SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

Final Project Report

Title: CRITICALLY EVALUATE TECHNIQUES FOR THE IN SITU TESTING OF STEEL TENDON GROUTING EFFECTIVENESS AS A BASIS FOR REDUCING FALL OF GROUND INJURIES AND FATALITIES

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Research
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EXECUTIVE SUMMARY

The quality of installation and grouting of rock reinforcing tendons is seen as a serious problem by the mining industry. Up to half of all full-column grouted steel tendons or rock bolts installed in South African gold and platinum mines are not as effective as they should be, owing to defects such as incomplete grout coverage or incorrect water to cement ratio; or post installation deterioration due to corrosion or rock deformation. The extent of the problem is not accurately known (no suitable study has yet been performed in South Africa), but is surmised from limited statistical data from accident cases and international results. Ineffective grouted tendons increase the risk of falls of ground and hence constitute a hazard of death or injury.

The only established ways to check such tendons after they are installed are to overcore and visually inspect the tendon-grout-rock interface, or to apply the "pull-out" test. Both methods are destructive and time consuming, and the pull-out test is not fundamentally sound for this type of tendon because it provides no information on the state of the grout annulus beyond the critical bond length for the particular installation.

This problem is recognised wherever fully grouted rock reinforcement is used, and over the past 20 years a number of research efforts have been made, both in South Africa and overseas, to develop a non-destructive test method for assessing grouted tendon effectiveness in situ - with partial success in one case and no success in the others. The aim of this project was to review that work in order to understand the reasons for failure, and then, taking into account more recent technology advances, recommend the most promising directions for future development that could finally solve the problem.

The problem requires measuring both the installed length of the tendon, and the distribution of grout bond (or effectiveness of mechanical coupling between the steel and the rock) as a function of distance along the tendon. It is complicated by the lack of access to the grout annulus except at one end, and the variation in the large number of parameters that can affect the measurement - chiefly the degree of fracturing in the rock, water to cement ratio in the grout, elastic and electrical properties of the rock, the type and profile of the tendon and the presence of peripheral support elements such as mesh and lacing. An inability to account for or measure all of these simultaneously accounts for the lack of success. In South African gold and platinum mines about 60 per cent of tendons are shepherd's crooks, whose shape presents problems when using acoustic non-destructive test methods.

The review found that the "Boltometer", an ultrasonic instrument developed in Sweden over a period of 10 years and currently available commercially at a cost of US$ 40 000, can measure both bolt length and quality of grouting under favourable conditions, and is the tool nearest to a solution. Its chief limitations are an inability to measure shepherd's crooks and a reduced performance in the presence of mesh, lace and washers. No solutions to these problems are apparent, but the Boltometer could find useful specific application in South African mines and it is recommended that an instrument be purchased for evaluation and research purposes.

Research work carried out in South Africa between 1987 and 1991 by the Chamber of Mines Research Organization (COMRO), and by Wits University and CSIR Mattek under the auspices of COMRO, was somewhat hampered by an inability to learn from the Boltometer experience due to political sanctions in effect at the time.

A variety of other possible testing techniques, using mostly acoustic or electromagnetic principles, was reviewed. Several of these could feasibly measure the length of the tendon, but not the grouting quality. None of the techniques appear attractive for further development at this time, either because of fundamental limitations, or because the time and effort required to reach a satisfactory solution is likely to be too great.

Instead it is recommended to focus future effort on improving the installation quality of new grouted tendons, by firstly investigating the extent of the current grouting problems, and secondly devising tendons and/or grouting processes that are more consistently effective and, moreover, are themselves testable. In particular the use of unwaxed cone bolts should be evaluated as a partial solution to the grouting quality problem.

CONTENTS

ROCK BOLTING - REFERENCE BANK: AMFO 84-0847 Final Report
By H Thurner, Geodynamik AB, Stockholm, February 1994
Translated from the Swedish courtesy of CSIR: Mining Technology, February 1996
(33 pages, 25 figures, 2 tables, 19 references)

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1 INTRODUCTION

This report presents the findings of SIMRAC project GAP205, "Critically evaluate techniques for the in situ testing of steel tendon grouting effectiveness as a basis for reducing falls of ground injuries and fatalities". Grouted steel tendons (also known in some forms as rockbolts or roofbolts) constitute the predominant element of tunnel rock reinforcement systems used in South African gold and platinum mines. This research was motivated by the occurrence, over many years, of a number of falls-of-ground accidents involving failure of the tendon reinforcement that was attributed to inadequate installation of grouted tendons. The effectiveness of existing tendon installations is known to vary widely and to depend heavily on the quality of the grouting process used. At present there is no reliable, cost-effective method for determining the grouting effectiveness of steel tendons after they have been installed, so rock engineers are often faced with considerable uncertainty about the adequacy of rock reinforcement in sections of tunnels, particularly where the reinforcement was installed without their direct supervision. It is possible to gain an indication of installed tendon strength using hydraulic pull testing, but this technique is at best an inadequate measure of the tendon's actual performance in situ, and is often destructive.

This problem is recognized internationally wherever grouted rock bolting is used, and since the late 1970's, a number of research efforts were initiated aimed at developing a non-destructive in situ method for testing the quality of grouted tendon installations, including a project sponsored by the South African mining industry through the Chamber of Mines Research Organization between 1988 and 1991. To date, none of these efforts has resulted in a widely accepted solution, and most of this work appears to have terminated.

The aim of the present project was to critically review past local and international research work in an attempt to understand why the techniques contemplated did not achieve the desired result, and then, taking into account more recent advances in technology and understanding, recommend the most promising direction for future development that could finally lead to an acceptable method for measuring the quality of grouted tendon installations in situ. Emphasis was placed on exploring the possibility of international cooperation in such a development effort (an approach that, due to circumstances operative at the time, was difficult to pursue during the earlier South African research project).

The work methodology comprised a literature review, consultation with persons involved in relevant work, discussions with the manufacturer of the most promising instrument (the Swedish "Boltometer"), and an analysis of the findings. The project was confined to a "paper study" that did not allow for any experimental development or testing, nor did it provide scope for a full investigation of tendon grouting problems in South African mines. The work was conducted by personnel of the CSIR: Division of Mining Technology (Miningtek), over the period April 1995 to March 1996.

Chapter 2 of this report considers the problem in more detail, based on the literature and past work. It discusses the significance of grouted tendons as a reinforcement element, the installation process and its effect on reinforcement performance, the need to measure the effectiveness of tendons after installation, and the problems surrounding such measurement. This chapter seeks to establish the context for the technology review and assessment that formed the core of the project.

Chapter 3 presents a critical review of previous research and development aimed at devising a technique and instrumentation for non-destructive testing of grouted tendons in situ. It covers the earlier South African work and international efforts that were known at that time, as well as more recent developments as gleaned from the literature and discussion with some of the parties involved. The chapter is structured according to techniques relevant to the present problem that have been researched. For each technique an attempt is made to identify the key factors which either limit success, or offer promise given further development.

Chapter 4 provides an assessment of the possibility of improving the most promising developments reviewed in Chapter 3 so as to achieve an acceptable non-destructive test instrument for grouted tendons installed in South African mines. This assessment is based upon the review as well as discussions with persons responsible for these developments.

Chapter 5 concludes the report, making recommendations for further work on the premise that the need to test grouted tendons in situ is one part of a broader problem, namely the need to improve the installation process quality and operational characteristics of these reinforcement elements.

During the course of this work, a research report on the Boltometer was obtained from the instrument's manufacturers, Geodynamik AB, in Swedish. That document was judged to be particularly relevant, and accordingly an English translation was made, which is appended in full to this report.

2 NATURE OF THE PROBLEM

Grouted tendons are generally used as part of a system to stabilize the rock surrounding tunnels. Such tendons may be ineffective for a number of reasons:

1. Inadequate design of the support or reinforcement system as a whole (e.g. choice of tendons that are too weak, too short, or too widely spaced).

2. Inadequate installation in comparison with the intended design (e.g. poor grouting process, installing shorter tendons than intended).

3. Failure or damage occurring to the tendons after installation, in a way that goes undetected and uncorrected (e.g. shearing of the tendon inside its borehole, corrosion of an ungrouted portion of tendon inside its borehole).

In any of these events, further loading of the tendon due to the changes in the stress field surrounding the tunnel, whether such loading is of a quasi-static or a dynamic nature, is more likely to lead to failure. This results in falls of ground which in turn constitutes a hazard of injury or death to personnel.

A discussion on the design adequacy of tunnel reinforcement and support systems is beyond the scope of this work, which is instead concerned with the latter two points, and specifically: how can one determine, after tendons have been installed, that they will fulfill their designed function? To put the problem into perspective, it is necessary to understand:

a. The role that grouted tendons play in tunnel reinforcement systems, and particularly the role of the grouting: during installation, load bearing and failure of the tendon. In the course of this, we examine the appropriateness of established test techniques, and the difficulties involved.

b. The significance of the problem, i.e. what proportion of failures in tunnel reinforcement systems in South African gold and platinum mines is due to ineffective installation of grouted tendons (in comparison with the intended design), or undetected damage to grouted tendons.

The first aspect will lead to a clearer understanding of the requirements for such a test technique.

The second aspect is difficult to deal with in absolute terms, because there is a paucity of quantified observational data on the installed quality of grouted tendons in South African mines. One reason for this is the present lack of a convenient non-destructive test method. To obtain the necessary data in these circumstances would require physically examining a representative sample of installed grouted tendons by overcoring and inspecting them, a task which was unfortunately beyond the scope of the present project. However, it is possible to obtain an indication of the extent of the problem by surmising the results of limited similar work carried out internationally.

NOTE: Most of the material in Sections 2.1 and 2.3, covering the types and behaviour of tunnel reinforcement elements, is included for the benefit of readers who are not particularly familiar with tunnel reinforcement. Readers with a rock engineering background may wish simply to note Figure 7 on page 10. However, Section 2.2 on installation of grouted tendons, and particularly 2.2.2 on quality defects, is central to the problem statement of this project.

2.1 The Grouted Tendon as a Tunnel Reinforcement Element

The need to stabilise tunnels in South African deep mines arises from conditions encountered at typical mining depths of 2000 m or more below ground level. The virgin stress of rock is sufficient to ensure that all tunnels driven at this depth are surrounded by an envelope of fracturing [1]. Depending upon the actual depth, the virgin stress field and the additional stress induced by nearby mining, this fracture zone can extend (particularly into the sidewalls) to a depth of twice the tunnel height [2]. Without support or reinforcement, the presence of these fractures always poses a danger of loose rock slabs falling into the tunnel. In addition, as the stress field surrounding the tunnel changes in response to the progress of nearby mining excavations, the fractured rock dilates into the tunnel opening. Dilation can occur under both controlled, quasi-static conditions (usually resisted by installed support or reinforcement), or under dynamic, rockburst conditions (where in extreme cases, slabs of rock may be violently ejected into the tunnel opening).

Grouted steel tendons play a critical role in systems designed to maintain the serviceability of tunnels by counteracting these dilation forces, ideally in such a way that the rock can be contained even under rockburst conditions. This role is discussed in the sections below.

2.1.1 Tunnel Support and Reinforcement Systems

In a study published in 1995, Roberts [1] provides a useful overview of current tunnel support and reinforcement[1] systems used in South African gold and platinum mines. The most common type of reinforcement system used in highly stressed tunnels consists of a grid of steel tendons anchored in boreholes drilled at regular intervals perpendicular to the tunnel walls. This is frequently augmented by

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[1] In this report, the terms "support" and "reinforcement" are used distinctly as proposed by Windsor and Thompson [3], where "support" refers to stabilising elements applied externally to the tunnel walls, e.g. mesh, lace, steel set arches or props; whereas "reinforcement" refers to elements applied within the rock mass itself. The latter includes all forms of tendon or rock bolt.

a layer of wire mesh which covers the tunnel walls and is held in place via a lacing network of wire ropes attached to the exposed ends of the tendons (Fig. 1). The function of the mesh is to provide areal containment of loose rock at the tunnel walls.

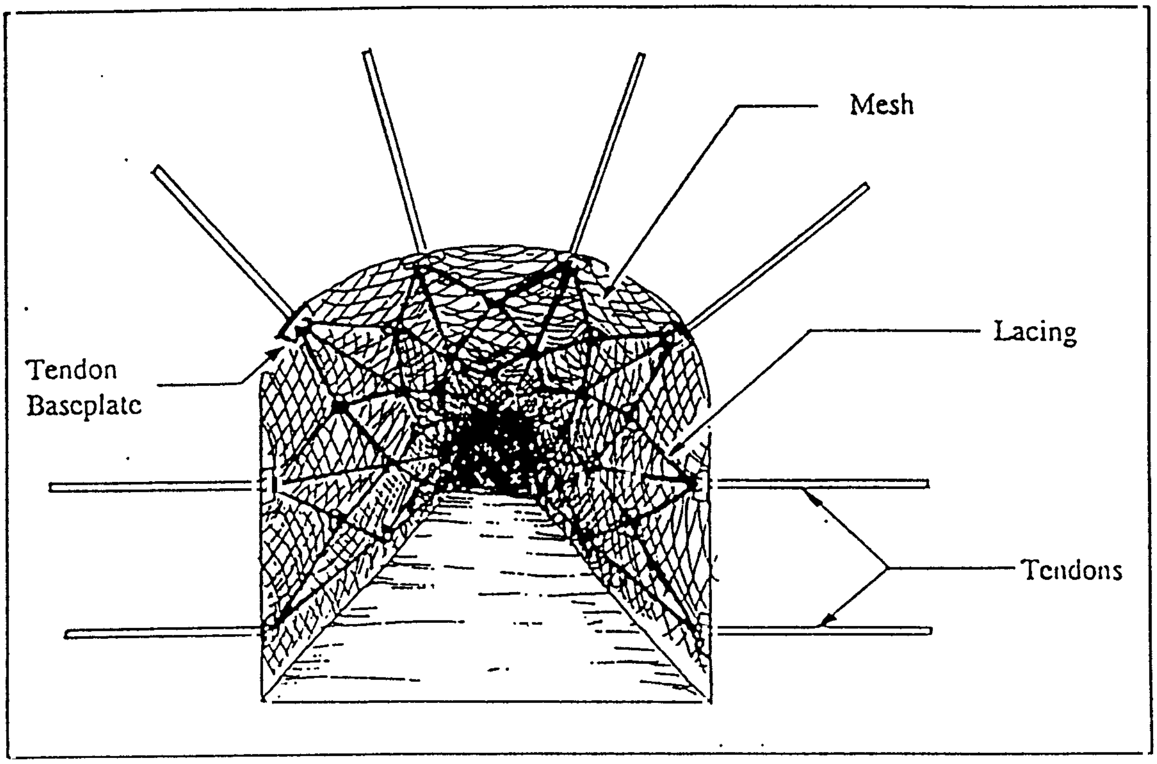

Figure 1. Perspective view of a tunnel illustrating typical reinforcement and support elements (after Roberts [1]).

