourne, Australia	Shaft stability, jointing
Dr. Bill Bamford	Melbourne University	Melbourne, Australia	Civil tunneling
Wilhelm J. Kogelmann	Atlas Excavation & Tunnels	Nederland, Texas, U.S.A.	Continuous shaft cutting machines, shaft sinking in Texas area, Supercollider example
Markel Hoffman	White County Coal Corporation	Carmi, Illinois, U.S.A.	Constructed shaft conventionally through flowing aquifers with pre-freezing.
Mike Woof	World Mining Equipment	www.wme.com	Mining equipment, raisebore and shaft drilling machine manufacturers.
Juergen Schauwecker	Deilmann-Haniel company	Germany	Shaft Cutting Machines, shaft drilling
	SE Tecnologie Avanzate (Powermole)	Ortona, Italy	Air supported drilling of grout holes
Alan Halse	Atlas Copco Construction & Mining Australia	Whealers Hill, Australia	Raiseboring expert, drillability expert
Nick Morgan	Geotechnical Engineering	www.geotech.net.au	Expert on minipiles for civil construction
	Wellbore Navigation Inc.	www.wellnavinc.com Tustin, Canada	Manufacturer of Navi-drill accurate drilling equipment
	Deep Foundations Institute (ASCE); formerly Institute of Shaft Drilling Technology	Seattle, U.S.A.	Reference for excellent drilling and grouting articles
Steve Coughlan	Byrncut Mining Pty Ltd.	Kalgoorlie, Australia	Conventional shaft sinker and aiseborer
	Stanley Mining Services	Malaga, Australia	Good contractor in grouting drilling

Mark Berry	CSIRO Exploration & Mining (Head of Mining Geoscience Group)	www.dem.csiro.au Kenmore, Australia	Assesment of ground behaviour during mining
Dr. Jim Boland	CSIRO Exploration & Mining (Head of Rock Cutting & Drilling Group)	www.dem.csiro.au Kenmore, Australia	Head of study group studying rock cutting mechanisms and drillability
Sharyn Dawson	CSIRO Exploration & Mining (Head of Mining Automation Group)	www.dem.csiro.au Kenmore, Australia	Head of group studying automated mine systems / robots
Alain Dumont	Montali Inc.	www.montali.com Quebec, Canada	Specialist contractor n complex projects: shaft sinking & Alimak raising
Bill Shaver	Dynatec Corporation, mining services division	www.dynatec.ca Ontario, Canada	Specialises in complex projects: shaft sinking, caisson style sinking raiseboring & shaft lining.
Alan Zeni	Zeni Drilling Company	www.ardent underground.com Morgantown, United States	Expert contractor: Blind hole drilling.
D. Keward	Dosco Overseas Engineering Ltd.	Newark, United Kingdom	Retailer of shaft excavation machines
Dan O'Toole, Delia Sidea Bob Gee	Coffey Geosciences AUCTA	Perth, Western Australia Rhodes, Australia	Mining Consultant: Expert horadial technique Expert Civil tunnelling engineer. Head of AUCTA.
J. Donohoe	FreezeWall	www.moretrench.com Rockaway, U.S.A.	Expert wall freezing contractor.
Eric Downing	Walter Construction		Shaft support specialist
	Freysinnet (Austress in oz)	www.freyssinet.com/ Vélizy , France	Jetgrouting experts, Cannington mines.
	Soletanche-Bachy	www.soletanche- bachy.com	Expert grouting contractor.
Michael Cals	Wirth Europe	www.wirth-europe.de	Blind Hole Drilling expert.

Manfred Voerckel	Wirth Europe	www.wirth-europe.de	Raiseboring / Shaft sinking equipment expert
George Martin	J.S. Redpath	www.jsredpath.com Ontario, Canada	Raiseboring / Shaft sinking equipment in Canada
Henry Laas	Murray & Robberts RUC	www.murrob.com/RUC/ South Africa	Raiseboring and shaft drilling expert (Formerly RUC)
Marius Oosthuizen	Murray & Robberts RUC	www.murrob.com/RUC/ South Africa	Accurate drilling expert, Examples of superb accuracy (<500mm over 300m)
	Indau	Finland	Pre-grouting machinery manufacturer
	Skansk	Sweden	Raiseboring machinery manufacturer
Gunnar Nord	Atlas Copco	Sweden	Innovative problem solver in tunneling and drilling
Jol Jardine	Mechanised mining services	Australia	Helpful practical mining Engineer
karl Guilfoyle		Australia	Mining engineer, expert on surveying. Knowledge of shaft collapse at Stawell minesite.
	Lombardi Engineering	Minusio, Switzerland	Expert on rock mass grouting
Mark Berry	CSIRO Exploration & Mining (Borehole Surveying)		Research group on accurate borehole surveying
Kjell Gustaffson		www.reflex.se	Expert surveying equipment manufacturer.
	Frontier Geo	www.frontiergeo.com	Surveying equipment manufacturer
	IceField Tools (IFS)	www.icefieldtools.com/docs/	Surveying equipment manufacturer.
	MG Bennet & Associates Ltd	www.bennetmg.co.uk	Shaft sinking for water basins, Engineering Design Consultants
David Holton	Serco Assurance	www.sercoassurance.com Harwell Didcot, United Kingdom	Developer of connectflow geohydrology package
W. Heinz	Rodio	Freestate, South Africa	Expert on pre-reinforcement. Extensive knowledge of shaft collapses in South Africa
	Verstraeten Funderingstechniek	www.fundex-group.nl Oostburg, Netherlands	Expert on cut-and-cover methods, shaft drilling in soft soils.