The tendons, whose length is ideally chosen to exceed the depth of the fracture zone, are often fitted on their outer ends with a bearing plate which generally has some kind of ring attachment (or the outer end of the tendon may be looped) for securing the lacing ropes. The tendons may be end-anchored (attached to the borehole only at the inner end, in which case some kind of bearing plate at the outer end is necessary to complete the reinforcement function) or they may be continuously coupled to the rock throughout the length of the borehole (in which case a bearing plate may not be necessary).

The role of the tendons in such a system is two-fold [1]. Firstly, they provide reinforcement intended to hold the fractured or jointed rock in place. The reinforcement mechanisms are often described in terms of simple models [3], including arching (the ring of tendons create a self-supporting arch from the fractured rock in the hanging- and sidewalls), keying (the tendons hold certain key blocks of rock in place, which in turn prevent other, interlocked blocks from falling), and beam building (in cases where the hangingwall rock is predominantly layered horizontally, the tendons can "tie" these layers together, creating a beam of rock which is thick enough to be self-supporting).

In its reinforcement role, a tendon may bear a combination of both tensile and shear loads. These loads are due to another combination of dilation forces (around the fractures) and the weight of the rock slabs suspended. The amount of dilation (and therefore load) borne by the tendon theoretically reaches a maximum at the tunnel wall and decreases to zero with distance into the tunnel wall. Observations confirm this as a general trend, however some field measurements [4] indicate that dilation as a function of depth may well be irregular and unpredictable. Tendons may provide active or passive reinforcement. Active reinforcement is achieved by deliberately applying tension to the tendon through the bearing plate during or after installation. In passive reinforcement, the tendon bears load only when the fractured rock begins to dilate. Note that continuously coupled tendons without a bearing plate can only provide passive reinforcement.

The second role of tendons is one of <u>anchoring</u> to contain the broken rock within the confines of the support system, either through the bearing plate alone, or via the mesh and lace. In this role, they bear additional tensile load from the rock at the skin of the tunnel wall, carried to the inner end of the tendon (anchored in, it is hoped, more stable ground deeper into the walls).

2.1.2 Types of Tendon and Distribution

It is beneficial to consider the grouted tendon in the context of all tendon types encountered in gold and platinum mines, firstly as a means of assessing their relative importance, and secondly to highlight the differences in function and hence the different requirements for testing.

Tendons may be divided into three classes according to their load-bearing behaviour [1], [3]:

1. Continuous mechanically coupled elements. These form the main focus of the present project, because this class includes all full column grouted tendons. These tendons can be divided into solid steel bars or cable anchors (the latter often made up from destranded used hoisting rope). Solid steel varieties may be further divided into straight bars (Fig. 2) or shepherd's crooks (Fig. 3). The surface profile of the solid steel tendons varies - the most commonly encountered profiles being rebar, smooth, V-bar and spiral bar types. The diameter of the steel bar is typically 16 mm or 20 mm, occasionally 25 mm [1]. These tendons are generally passive and can only bear load after the grout has set. They are used for both primary (during development) and secondary (permanent) tunnel reinforcement.

2. Continuous friction coupled elements (e.g. Split Sets, Fig. 4 and Swellex bolts, Fig. 5). These tendons provide load-bearing capacity immediately upon installation, typically passive. The amount of exposed steel makes these tendons more easily subject to corrosion damage than full column grouted types. They are most often used for primary reinforcement to stabilise the rock immediately after excavation. In an effort to protect against corrosion, Split Sets are sometimes filled with grout after installation.

3. Discrete mechanical or friction coupled elements (i.e. resin or mechanically end-anchored bars and cables, see Fig. 6). These are usually actively tensioned upon installation, thus immediately bearing load. They are also easily subject to corrosion damage, and hence are sometimes full-column grouted after installation, whereafter they behave in effect as continuous mechanically coupled tendons. They may be used for both primary and secondary tunnel reinforcement.

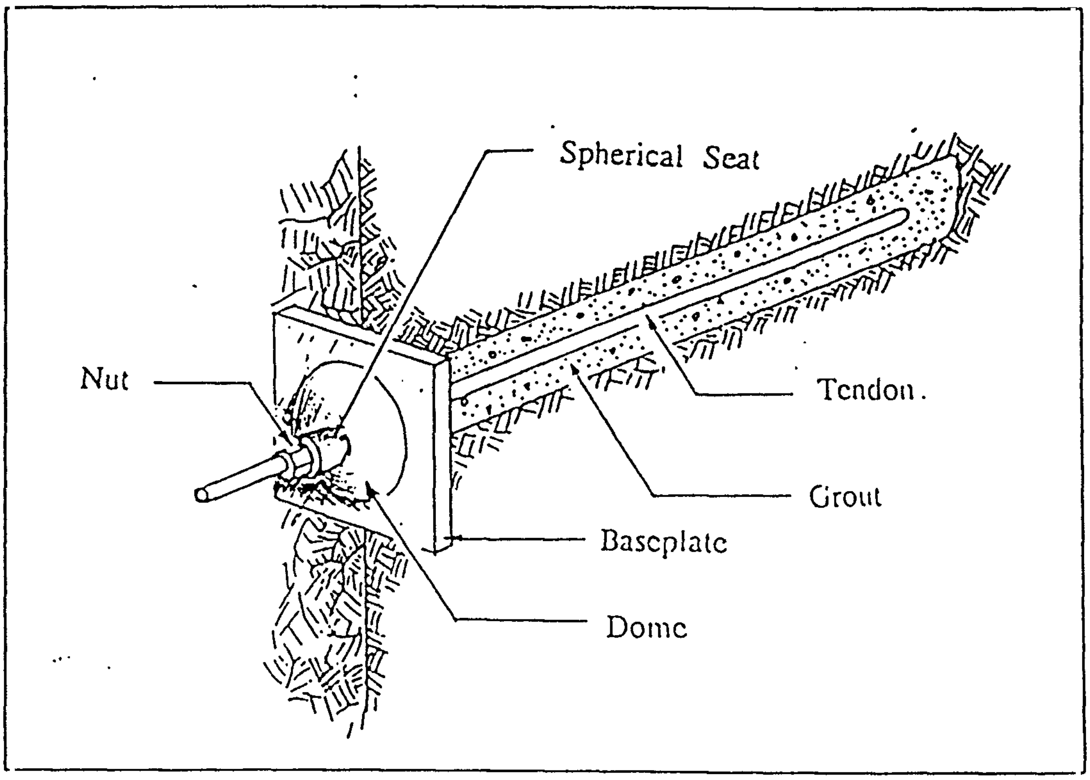

Figure 2. A typical straight bar grouted tendon with base plate and nut (after Roberts [1]).

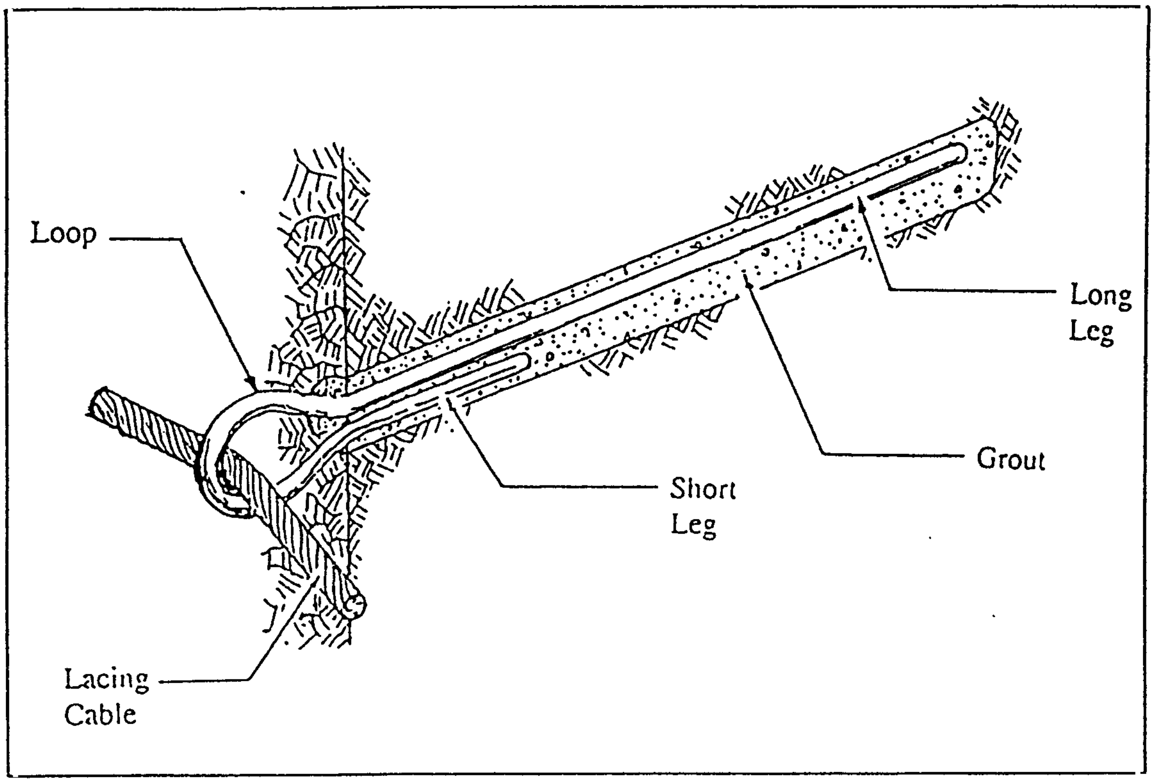

Figure 3. A typical shepherd's crook grouted tendon (after Roberts [1]).

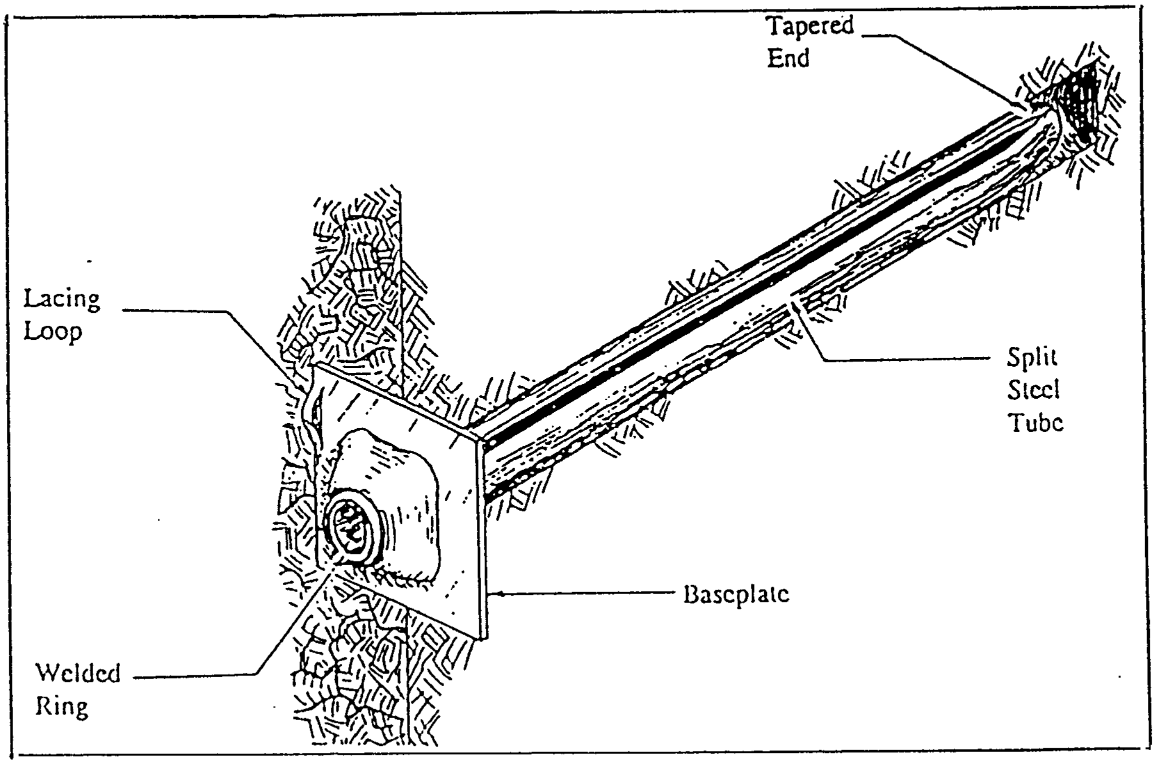

Figure 4. The Split Set stabilizer (Ingersoll Rand) is formed from an oversized steel tube split longitudinally, with a tapered end. It achieves continuous friction coupling with the rock by being driven into an undersized borehole (after Roberts [1]).

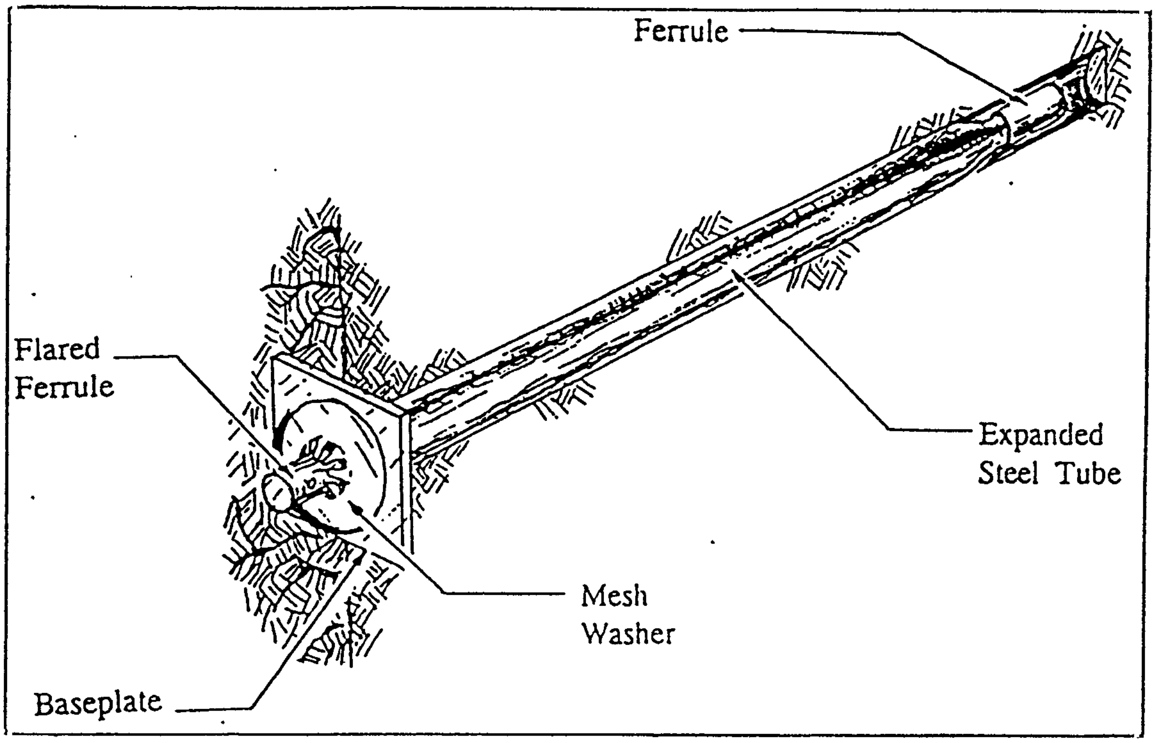

Figure 5. The Swellex bolt (Atlas Copco) is formed from a tube which, on manufacture, is compressed into a kidney-shaped profile and closed at each end. A small hole is drilled into the tube at the outer closure. After inserting into the hole, water is pumped into the tube through the hole to a pressure of 30 MPa, causing the tube to expand and achieve continuous friction coupling with the rock (after Roberts [1]).

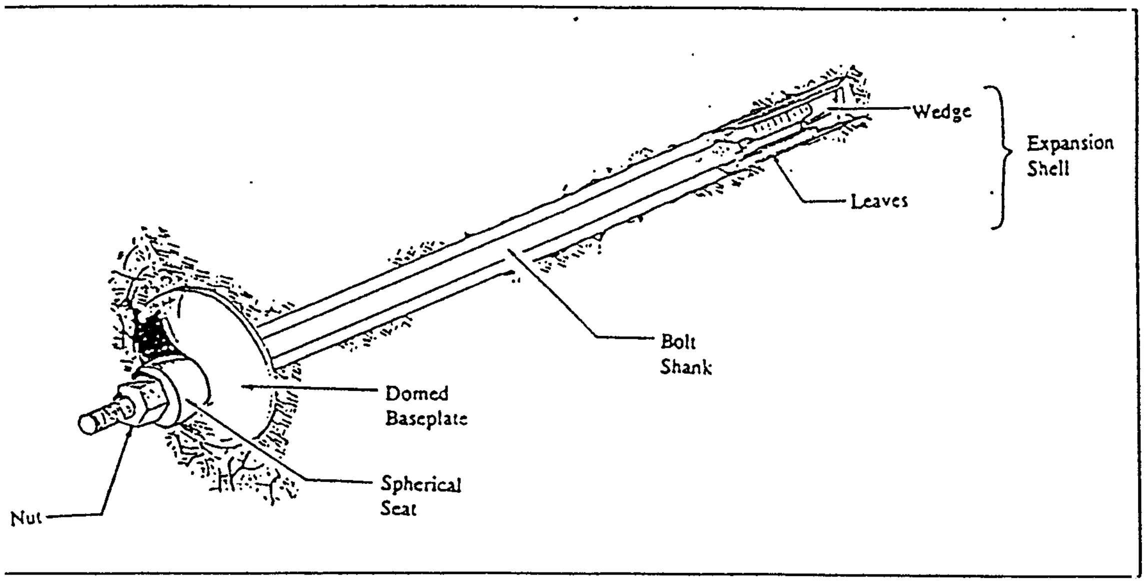

Figure 6. Typical mechanically end-anchored rockbolt (after Roberts [1]).

More than 10 million tendons are installed annually in South African gold and platinum mines. An approximate distribution of the various types [5] (see Fig. 7) indicates that full column grouted solid steel tendons make up the majority, with shepherd's crooks alone constituting some 60 per cent of the total.

Full column grouted			End-anchored or Continuous friction (not fully grouted)
Solid steel		Cables, loops	
Shepherd's crooks	Straight		
60 %	10 %	10 %	20 %

Figure 7. Approximate distribution of tendons by type in South African gold and platinum mines.

Applegate [6] provides some explanations for the relative popularity of the different types of tendons. Considering the volumes used, cost is obviously an important factor. Steel cables are the cheapest, followed by shepherd's crooks. Mechanical rock bolts and continuous friction types are significantly more expensive. A second factor is ease of use: shepherd's crooks do not require a base plate, are easy to install, and lend themselves directly to lacing. Cables are harder to grout, and mechanical bolts yet more difficult to grout. Reliability is another factor: the fix of mechanical bolts can be unreliable, especially in soft shales, and they may lose their anchorage in the presence of vibrations from nearby blasting, or become untensioned as a result of rock spalling around the bearing plate. These bolts should be regularly retensioned, but in practice this is not always done. The increased susceptibility of ungrouted mechanical or friction bolts to corrosion is also a reliability consideration.

The load-bearing behaviour of full column grouted tendons, in contrast to that of end-anchored types, is discussed in section 2.3.

2.2 Installation of Grouted Tendons

Of all the above tendon types, full column grouted tendons are the most prone to problems occurring during the installation process which may render the tendon ineffective as a reinforcement element. The main reason for this is inadequate grouting, which can easily occur and is very difficult to detect after installation, because the grout at the collar of the borehole effectively hides any grouting deficiencies which may occur inside the hole. In this section we examine the grouted tendon installation process and the commonly encountered defects associated with it.

2.2.1 The Installation Process

The installation process for grouted tendons starts with drilling of the borehole: a rotary-percussive drill is normally used. The depth should be slightly greater than the length of the tendon. The diameter is typically 30 mm or 38 mm, depending on the diameter of the tendon itself.

Thereafter, installation depends on the grouting system used. In South African mines, the predominant form is cementitious grout, supplied in the form of tubular capsules containing pre-accelerated dry cement powder, which are soaked in water for a few minutes before installation. The skin of the capsule is porous in such a way that water take-up is controlled whilst grout does not easily run out. The design of the capsules also attempts to optimise expansion of the wet grout so as to match the borehole diameter, and to maintain packing density of the material so that the tendon can be easily inserted [7]. The saturated capsules are then stemmed into the hole, either by manual emplacement, or with the aid of a compressed air gun. Finally, the tendon is pushed, hammered or spun into the capsules, so as to break the skin and allow the grout to distribute evenly in the annular space between the tendon and the borehole wall. Naturally, the broken capsule skins remain lodged in the hole. The setting times for various types of cementitious grout capsules range from about 15 minutes to several hours.

Another common method of installing cementitious grouted tendons involves the use of a grout pump. This is particularly important for cable tendons (which cannot be driven through grout capsules) and for post-grouting of mechanical rock bolts. Assuming an upwardly inclined borehole, a breather pipe is inserted to the end of the borehole alongside the tendon, and the spout of the pump is then attached to the collar of the borehole together with some kind of seal or stemming arrangement to prevent grout pouring out of the collar. Pre-mixed liquid grout from a reservoir is then pumped into the hole starting at the collar, whilst the air escapes through the breather pipe. The hole has been filled when grout starts to issue from the breather pipe, whereafter pumping continues as the breather pipe is extracted, so as to ensure complete grouting of the borehole. The process for downwardly inclined boreholes is similar. The setting times for pumped grout are usually longer (about 24 hours) than for encapsulated grout, because of the higher water to cement ratio necessary to produce a viscosity that is easily pumpable. The method is therefore more messy and labour intensive than that of encapsulated grout; however, the materials cost is lower and the process does not leave foreign material embedded in the grout.

A less frequently used grouting system in South African mines is polyester or epoxy resin, which is supplied in capsules similar in appearance to those used for cementitious grout capsules. The major difference is that the resin is self-activating. The skin of the resin capsules is impervious and the capsules contain two separated materials: a liquid base and some form of catalyst. After stemming the hole with the capsules, it is necessary to spin the tendon into the capsules so as to break the separation between the materials and allow them to mix, which activates the setting process. Setting times for such resins can be very fast, providing almost immediate reinforcement. The main reasons that these grouting materials are not commonly used on gold mines are their higher cost and more stringent installation requirements.

2.2.2 Quality Defects

Table 1 lists aspects concerned with the grouted tendon installation process that can lead to inadequate reinforcement. In addition to a poor installation environment or mistakes, it sometimes occurs that an installation crew will deliberately skimp on the installation procedure in order to save time or materials. This malpractice usually takes the form of installing bolts shorter than specified, using too few grout capsules, or grouting only near the collar of the borehole. Unfortunately, once the grout has set it is very difficult to detect such practices, short of extracting and inspecting random sample tendons, or carrying out time consuming pull-out tests which can only identify very poorly grouted tendons.

Table 1. TYPES AND RESULTS OF QUALITY DEFECTS ASSOCIATED WITH THE INSTALLATION OF FULL-COLUMN GROUTED TENDONS (partly from [9]).

Grout Type	Condition	Result
Any	Insufficient grout in hole	Ungrouted segments of tendon not contributing to the reinforcement.
Any	Hole diameter too large for tendon	Excessive size of grout annulus leading to weaker reinforcement, alternatively insufficient grout leading to ungrouted segments.
Any	Hole length too long for tendon	Can lead to insufficient grout coverage
Any	Open fissures in hole causing loss of grout	Possible ungrouted segments.
Any	Grease on tendon (esp. cable tendons)	Inadequate bond between tendon and grout (but this may be an advantage if slipping behaviour under rapid loads is deliberately sought: see section 2.3)
Any Cement	Water : Cement ratio too high	Reduced grout strength, possible shrinkage.
Pumped Cement	Poor pumping technique	Air bubbles and voids in grout, grout covering only a portion of the annulus (horizontal holes).
Any Capsules	Improper capsule stemming, leading to voids in hole	Ungrouted segments.
Resin Capsules	Excessive storage time	Resin is partially set before installation, leading to poor bonding in hole.
Resin Capsules	Over-spinning tendon on insertion	Induces potential shear failure surfaces.
Resin Capsules	Under-spinning tendon on insertion	Does not allow resin components to mix properly, causing inadequate setting.
Resin Capsules	Low temperatures	Can prevent resin from setting properly.
Resin Capsules	Wet holes	Can lead to shrinkage problems.

The extent to which these problems occur in South African mines is hard to judge in the absence of suitable studies. A few limited sets of measurements indicate that up to 50 per cent of tendons were inadequately grouted [8].

However, a study conducted in Sweden by Thurner (see Appendix), in which a number of test and production grouted tendons were overcored or otherwise released from the rock and then inspected, provides a fair representation of the problem. In a surprisingly large number of installations the quality was found to be lacking with:

- large air bubbles in the grout;
- grout not set properly;
- short bolts;
- holes whose diameter increased from the collar inwards (resulting in insufficient grout coverage at the inner end of the hole);
- especially in horizontal holes, grout covering only a portion of the circumference of the bolt;
- grout installed via cartridges often resulting in cartridge cases being collected in "lumps"; in these areas grout quality was typically poor.

Thurner concluded that "up to 50 % of all tested bolts did not have the expected function, and the quality of a portion of the bolts was surprisingly inferior".

2.3 Operation and Failure Mechanisms

In discrete coupled (end-anchored) tendons, all tensile loads are carried by the entire length of the tendon as it reacts against the total dilation applied between the inner anchorage and the outer bearing plate. This allows relatively simple modeling of tendon load-bearing and failure behaviour. Tensile failure can occur either in the anchorage, the bearing plate or the tendon itself. Shear behaviour is more complex, with the tendon initially providing limited resistance only through the resolved component of axial load and stiffness. As shear displacement increases to the point that the tendon is jammed between opposite sides of the borehole wall on either side of the shearing fracture, the shear resistance increases towards that of the tendon itself, modified by crushing of the rock surfaces and bending of the tendon in the region of the shear.

In contrast, the presence of the grout in continuous mechanically coupled tendons makes the behaviour of these elements under load more difficult to model and predict, owing to the distributed load-bearing action and the presence of two interfaces (tendon-grout and grout-rock) throughout the length of the grouted tendon.

After installation, grouted tendons will also be subject to possible corrosion damage wherever the tendon surface is exposed due to inadequate grouting or to fractures occurring in the rock and grout. Thurner (see Appendix) observed cases where water-bearing fissures intersecting the borehole had caused grout to be washed away locally and the tendon to be attacked. The presence of the grout aggravates the effects of corrosion, because corrosion products occupy two to three times the volume of the metal consumed, and can therefore impose additional stress on the grout, leading to further grout cracking [10].

2.3.1 Tensile and Compressive Loads

The continuous bond between a fully grouted tendon and the surrounding rock has a profound effect on its behaviour under dilationary loads in the fractured rock surrounding a tunnel. Depending on the degree of bonding between the tendon and the grout, when fractures open up along the span of the tendon, the load and strain may be localised to very short lengths of the tendon in the regions surrounding the fractures, whilst other parts of the tendon may remain relatively unstressed, or even be stressed in the opposite direction, viz. compressively [1].

The term "bond" refers to the axial load transfer capability between the tendon and the grout, and between the grout and the rock. Bond operates on three basic load transfer mechanisms: adhesion, mechanical interlock and friction [3], [10]. These in turn depend on properties such as the grout mix, grout particle size, grout shear and compressive strength, the tendon surface profile, and the strain in the tendon. Adhesion between the materials is argued to be the least important of the three [3]. Under load, once the adhesion resistance is overcome, further resistance is provided by the mechanical interlock; this describes the effect of having a tendon surface profile that keys into the grout, to the extent that material failure must occur rather than having a simple sliding mechanism at the interface. Once this failure has occurred (usually over a relatively small displacement) and assuming the grout failed rather than the tendon, resistance is still provided by frictional sliding. The level of this final resistance depends on the coefficient of friction (tendon surface microroughness, grout particle size) and the radial stress on the sliding interface. The latter will be determined by factors such as the expansion or contraction of the grout upon curing, and the Poisson effect contraction of the tendon itself whilst under tension.

The total strength of the bond between a grouted section of tendon and the surrounding rock depends on the length of the continuously bonded section, and for each type of tendon-grout-rock combination there exists a critical bond length (CBL). The CBL is the length of grouting above which a tendon, loaded in tension from the free end of the grouted section against the rock, will fail before the bond fails. For grouted sections shorter than the CBL, the same kind of load will pull the tendon through the grout rather than cause failure of the steel itself.

Thus two failure mechanisms of grouted tendons under axial load are evident: breaking of the tendon itself at high loads and short displacements, and sliding through the grout usually at lower subsequent loads and larger displacements. The latter mechanism is generally regarded as preferable behaviour for tendons installed in highly stressed tunnels where dilations are expected to be large, provided that the bond still offers adequate resistance during slippage. This kind of behaviour is especially demanded of tendons installed in tunnels prone to rockbursts [11], and in these conditions the types of tendon will often be chosen based upon their ability to yield through the grout interface, e.g. un-degreased destranded hoist rope [6] or cone bolts [2].

In practice the overall bond between a grouted tendon and the surrounding borehole may be divided up into a series of continuously grouted sections separated by gaps in the grout (which occur during installation) or by the opening of intersecting fractures (which occur after installation). Some of these sections may be shorter than the CBL, others longer - for example, Thurner (see Appendix) observed critical bond lengths as short as 20 cm with rebar tendons of 25 mm diameter in cementitious grout. Each of the grouted sections may transfer load independently of the others, so it is possible for a single installed tendon to have debonded in one section, broken completely in another, and yet appear fully bonded and free of load at the exposed outer end.

2.3.2 Shear Loads

In well installed, continuous mechanically coupled tendons, the grout completely fills the annulus between the tendon and the borehole walls. When shear movement takes place along an intersecting fracture, the tendon can therefore provide immediate resistance. The general effect is illustrated in Fig. 8.

Under quasi-static loading, the grout tends to have a cushioning effect, allowing the tendon to deform across the discontinuity. Consequently, grouted tendons are initially "soft" in shear during crushing and densification of the grout, during which the angle of the tendon changes. When this occurs the tendon starts to act somewhat in tension rather than pure shear [3]. Failure then occurs in a combination of tension and shear, at a significantly higher load than the pure shear strength of the tendon material. This was confirmed experimentally in a series of tests by Roberts [1].

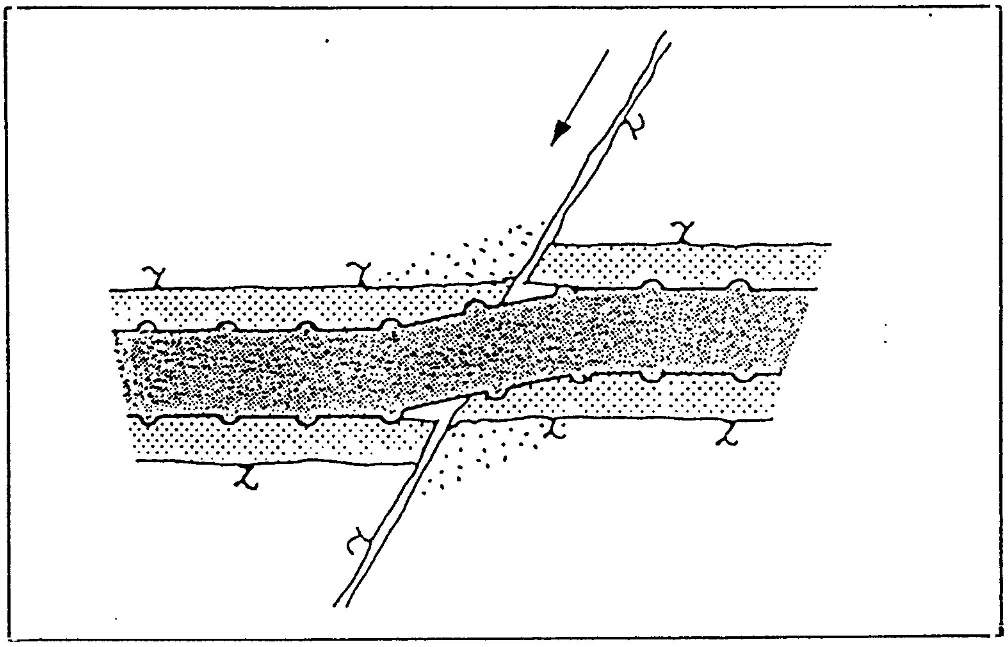

Figure 8. Fully grouted tendon subjected to shear loading (after Roberts [11]).

Under the dynamic shear loading that can be expected during a rockburst, grouted tendons may behave differently, depending chiefly upon the tendon surface characteristics and the construction of the tendon itself. For example, Roberts found experimentally that smooth bar tendons performed equally well in dynamic and quasi-static shear, whereas rebar tendons were significantly weaker in dynamic shear than in quasi-static shear. Apparently the increased mechanical interlock component of bond due to the rebar surface inhibits tendon movement and plastic bending under dynamic loads, and brittle failure occurs or the tendon is guillotined. Turner [12] documented the guillotining of rebar tendons in rockbursts. Roberts also found that destranded hoist rope performed better in quasi-static shear than equivalent diameter solid bar tendons, owing to the ability of the strands to move around one another. However under dynamic shear, the individual strands presented a disadvantage in that the outer strands quickly failed in shear, leading to a significantly lower overall tendon shear resistance. Cone bolts also exhibited a superior performance under quasi-static shear loading as a result of their designed ability to slide through the grout.

In summary, the shear behaviour of fully grouted tendons depends on the following factors:

1. the axial properties of the tendon,

2. the bending properties of the tendon,

3. the axial load transfer between the tendon and grout, and
4. the properties of the grout / rock in response to crushing.

Clearly the grout (where present) plays an important role during shear, both by "cushioning" the tendon at the shear interface, and by distributing and absorbing some of the shear forces.

2.4 Measuring Grouted Tendon Effectiveness

Figure 9 graphically illustrates the most important characteristics of grouted tendon installations that influence the testing problem. In the sections that follow, the parameters that need to be measured are discussed, as well as the desired characteristics of the test technique, the limitations of existing test techniques, and the inherent difficulties of this testing problem.

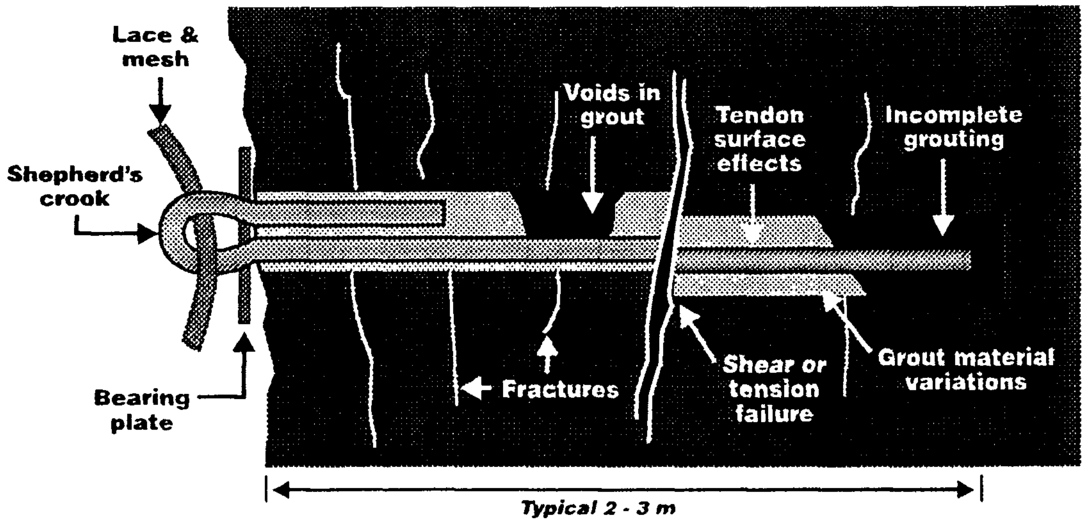

Figure 9. Grouted tendon typical in situ conditions.

2.4.1 Requirements of a Measurement Technique

From the discussion in sections 2.1 to 2.3, the parameters that should ideally be measured in order to determine the effectiveness of an installed grouted tendon can be summarised: refer to Table 2. The function of a full column grouted tendon depends on the distribution of load-bearing capacity along the entire length of the tendon. The local load-bearing capacity is itself a function of properties that can vary along the length of the tendon. If any weak points are present along this length, the tendon has suboptimal effectiveness and is likely to fail preferentially at one of those points, and at a failure load expected design strength. Therefore, proper measurement of grouted tendon effectiveness ıany of these parameters to be determined as a function of distance along the tendon.

t to which it is necessary to accurately measure each of these parameters individually depends rigourously one wishes to approach the problem. For example, if the measurement of bolt icates a shorter continuous length than expected, this implies an ineffective tendon, and the ı of whether the original tendon was too short, or was of the correct length but has ıtly broken, is of little practical importance. Likewise, provided one can measure the effective ɔupling between the tendon and the rock as a function of distance along the tendon, it is of only importance to distinguish whether defectively bonded segments are due to insufficient grout poor grout properties, or poor adhesion. Proceeding in this manner, the measurement problem ore be reduced for practical purposes to three distinct parameters:

ective length of the tendon (as viewed from the outer end);

gree of bond between the tendon and the surrounding rock as a function of distance along the ı;

esence of significant disturbances to the uniformity of either the tendon (e.g. due to spots of ıion damage) or the grout (e.g. due to clumps of grout capsule skins) as a function of distance the tendon.

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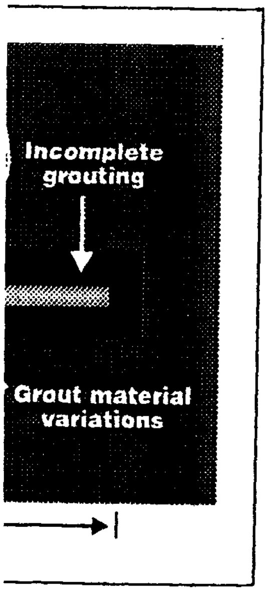

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Table 2. PARAMETERS THAT SHOULD IDEALLY BE MEASURED TO DETERMINE THE EFFECTIVENESS OF FULL-COLUMN GROUTED TENDONS

Parameter	**Function of distance along tendon?**	**Relevance**
Installed tendon length	No	The tendon's capacity to reinforce the fractured rock surrounding the tunnel is directly proportional to its length. The tendon's capacity to anchor the loose rock and external support elements relies on it being long enough to penetrate into more stable rock deeper into the walls. If the tendon installed is shorter than intended, it will not be able to provide the expected level of support.
Break or significant damage in tendon	Yes	A break reduces the effective reinforcement length of the tendon to that of the outer broken segment, and destroys the anchorage role of the tendon. Significant local damage to the tendon constitutes a point of weakness or potential breaking point.
Corrosion damage to tendon	Yes	Constitutes an area of weakness in the tendon, destroys the bond, and corrosion products may additionally weaken the surrounding grout.
Presence of a grout bond between the tendon and the borehole wall	Yes	Ungrouted segments provide no load transfer capability at all.
Density of grout: does it completely fill the annulus?	Yes	Grout that only covers part of the annulus, or is contaminated by capsule skins or contains a lot of air bubbles, reduces the bond strength - especially the mechanical interlock and friction components. An incomplete grout annulus also reduces the ability to absorb shear loads by crushing of the grout and bending of the tendon.
Water : cement ratio (cementitious grouts) - OR - Resin mix (resin grouts)	Sometimes, especially when grout capsules are used	This parameter determines the strength of the grout, which affects all three components of the bond between the tendon and the rock: adhesion, mechanical interlock and friction, as well as the resistance of the grout to crushing under shear loads. With resin grouts, sometimes the resin does not set at all, hence providing no bond and no crush resistance.
Adhesion tendon / grout, Adhesion grout / rock	Sometimes	A lack of adhesion, due to e.g. grease on the tendon surface or borehole wall, will reduce the bond strength, and especially the friction component thereof.

Turning now to the measurement technique itself, the required characteristics can be summarised as follows:

- non-destructive;
- appropriate to in situ conditions underground (mine-worthy);

- quick to apply (owing to the very large number of tendons installed, and the large rate at which these are installed);
- reasonable capital and operating cost.

Any proposed measurement technique should thus be evaluated firstly in terms of its ability to measure the listed parameters, and secondly in terms of its ability to meet the above characteristic requirements.

2.4.2 Established Test Techniques

Currently, the only widely known in-situ technique for indicating the effectiveness of grouted tendons after installation is the so-called "pull-out test" [13], [14], [15], in which a hydraulic jack, bearing against the tendon base plate or the rock at the collar of the borehole, is used to pull the exposed end of the tendon out of the hole as the load and extension is recorded. If the intention is simply to establish that the tendon meets a certain minimum bond strength which is less than the material strength of the steel tendon itself, then load can be applied up to the required level and the test stopped, in which case a tendon that meets the criterion may not be damaged by the test. However, if the intention is to establish the actual strength of the tendon installation (the tendon itself as well as its bond with the rock via the grout), then load is generally applied until failure occurs.

It is readily apparent that, in many cases, such a test cannot provide a good indication of the effectiveness of an installed full column grouted tendon, particularly where the length of the grout column exceeds the critical bond length (CBL). In such cases, the tendon itself will fail at a point outside of the grout before the tendon-grout-rock interface is fully mobilised, and there is no information about the effectiveness of that portion of the grouting which lies beyond the CBL; this deeper grouting may even be non-existent, in which case the tendon offers no deeper reinforcement at all. This is a pervasive problem because the CBL is much shorter than the tendon itself in most installations (see e.g. Thurner [Appendix, page 30, point 4]).

In addition, the pull-out test simulates tunnel dilation forces only to the extent that these are compatible with a dilation characteristic that decreases uniformly as one moves from the skin of the excavation into the tunnel wall. In practice, as pointed out in 2.1.1 above, one cannot rely on a uniform load or dilation profile as a function of depth into the tunnel wall. It may easily happen that the segment carrying the greatest load is buried somewhere in the middle of the tendon, rather than near the exposed end. Further difficulties with the pull-out test include the fact that an adjustment must be made to account for the free length of tendon between the grout column and the jaws of the pulling device [3], and the practical difficulties of dealing with a heavy jack underground in a series of time-consuming tests.

Considering laboratory tests, Pells [16] described a double-embedment axial test method that is more representative of the behaviour of a grouted tendon crossing a dilating discontinuity than the conventional single-embedment pull-out test (see Fig. 10(b)). Unfortunately this test cannot be applied in situ. Finally, in respect of shear testing, a number of laboratory tests have been devised and executed, but again these cannot be applied in the field (at least not without considerable expense and difficulty).

It is therefore clear that established test techniques are not adaptable to the full column grouted tendon effectiveness problem, necessitating a completely new approach, e.g. that used by the Boltometer (dealt with in section 3.2.1).

On the other hand, there are established methods for determining the reinforcement function after installation of the continuous friction and end-anchored types of tendon. An indication can be obtained of the coupling in a Split Set stabilizer upon installation by measuring the force required to insert the split tube, and by visually inspecting the width of the split after insertion. In a Swellex bolt, the hydraulic water pump can at any time be re-connected and the setting pressure checked, which provides an indication of the coupling of the bolt to the rock. In end-anchored bolts or cable anchors, the tension can be checked at any time, and, in addition, the pull-out test gives quite acceptable results for this kind of tendon. These methods are reasonably effective but not always convenient. For this reason, it would be useful if a new convenient non-destructive test method for grouted tendons was also applicable to continuous friction and/or end anchored types.

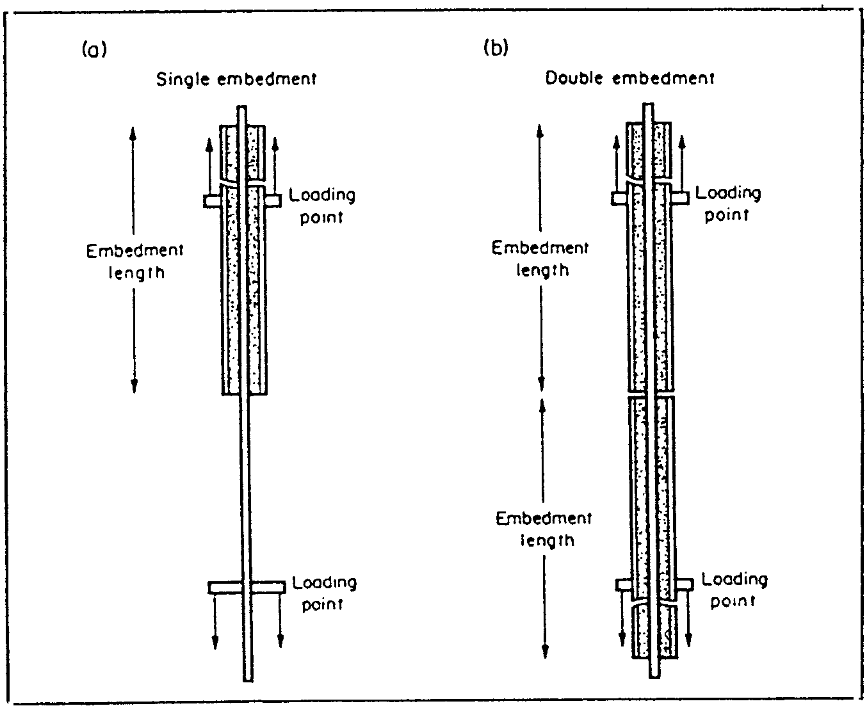

Figure 10. (a) Single and (b) double embedment length laboratory axial tests (after Windsor and Thompson [3]).

2.4.3 Restricted Access; Awkward Geometry; Range vs. Resolution

Any proposed in situ grouted tendon test method must use some physical mechanism to derive information about the tendon, and about the region of the grout annulus between the tendon surface and the borehole wall, preferably in a way that can detect variations with depth in the borehole. Such a mechanism must in effect be able to penetrate the steel, grout and/or rock to the depth of the inner end of the tendon.

Any technique that uses the interaction of directional energy with the tendon surface and grout annulus to derive information (for example, acoustic and electromagnetic techniques) is immediately placed at the disadvantage that access is restricted to only one end of the tendon. This geometric restriction is not really problematic in determining the length of the tendon, but generally presents a very unfavourable angle for "looking at" the tendon-grout-rock interface.

Some proposed techniques have tried to deal with this problem by moving transducers away from the tendon itself, and onto the surrounding tunnel wall, so that the annulus is faced from an oblique direction. This is still not a very good angle for reflection or transmission techniques, and additionally further exposes the measurement technique to the unpredictability of the complex, fractured environment of the tunnel wall rocks.

Suggestions have been made to "look at" the tendon from a nearby, roughly parallel borehole (e.g. that of the next tendon to be installed). Whilst this angle would be more favourable, the distance between adjacent tendon boreholes is usually large in comparison with the size of the target annulus, which would lead to problems in obtaining sufficient resolution for the measurement range.

With acoustic and radio wave techniques generally, the penetration range decreases and the resolution increases with increasing frequency for a system with a given dynamic range (transmitter power divided by receiver sensitivity). It is considered that, given the geometry of the problem, it would be very difficult to devise an approach that could provide enough detailed information about the grout annulus from the range of an adjacent tendon borehole.

A further problem regarding restricted access concerns the location of tendons within the tunnel: many of these are to be found in the hangingwall and in the corners of the excavation, which makes access awkward for any technique.

Finally, the geometry at the exposed end of the shepherd's crook tendon itself presents difficulties for many techniques, which could otherwise model the tendon as a simple cylinder.

2.4.4 Variation in Measuring Environment

A grouted tendon testing technique must deal with considerable variation (from tendon to tendon, and to a lesser extent within the environs of a single tendon) in the properties of the rock, the tendon, the grout, and the surrounding environment in the tunnel opening. This applies to any physical mechanism used for measurement, but particularly to acoustic and electromagnetic techniques.

The rock varies in density and hardness (acoustic properties). It also varies widely in terms of its dielectric and electrical conductivity properties, even for rocks of ostensibly the same type. The possible presence of ground water is significant with electromagnetic techniques.

The degree of fracturing in the rock is critical in acoustic, electromagnetic and most other techniques. Cracks limit the penetration of wave energy and (worse) reflect and disperse the energy in mainly unpredictable directions.

The tendon will vary in its surface properties (rebar, smooth), length, and geometry at the exposed end (for example, the presence of a nut, or the flatness of the tendon end). These variations are typically very significant when considering acoustic techniques.

The grout can vary widely, particularly in its acoustic properties, most significantly due to variation in the water : cement ratio of cementitious grout (see Thurner [17] or Appendix).

The tunnel environment varies in respect of the presence or absence of other support elements such as bearing plates, mesh and lacing. These can have a profound effect on the performance of acoustic or electromagnetic techniques.

The significance of these kinds of variations can be illustrated by noting that even in the case of a state-of-the-art instrument such as the Boltometer, it is necessary to calibrate the instrument against a reference installation for each combination of tendon type and length, grouting technique and rock type, before reliance can be placed upon the measured results (see Appendix, page 10).

2.5 Concluding Remarks

From the above discussion, the need for, the required characteristics of, and the difficulties involved in, the development of an effective non-destructive grouted tendon test technique for general application in South African gold and platinum mines, should be at least qualitatively clear. This understanding provides the basis for reviewing and assessing technologies that have been developed both locally and internationally, including those technologies that were developed to address rather different needs.

3 REVIEW OF RESEARCH RELEVANT TO THE DEVELOPMENT OF A GROUTED TENDON TESTER

The core of this project was to critically review research efforts that have been carried out world wide in an effort to develop a technique and instrumentation for non-destructive testing of grouted tendons in situ. The objective of this review was to identify any technologies developed which could potentially form the basis of a solution to the problem discussed in Chapter 2. The approach adopted was as follows:

1. To critically review earlier work known to us. It was hoped that, by identifying the reasons for failure, cases might be discovered where more recent advances in technology could offer a way to overcome the problems. In this regard, the work that was carried out under the auspices of the Chamber of Mines Research Organization (COMRO, the forerunner of CSIR: Mining Technology), on which detailed information was available, was revisited. Relevant overseas projects known from that time, for example the Swedish "Boltometer" development and the US Bureau of Mines "Rock Bolt Bond Tester", were also reviewed.

2. To conduct a literature search with a focus broad enough to gather information on related problems (e.g. grout testing generally, or non-destructive testing applied to structures in civil engineering), in the hope that technologies would be brought to light which could have a bearing on the present problem. The search resulted in over 100 abstracts, of which about 20 warranted further study, and fewer still proved to be of sufficient relevance for inclusion.

3. To discuss the problem, verbally or through correspondence, with persons identified as important, either as key people in earlier research efforts, or as people with a broad knowledge of current developments in rock bolting technology.

Concerning item 3, early in the course of this project contact was made with international experts in the field of rock bolting, in particular Christopher Windsor[2] of the Rock Reinforcement Group, CSIRO Division of Exploration and Mining in Western Australia, and Professor Peter Kaiser of the Geomechanics Research Centre, Laurentian University, Sudbury, Ontario, Canada. The discussion aimed at ascertaining whether these people were aware of any relevant recent developments, or could point us to other experts who may have been able to contribute. Neither was aware of any promising developments since that of the Boltometer, and the other contacts whom they suggested were either

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[2] Author of the chapter on rock reinforcement in the International Society for Rock Mechanics' 1993 book "Comprehensive Rock Engineering", see [3].

already known to us, or were also unable to shed new light on the problem. It was learned that, during the 1980's, the CSIRO Rock Reinforcement Group had considered undertaking a development project along the lines of the Boltometer, but the project had not materialised[3].

Other people contacted were chiefly those concerned with the Boltometer (see section 3.2.1) and more recent developments at the US Bureau of Mines (see section 3.2.6).

The remainder of this chapter presents the results of the review of earlier work and the literature. In the case of the COMRO-directed project, this review also serves as a record of a body of work whose results have not been summarised and published as a whole until now. For ease of comparison, the subject matter in this chapter has been ordered according to the physical principles upon which the proposed measuring techniques were based, rather than in historical sequence. Instead, techniques discussed within each group are rather ordered by describing the most advanced work first, so that the shortcomings of earlier work are more easily apparent. However, a historical perspective is important in any review of research, so a brief chronology is provided in section 3.1.

The bulk of the tendon testing techniques that have been proposed or developed (excluding the "pull-out" and related test methods) have relied on acoustic principles, as discussed in section 3.2. Electromagnetic techniques have also received some attention: see section 3.3. Other physical principles are discussed in section 3.4. In discussing each technique researched, an attempt is made to:

a. describe the basic principles according to which the technique is supposed to function;

b. identify the key shortcomings of the technique in relation to the present problem (in the case of work that terminated without success, this amounts to identifying why the technique failed);

c. judge whether improvements in technology could overcome these shortcomings.

To conclude the review, section 3.5 provides a tabular summary of all the techniques.

3.1 Chronological Sequence

Table 3 provides a historical perspective, from a South African mining industry viewpoint, on research carried out over the past 20 years that was significant to the present problem.

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[3] It was also learned that the CSIRO Rock Reinforcement Group had recently completed a major study on the use of rock reinforcing in Australian and Canadian mines, culminating in ten volumes of recommendations, which the group planned to condense into a text book due for publication at about the time of writing this report (publication details unknown at the time of writing).

Table 3. CHRONOLOGY OF RESEARCH AND EVENTS RELEVANT TO THE GROUTED TENDON TESTING PROBLEM (cross references refer to sections of this report where the work is reviewed)

Time	Organization	Ref.	Description of research / event
1977	Geodynamik	3.2.1	Under contract to Boliden Mineral AB, Geodynamik AB of Sweden began the research that ultimately led to the Boltometer. After about two years, initial findings prompted the start of a development programme funded by the Swedish state.
early 1980's	USBM	3.2.5, 3.2.6	The US Bureau of Mines developed the "Rock Bolt Bond Tester", but abandoned the work due to inconsistent results. In a separate effort, the USBM began work on an ultrasonic technique for measuring loads in tendons.
1983	Spiedel (SA)	3.2.4	COMRO became aware of the Boltometer when a local company, Spiedel, demonstrated the instrument and offered it for hire. There was little real interest and apart from a brief trial, the instrument was not used in SA
1987	Geodynamik	3.2.1	The Boltometer reached commercial production stage, and Thurner of Geodynamik published an international paper on the instrument (see [17]).
1987	COMRO	3.2.4	COMRO began work on a project to devise a technique and instrument to measure the effectiveness of grouted tendons in situ. The Boltometer was considered as a starting point, but political sanctions in effect at that time prevented any collaboration with Sweden. A focus was placed on achieving a method that did not require tendon surface preparation. A number of ideas for possible techniques were conceived, and two were developed to laboratory test level without success. The project had been under-resourced and to proceed further, it was recognised that additional manpower and expertise was needed, so Wits University was approached.
1988	USBM	3.2.6	The USBM's ultrasonic instrument for rock bolt load determination became commercially available.
1989	Wits (Agnew)	3.2.3	Under contract to COMRO, Agnew, a graduate student of the Department of Electrical Engineering, tackled the problem culminating in a report in 1990 [18]. As part of this work, he reviewed the literature, examined the Boltometer to the extent that information was available, analysed the feasibility of the various COMRO ideas, and proceeded to develop to laboratory test stage an acoustic technique that showed some promise, but still required extensive test and development work to determine whether it could offer a genuine solution.
1990	CSIR: Mattek	3.2.2	Early in 1990 when it appeared that Agnew's technique had limited chance of success, COMRO approached the Sensor Systems Programme of CSIR's Division of Materials Science and Technology (Mattek), which offered specific expertise in acoustic instrumentation techniques. In a project that overlapped slightly with the end of Agnew's work, Basson of Mattek led a team that again investigated the problem, taking an acoustic imaging approach. Two techniques were investigated, one of which was developed to the stage of a laboratory test instrument that did not succeed in practical tests. In its 1991 final report [19], Mattek concluded that acoustic imaging techniques were not appropriate to this problem. This concluded the reported South African efforts to address the problem, until the present project.
early 1990's	USBM	3.2.6	Tadolini [22] published studies using the USBM's ultrasonic instrument for rock bolt load determination. (This development was discovered during the present project).
1995	Miningtek		The present project was conducted. "New" literature reviewed for this purpose dated from the mid-1980's to the present.
1996	Geodynamik	3.2.1	At the time of writing, Geodynamik were considering developing an intrinsically safe version of the Boltometer for use in coal mines.

3.2 Acoustic Techniques

In all the work reviewed where researchers directed their attention specifically at testing grouted tendons (other than by destructive mechanical means), by far the greatest effort went into measurement techniques based on sound waves. This makes intuitive sense when one considers that the acoustic behaviour of a system comprising distinct materials (steel, grout and rock) depends directly upon the elastic behaviour of the individual materials and the degree to which these materials are elastically coupled to one another, which properties are in turn closely related to the strength of the individual materials and the degree of bond between them. In addition, acoustic transducers are relatively convenient to use, being generally small and consuming very little power.

In his 1990 work, Agnew [18] reviewed a variety of possible technologies for testing grouted tendon effectiveness and concluded that "... an acoustic method is the only viable principle for measuring grout quality". Here he was distinguishing the need to measure the degree of bond between the tendon and the rock (and to detect disturbances to the tendon), from the need to measure the effective length of the tendon. The latter is a much easier problem, and as the review found, there is a diverse range of techniques that can feasibly measure installed tendon lengths without providing any indication of grouting quality.

3.2.1 Boltometer

The Boltometer is by far the most advanced of all developments that are relevant to this problem, and for practical purposes it constitutes the "state of the art in grouted tendon testing". It is the only directly applicable technology that exists in the form of a commercially available instrument. The current model of the instrument embodies some 10 years of active development and a further 10 years of ad hoc improvements. No comparable development has involved anywhere near this amount of effort and experience. Yet the Boltometer is not sufficient to solve the present problem on South African gold mines.

The Geodynamik report "Rock Bolting - Reference Bank", included as Appendix to this report, provides a fairly comprehensive, well illustrated description of the Boltometer. A paper by Thurner [17] contains much the same information in condensed form. The description below is drawn from this material, from a visit to Geodynamik where the instrument was demonstrated, and from an analysis by Agnew [18].

Principle:

The Boltometer makes use of a hand held piezo-electric transducer set to launch ultrasonic waves into the grouted tendon from the exposed end, and to measure the reflections of those waves. Such reflections arise principally from the inner end of the tendon, and from discontinuities in the tendon or grout annulus. The Boltometer makes use of both compressional (primary or P) and flexural (secondary or S) wave modes, and the transducer set is carefully designed to separately stimulate and measure each type of wave. An annotated typical recorded signal is shown in Fig. 11.

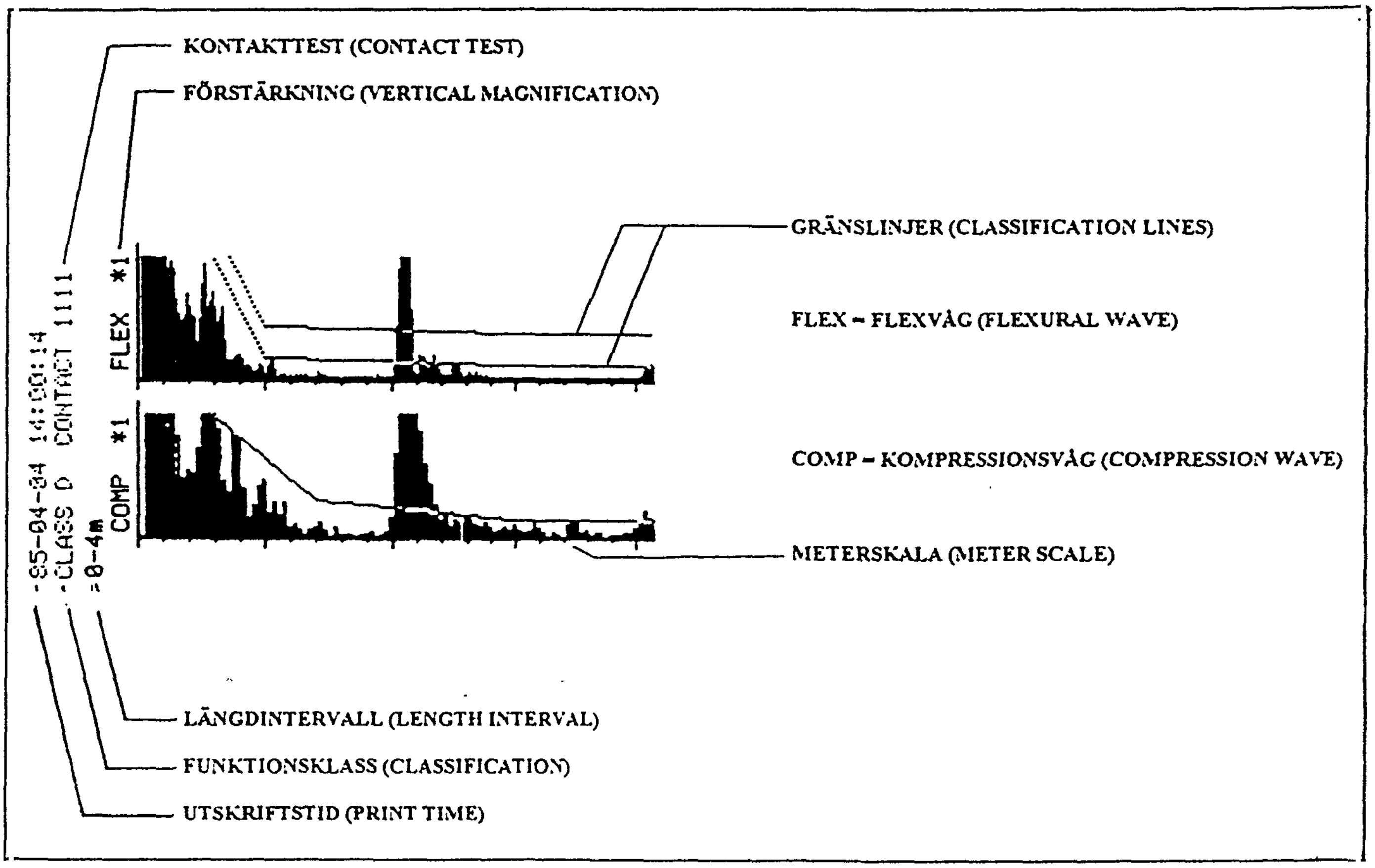

Figure 11. Hard copy from the Boltometer's built-in printer (from Appendix).

The compressional waves are excited at a frequency of about 50 kHz and are reflected by the inner end of the tendon, but are generally not particularly diagnostic of discontinuities in the grout. They are used primarily to detect the effective length of the tendon by measuring the time delay of the end echo and multiplying this by the velocity of sound in the tendon.

The flexural waves are excited at a frequency of about 30 kHz and are a distinguishing characteristic of the Boltometer: no other acoustic technique reviewed made deliberate use of this propagation mode. The flexural waves are also reflected by the inner end of the tendon, but more importantly, they are sensitive to the quality of the grout and echoes can be seen at grout discontinuities. They are also less heavily attenuated than the compressional waves, and consequently they allow the instrument to make meaningful measurements on longer tendons than would be the case if only compressional waves were used. As pointed out by Agnew, the Boltometer evidently makes use of the grout annulus as a waveguide; provided that the speed of sound in the grout is lower than that in both the steel and the rock, and provided that half the wavelength is of the order of the borehole diameter or less, it is possible for a shear wave mode to exist in which total internal reflection occurs at the borehole walls, resulting in much reduced attenuation and hence greater penetration range. The importance of this waveguide mechanism has not however been checked with Geodynamik.

The main principle behind the instrument's determination of grouting effectiveness is in fact the simple one of energy absorption: if a tendon is well grouted, and hence well coupled to the rock throughout its length, most of the acoustic energy will be transmitted through the grout and dispersed in the surrounding rock, and very little echo will be seen in the recording of received signal vs. time. On the other hand, significant gaps in the grouting will not only provide interfaces against which the waves can reflect, but also absorb less of the available reflection energy. Consequently, the Boltometer classifies grouted tendons into four classes: A ("optimum"), B ("reduced"), C ("deficient") or D ("very poor"), based upon the level of echo energy observed in the recording. The flexural wave response is more important for this classification than the compressional wave.

Characteristics:

The latest commercially available version of the Boltometer is the model 011S, which dates from 1991. It costs approximately US$ 40 000. The instrument can be used for a quick, rough estimation of tendon performance (and actual length); or for a more thorough documentation of the tendon installation. Measurements can be repeated over time to judge whether any deterioration has taken place in a particular installed tendon. The interpretation of the Boltometer signal is in general not simple because the recording typically contains complex interacting effects.

The penetration range of the instrument (for detecting the end echo and hence the length of the tendon) varies from 1,5 m to about 5 m, depending on the type of grout and especially the water to cement ratio: a lower water ratio results in stiffer grout and a stronger bond, which absorbs more acoustic energy and hence reduces the penetration range. More generally, the penetration range depends on the quality of grouting: the better the grouting, especially near the outer end of the borehole, the lower the penetration range. For example, in a 3 m tendon with 1,5 m of continuous grouting, if the grouting occurs in the outer 1,5 m, the Boltometer will show an "optimum" class tendon of unknown length. In contrast, if the same length of continuous grouting is further down the hole, the instrument will probably show the actual situation, i.e. the true length of the tendon as well as large reflections from the grout interfaces. If the inner end of the tendon is firmly coupled to the bottom of the hole, this can eliminate the end echo. When used with resin grouts, the Boltometer has yielded penetration ranges of up to 10 m in the case of polyester resins, but with epoxy and thermoplastic resins the range is restricted to about 1 m.

The Boltometer can measure solid steel tendons with a diameter ranging between 16 and 32 mm (if the diameter is too small, insufficient energy is coupled into the tendon; if the diameter is too large, the characteristic impedance of the tendon no longer matches the driving impedance of the sensor). With regard to the tendon surface, the Boltometer is able to measure tendons with both smooth and rebar profiles. It has been found to sometimes detect very small defects in the surface of the tendon (rust, nicks, bends, grout cracks) - but at other times it has "missed" quite large defects of similar type. It was designed for full-column grouted tendons, and is not very useful for end-anchored bolts.

Shortcomings:

The most critical shortcoming of the Boltometer in relation to the present problem is the instrument's inability to measure shepherd's crooks and cable tendons. This is due to the fact that the instrument relies for its operation on a simple cylindrical model of the tendon. The outer shape of a shepherd's crook does not allow the wave energy to be properly directed along the cylindrical straight part of the bolt, and causes much of the energy to be lost at the exposed end. In cable tendons, the stranding results in an acoustic response which is too complex to interpret correctly.

A second shortcoming is the need to ensure that the exposed end of the tendon is clear and unencumbered before Boltometer measurements are attempted. The presence of nuts, washers, and to some extent mesh, lace or shotcrete, causes problems as this results in a large portion of the acoustic energy disappearing into the rock via these peripheral support elements, rather than propagating along the tendon itself. In addition, for a reliable reading, the outer end of the bolt needs to be planar (cut and ground flat), and acoustic gel should preferably be applied to achieve good coupling between the sensor and the bolt end. Whilst this surface preparation was treated as a major concern in COMRO's earlier work on the problem, the use of a simple cutting and grinding tool makes the procedure quick and simple, as witnessed by CSIR: Mining Technology in a recent Boltometer demonstration at Geodynamik. Such a procedure cannot be used in coal mines due to the danger of sparks; however, at the time of writing it was learned that a spark-free cutting technique has recently been devised to overcome this problem.

A third practical impediment with the Boltometer is that, to obtain meaningful measurements, it is necessary to calibrate the instrument and optimise settings very specifically against the type of tendon installation to be measured. This requires installing reference tendons of the same type and length, using the same grout consistency, in the same type of rock as the target tendons. It is recommended that three such tendons of each combination be installed under carefully controlled conditions. Clearly this has cost and practicality implications for the use of the instrument, but once having been carried out for a particular geotechnical environment, it does not have to be repeated.

The need to calibrate against rock type arises because of the reliance of the Boltometer's shear wave mode on the grout waveguide effect. If the surrounding rock is about the same stiffness as the grout, much of the wave energy will dissipate into the rock, making end- or part-echoes difficult to see. For this reason it can be impossible to distinguish between a poorly grouted tendon in soft rock and a well grouted tendon in stiff rock.

Conclusion:

The possibility of overcoming the above problems is discussed in section 4.1. It is worth noting here that most of these difficulties were found to be common to all the other acoustic techniques.

The Boltometer nevertheless seems to work well in cases where these shortcomings are not encountered, and it could be usefully applied on a limited scale in South African mines, particularly for tendon installation research and where straight bar tendons are used.

3.2.2 Mattek, CSIR

From April 1990 to March 1991, the CSIR's Division of Materials Science and Technology (Mattek), under contract to COMRO, conducted a project aimed at developing a method for testing grouted tendons according to the present problem definition. The project was led by D Basson of Mattek's Sensor Systems Programme, a group with recognised expertise in acoustic instrumentation techniques. This was the last known South African attempt to address the problem until the present project. Mattek reviewed the earlier South African work and further literature, and then took an acoustic imaging (as opposed to acoustic absorption) approach to the problem. Two techniques were investigated: the "standing wave method" which was ruled out early in the project because it was found too difficult to analyse; and the "CTFM method" which was developed to the stage of laboratory test equipment. Laboratory tests yielded promising results, but field tests using reference tendon installations were devoid of success. In its final report [19], Mattek concluded that classical acoustic imaging techniques were not appropriate to this problem. The CTFM technique is reviewed below.

Principle:

Mattek's technique was designed to stimulate the grouted tendon with acoustic waves propagating in an *extensional mode* [20]. These are compressional waves that propagate both inside and on the surface of the tendon. According to transmission line theory, if such waves encounter discontinuities such as start or stop interfaces in the grout, or the end of the tendon, they should be partly reflected. Furthermore, the phase of the reflection would indicate whether the interface was due to the start or the end of a grouted region. By detecting and recording the delay, phase and relative strength of all the reflections as a function of time, Mattek hoped to construct an image of the grouting along the tendon length.

The term CTFM (continuous time frequency modulation) refers to the method used to modulate the wave stimulus so as to facilitate the echo discrimination process. In contrast to single pulses, CTFM makes use of a continuous signal whose frequency is swept linearly as a function of time in ramp fashion between two frequency limits. If an interface at a given distance along the tendon causes a reflection, the reflected signal will appear at the sensor as a delayed version of the original stimulus signal, where the amount of delay is proportional to the distance along the tendon. Because of the fixed delay, at any point in time the instantaneous frequencies of the stimulus and echo signals will differ by a constant amount. By multiplying the two signals together and filtering out the higher frequency components of the product (a process known as *mixing* in electronic engineering), a signal will be obtained with a constant frequency whose value is directly proportional to the echo delay. By superposition, multiple echoes will result in a mixed signal with a frequency component corresponding to each echo delay. The mixed signal is then sampled and fast Fourier transformed to yield a graph showing the delay, phase and relative strength of all the echoes.

Characteristics:

The Mattek technique made use of a piezo-electrical transducer stack with a flat surface, which required a flat exposed tendon end in order to achieve adequate coupling. In Mattek's experience, this was the only way to couple sufficient acoustic energy to the tendon, and in their opinion there was no prospect of achieving a successful acoustic technique that did not require some form of tendon surface preparation in order to work.

Simultaneously with the development of laboratory instrumentation, Mattek performed software simulations of the technique so as to model its anticipated behaviour before test results were interpreted. This simulation provided some useful insights.

Shortcomings:

The most serious problem with the technique was encountered in the field tests but not in the laboratory: Mattek had expected that waves which passed from the tendon into the grout would be largely dispersed by the surrounding rock. However in practice it was found that these waves coupled randomly back into the tendon, making analysis of the received reflections meaningless.

At an equipment level, a number of problems were encountered with the design of the experimental instrumentation. In particular, the transducer coupled a strong image of the transmitted signal into the received signal, shifted slightly in phase such that a large low frequency component was present in the mixed signal, which tended to swamp the "real" echoes. The design also turned out to be subject to fairly onerous physical constraints: it was found that the choice of acoustic frequencies that could be used was limited at the lower end to 30 kHz in order to achieve sufficient resolution, and at the higher end to 50 kHz in order to ensure that an extensional wave mode could exist. A simulation revealed that as the number of echoes increased, so would the noise and phase jitter in the response, making echo interpretation much more difficult. To counteract this it would be necessary to increase the sweep time, which would in turn require changing the data acquisition rate.

Conclusion:

Mattek did not rate any of the specific instrumentation problems as insurmountable, but eventually rejected the technique as a whole in principle, as a result of the first-mentioned difficulty. There is little scope to doubt this assessment.

3.2.3 Agnew, University of the Witwatersrand

From July 1989 to August 1990, the University of the Witwatersrand's Electrical Engineering Department, working under contract to COMRO, conducted a project aimed at addressing the present problem. The work was performed chiefly by G Agnew, a graduate student under the supervision of Prof. H Hanrahan. The brief of the project was in part similar to that of the present project in that it included reviewing the work that had been done earlier by COMRO and others, evaluating the untried testing techniques suggested by COMRO, conceiving other possible techniques, and proposing the most promising technique for further development.

The second part of Agnew's project concerned the development, to laboratory testing stage, of the acoustic absorption technique that he felt was the most promising. At the end of his involvement, Agnew had performed theoretical modeling of the problem, conducted extensive laboratory and some field testing, and had achieved some limited experimental success. Note that this work had been performed before he became aware of the basic principle of operation of the Boltometer. Agnew judged in the conclusion of his report [18] that he had achieved his main objective, namely to lay the groundwork for further research and development. Indeed, the report presents a comprehensive recommended programme of work towards developing an effective grouted tendon testing technique.

This section deals with the second part of the project: where relevant, other techniques evaluated theoretically or experimentally by Agnew are reviewed elsewhere in this report.

Principle:

Agnew's technique was based upon launching an ultrasonic pulse into the exposed end of the tendon which would propagate in a compressional mode, be reflected from the inner end, and be detected by a sensor placed at the exposed end of the tendon. By measuring the delay of this echo, the length of the tendon could be deduced. Agnew argued that the degree of mechanical coupling between the tendon and the surrounding rock, or the degree of grout coverage of the tendon, would affect the attenuation of the pulse as it traveled to the inner end of the tendon and back: the better the grout coverage, the greater the attenuation. Hence, by measuring the amplitude of the end echo and comparing this with measurements from reference tendon installations, it was hoped that the percentage of grout coverage could be deduced. This argument was supported by laboratory tests in which he found that the presence of different degrees of grout coverage affected the echo pulse amplitude in a significant way, which appeared to be relatively insensitive to the distribution of this grout coverage. From these laboratory tests he also noted that discontinuities in the grout coverage did not produce substantial additional echoes.

Agnew used a signal processing technique known as the *envelope cepstrum* as a means of detecting the delay and amplitude of small end-echoes which were often buried in large ringing responses and large background "noise". He found that this method performed substantially better than conventional time-domain echo detection techniques such as peak detection or autocorrelation.

Characteristics:

The technique made use of separate excitation and sense transducers for the acoustic pulses (see Fig. 12). For excitation, a magnetostrictive coil was used, which slipped over the exposed end of the tendon. For measurement, a conventional flat piezo-electric transducer was used, coupled to the tendon with Prestik. This approach was used primarily because it obviated the need to carefully prepare the exposed end of the tendon in order to couple sufficient acoustic energy into the tendon.

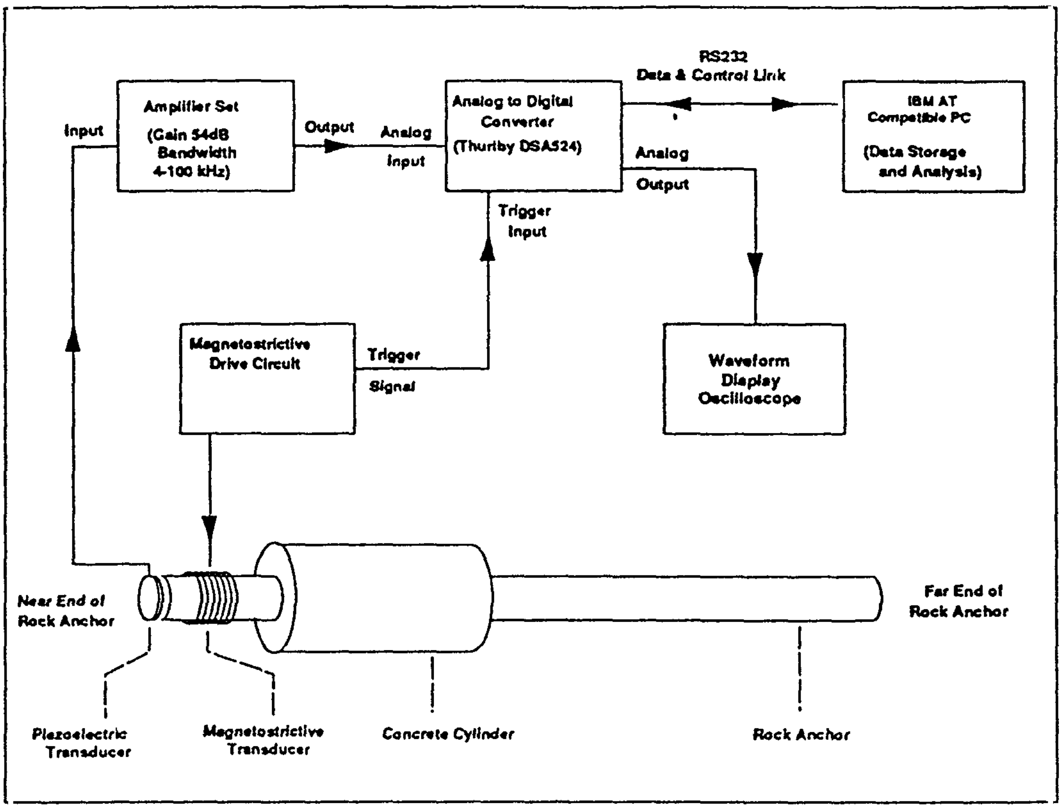

Figure 12. Agnew's Experimental setup (after [18])

In field measurements on reference tendons, certain problems were observed. Firstly, the end echo amplitude of two tendons of identical length grouted to the same degree differed by a factor of a 10 in one case. Agnew believed that this was probably caused by differences in grout stiffness (water to cement ratio variations). Secondly, the decaying oscillations from the stimulus pulse, due to resonance in the exposed end of the tendon, varied greatly in their decay time depending upon the free length of the tendon. Sometimes the decay was slow enough to obscure the end echo pulse.

Shortcomings:

The use of only a compressional wave mode limited the penetration range that the technique could theoretically achieve (e.g. in comparison with the Boltometer). It is apparent that the test instrumentation did not have sufficient dynamic range (i.e., ratio of acoustic excitation pulse power to minimum power of reflected signal that can be detected by the instrument). In the case of the field tests, the dynamic range was definitely limited by using an analogue-to-digital converter with too low a resolution.

It is not clear whether the inconsistencies - observed in measurements of echo amplitude for two tendons of the same length that were grouted to the same degree - were due to variations in factors such as the grout stiffness, which would be an effect beyond the control of the test method itself, or were due to some more fundamental shortcoming in Agnew's measurement principle. From the field tests he did discover that tendons grouted in rock behaved quite differently from tendons grouted in cylinders of concrete, and suggested that in future laboratory test work, only blocks of rock of sufficient size should be used for mounting tendons.

Conclusion:

Although Agnew's field test results were not very impressive, these must be treated as initial results. The field test site became available only towards the end of his work, and a time constraint on the project meant that opportunities for field testing were limited. There seems to be little that is fundamentally wrong with Agnew's approach: the main conclusion must therefore be that the method showed some promise, but still had "a long way to go". For example, it is possible that with further, probably extensive work, the magnetostrictive excitation transducer could be made a more effective means to launch acoustic energy into the tendon than the approach used in the Boltometer. It is also possible that the magnetostrictive transducer could eventually offer a solution to the elusive problem of coupling sufficient acoustic energy into shepherd's crooks.

3.2.4 COMRO

In 1989, as one of its several early attempts at tackling the problem, COMRO conducted an experiment with a simple acoustic energy absorption technique. Initial laboratory tests were promising, but field tests using reference grouted tendons were unsuccessful.

Principle:

The technique attempted to derive information about the degree of mechanical coupling between the tendon and the rock by examining the ringing behaviour of the tendon after it is struck by a blow from a hammer of some kind. Laboratory tests using a free tendon damped by vise clamps showed that the decay rate of the envelope - formed by full-wave rectifying and smoothing the ringing signal - depended on the amount of damping. It was hoped that by devising an instrument that could provide a repeatable blow excitation, the decay rate of this envelope would depend on the degree of bond between the tendon and the rock over the entire length of the tendon.

Shortcomings:

As pointed out by Agnew, the ringing behaviour of a tendon when grouted into rock is quite different from that when it is simply clamped by a few discrete mechanical clamps. Resonance near the exposed end of the grouted tendon will be independent of the grout bond further into the tendon. Traveling waves from the inner end of the tendon returning to the outer end will be relatively small because of their attenuation by the cladding of grout and rock, and these reflections will be masked by the ringing in the exposed end if this ringing is prolonged. By measuring the maximum envelope of the signal in this way, the useful information contained in the small, distant echoes is effectively destroyed, in favour of larger echoes from the immediate region of the exposed tendon end. These echoes provide no information on the length or overall grout quality of the tendon.

Conclusion:

The technique is fundamentally inadequate.

3.2.5 US Bureau of Mines: Rock Bolt Bond Tester

In the early 1980's, the US Bureau of Mines developed a grouted tendon test instrument to field prototype stage, called the "Rock Bolt Bond Tester", or RBBT. This work is reported in the development document by Moulder et al [21], and further information was obtained through correspondence between the USBM and COMRO. Agnew [18] provided an evaluation of the technique used by the RBBT. In the late 1980's the USBM abandoned the development of the instrument because their results were "inconsistent" and because they "could not induce enough ultrasonic energy into rock bolts". They "deemed the problem impossible to solve using ultrasonics".

Principle:

The RBBT attempted to measure the amount of acoustic energy absorbed by a grouted tendon in response to a standard excitation, and use this as an indication of the percentage grout coverage.

It made use of a PZT (lead zirconate titanate) piezoelectric transducer to excite the tendon and to detect its response to this excitation. The transducer was coupled to the exposed end of the tendon by means of a thin rubber ring. The excitation consisted of a tone burst at 20 kHz for 1,5 ms, after which the transducer resonance was halted for 0,35 ms by degenerative excitation. For the following 1 ms, the transducer was used in sensor mode to detect the response of the tendon. An envelope detection circuit was used to find the decay envelope of this response, and at the end of the 1 ms period, a sample and hold circuit sampled the decay envelope level. This sample was compared with two preset threshold levels to provide an indication of the percentage grout coverage of the tendon, by lighting one of three LED indicators: red for 0 - 50 per cent; yellow for 50 - 75 per cent; and green for 75 - 100 per cent.

Characteristics:

The RBBT did not attempt to measure the length of the installed tendon. It was designed for resin grouts but, according to Moulder *et al* [21], it had also been successfully tested on cementitious grouts.

Shortcomings:

As pointed out by Agnew, there are several probable reasons why the RBBT did not give reliable results. Firstly, it made use of a simple envelope detection technique that would mask the most useful information, as discussed in section 3.2.4, and instead emphasize resonant behaviour that would depend mostly on irrelevant factors such as the free outer length of the tendon. Secondly, the method of comparing the amount of energy in the "echo" against the energy in the excitation signal was probably unsatisfactory. The accuracy of such a comparison is vital where the acoustic interface is not repeatable. Thirdly, it is not clear how the instrument could discriminate between a 1 m long tendon which is fully grouted and a 2 m long tendon which is 50 per cent grouted, to give the correct class readings of "green" and "yellow" respectively. Finally, whilst the developers recognized the need to calibrate their instrument against rock type, they evidently did not discover that readings would also depend on grout type and water to cement ratio.

Conclusion:

With the benefit of familiarity with more thoroughly researched techniques such as the Boltometer, it is easy to see that the RBBT developers did not give enough attention to investigating the behaviour of the tendon, grout and rock as an acoustic system. A number of important effects were not taken into consideration, and taken as a whole these effects invalidate some of the principles upon which the instrument's design was based.

3.2.6 US Bureau of Mines: Ultrasonic Bolt Load Testing

Also in the early 1980's, the US Bureau of Mines began another, separate effort led by B Steblay to develop an ultrasonic technique for measuring the loads carried by (chiefly end-anchored) tendons. In the United States, federal regulations for mining require that the load on installed expansion anchor tendons and combination bolts be regularly checked by means of a torque wrench; one out of every four bolts must be checked immediately upon installation, and one out of every ten must be spot checked on a daily basis thereafter. The torque wrench method of load testing provides an accuracy of only ± 30 per cent, and in addition it can disturb or weaken the anchorage [22]. The motivation for the new development was therefore to improve accuracy and eliminate the disturbance caused by the test, and also to measure loads carried in fully grouted bolts (which could not reliably be determined with a torque wrench).

By 1988 commercial instrumentation was available [23], and in 1990 Tadolini published the results of two studies using this technique [22]. In the first study, full-column grouted tendons were installed in concrete blocks in the laboratory and loaded in tension from their exposed ends. Measurements were made of the distribution of elongation and load with distance along the tendon. In the second study, resin end-anchored tendons were installed in a coal mine and their loads measured at various times after installation, using the ultrasonic and the torque wrench technique for comparison. From these results, the ultrasonic technique seems to work well. In January 1996 the US Bureau of Mines ceased operations at its Denver Research Center, effectively terminating its involvement with this development. However, from correspondence it was learned that Steblay intended to continue work on the technique in his private capacity, whilst there remained a demand for such work.

The relevance of the ultrasonic bolt load measurement technique to the present problem is that it could potentially be used to measure the installed length of grouted tendons. In addition, whilst measurements of tendon elongation or load do not provide a direct measure of grouting effectiveness (which is rather a measure of the tendon's *potential to carry load over its full length*), these measurements would be useful for screening to detect tendons that are carrying excessive loads, so as to locate areas needing additional reinforcement. The technique would also be useful for purposes of research into grouted tendon behaviour.

Principle:

The technique is essentially a variation of an established non-destructive testing method for measuring the load on short, precision pressure vessel bolts, modified so as to work with long, relatively coarse rock bolts. Before installation, the tendon is prepared by machining the outer end flat (a minimum diameter of 18 mm is required for adequate transducer coupling), and by forming a reflection target somewhere along the tendon (typically a 1 mm diameter hole drilled perpendicular to the tendon's axis, alternatively the inner end of the tendon can be ground flat to serve as a target).

To make the measurement, an ultrasonic transducer is magnetically coupled to the exposed end of the tendon, where it launches a narrow pulse (centre frequency of several hundred kilohertz) which propagates along the tendon and is reflected by the target. The transducer then detects the reflection and measures the round-trip travel time of the pulse to a resolution of less than 10 nanoseconds. By comparing this travel time in the same tendon under stress, the change in length can be determined.

The determination takes account of the fact that the velocity of sound in a stressed tendon is lower than in an unstressed tendon; the difference in velocity being proportional to the change in the length of the tendon. The technique is capable of resolving elongations of less than 10 microns. Load is calculated from elongation using Hooke's law, which assumes that the material under test remains linearly elastic.

Characteristics:

The instrument can be programmed with a calibration factor for an entire production lot of tendons of a particular type, whereafter it can display the change in length of any tendon in the lot for any applied loading conditions. It can resolve load increments of less than 300 N at an absolute accuracy of about ± 3 kN [22].

In a 1995 discussion with Steblay, it was learned that the instrument had worked with tendons up to 2,4 m long (full-column resin grouted). For purposes of determining length only, it would be possible to prepare the tendon in situ by grinding the exposed end flat (provided that the inner end was already reasonably flat). Bending in the tendon often caused a loss of signal. The instrument could be purchased for approximately US$ 15 000, and it had not yet attained full intrinsic safety certification in the USA.

In [23] two forms of the instrument were reported as commercially available: the PDX-934 Bolt Gage manufactured by Raymond Engineering, which could measure the elongation between the bolt head and one reflector target; and the Bolt Mike model S-1 manufactured by Stresstel Corporation, which could take measurements on three reflector targets simultaneously.

Shortcomings:

The need, in general, for preparation of the tendon at both ends prior to installation would imply increased costs in new tendon installations, and make this technique effectively non-applicable to existing tendon installations.

The limited penetration range could be very significant: judging by results for the Boltometer, if the range with polyester resin grout is about 2,4 m, for cementitious grouts it could reduce to less than 1 m. The range limitation would in part be due to the very high ultrasound frequency used, which is necessary if pulse travel time is to be measured accurately enough to determine elongation in the elastic state.

Acoustically, the method is apparently designed specifically to reject the effects of the tendon surface profile and grout, by using a mode in which the tendon alone acts as a waveguide. Thus, it may not be possible to modify the technique so as to measure grouting effectiveness, without invalidating its basic principles.

Conclusion:

It may be possible to modify the technique so that it could be used to measure the length of most installed tendons, without having to prepare the inner ends of tendons before installation. This would probably require reducing the pulse frequency so as to increase the penetration range. However, this would reduce the instrument's ability to measure elongation and may completely change its acoustic behaviour.

The technique could not be made to measure grouting effectiveness without a complete redesign. However, as it stands it could be useful as a tool for research applications, where prepared tendons are installed and their behaviour under load is monitored. In such applications it seems to be more cost-effective and less intrusive than other techniques (e.g. strain gauges or vibrating wires) for measuring the load distribution on a fully grouted tendon.

3.2.7 Other Acoustic Techniques

The principles briefly discussed below arise from literature addressing applications that are only slightly related to the present problem. These ideas are included in the hope that they may stimulate further thought which could lead to a real solution.

Acoustic Imaging / Seismic Surveying:

The concept of acoustic imaging or seismic surveying is to place an array of acoustic / seismic sensors against the rock, and then to excite the rock with a controlled or known acoustic / seismic source from a chosen location or series of locations. Transmission or reflection techniques are possible.

In transmission techniques, one examines the received signal in comparison with the excitation signal and, assuming or calculating the path followed by the waves from source to sensor, attempts to deconvolve the rock's response into an image of rock acoustic properties (e.g. density) as a function of position in the rock. By this means it is possible to build up a one- two- or even three-dimensional image of the area of interest. The greater the number of source-sensor raypaths from different directions passing through a given region in the area of interest, the more reliable the image will be in that region.

In reflection techniques, one looks in the received signal for reflections of the excitation signal from discontinuities in the rock, and then builds up an image of the position of reflecting surfaces by solving for path distance and geometry, taking into account that variation in geology or materials through which the waves pass will affect the velocity of the waves. Again, one- two- or three-dimensional images can be constructed, and the more raypaths from different directions passing through a given region, the more reliable the data will be for that region.

Attempting to apply this to testing tendon grouting effectiveness, by placing an array of sensors on the rock face around a tendon and then stimulating either the tendon itself, or the rock at various points, is not likely to work at all well. This is because, as for ground penetrating radar (see section 3.3.1), the geometry is awkward and there is a likelihood that fractures near and parallel to the tunnel wall will dominate the reflection or transmission data. Indeed, if excitation frequencies are chosen high enough to achieve sufficient resolution to "see" the grout coverage, the waves are not likely to penetrate the rock further than the first few fractures, and the image that will be obtained will be mostly one of the fractures in the rock.

On the other hand, if it *is* possible to pass an acoustic wave through the grouting in such a way that the grout's effect can be separated from the overall rock effect, this would be very diagnostic: acoustic pulse velocity techniques have been successfully used, for example, to evaluate the quality of grout repairs to fractured concrete [24], and to detect or locate fractures in concrete [25]. Here the average velocity and attenuation of acoustic waves is measured over a "good" stretch of concrete versus an area with a possible crack or an inadequate grout repair: the presence of these defects will both slow down and attenuate the acoustic wave. In addition, it would be possible to determine whether the grout has set or is still in liquid form, by stimulating the region with *shear waves*, because liquids cannot propagate shear waves [26].

Acoustic Emission / Microseismicity (AE/MS):

All solid materials emit small acoustic signals and / or microseismic activity as they are stressed, and on the strength of this phenomenon, many people have attempted to build systems that predict when and where rockbursts or rock falls are likely to occur, without much success to date (because there are too many unknown variables). However, under controlled conditions it is possible to learn much by studying these small signals [27]. For example, Feknous *et al* [28] analysed the acoustic emission signals from samples of rock or concrete in which a disk of grout had been cast, as a load was applied between the rock / concrete and the grout. With some success, they applied pattern recognition methods to characterise the emissions into different types (failure of the grout, failure of the rock / concrete, failure of the bond between these components).

One possible application in grouted tendon testing would be to monitor AE/MS activity as a tendon is pull-tested (but not to destruction): the AE that occurs in this process should be diagnostic of the grouting effectiveness, provided that the signals could be correctly classified. Once again, however, the critical bond length may limit the "penetration" of this approach.

3.3 Electromagnetic Techniques

In addressing a variety of testing problems that are in some way related to the grouted tendon testing problem, a number of researchers have used electromagnetic waves as a means of "looking into" rock or concrete, as a means to detect cracks or to diagnose the state of embedded steel reinforcement. The waves have varied from ultra low frequency inductive modes, through radio and microwaves, up to X-rays at the high end of the electromagnetic spectrum. The wave-based techniques all rely on differences existing in the bulk electrical properties (chiefly, the dielectric and conductivity characteristics) between the materials, which cause the wave propagation to be affected in some measurable way - namely through reflection, refraction, diffraction, absorption or scattering.

An advantage of these techniques over acoustic methods is that they are generally insensitive to the internal construction of the tendon; in other words, cable tendons can usually be tested equally as well as solid bar tendons.

It is significant that, in regard to the testing of reinforcement using these techniques, much more effort has been put into problems involving concrete than those involving rock, and far more success has been attained in the former class of application. It is not difficult to see why: in comparison with rock, concrete is a relatively homogeneous medium, and the problem of extensive fractures, joints and bedding planes in rock walls is absent. In addition, the geometry of the problem in concrete is generally much more favourable, and typically one can "look at" the reinforcement target from a nearly optimum angle. Comparing this with the situation for tunnel reinforcement as discussed in sections 2.4.3. and 2.4.4, it can immediately be concluded that a technique, which might work satisfactorily in testing concrete reinforcement, will face a host of new difficulties when migrated to the tunnel reinforcement environment, and may offer no solution at all. This problem is unfortunately common to many of the techniques discussed below.

3.3.1 Ground Penetrating Radar

In the course of COMRO's earlier work on this problem, the possibility of using ground penetrating radar (GPR) to measure the length and/or grouting effectiveness of tendons was considered. In civil engineering, GPR has been successfully used to locate steel reinforcement in concrete [29], and even to determine whether tendons installed in ducts in concrete bridges have been properly grouted [30]. However, our theoretical evaluation indicated that this approach was not feasible in the present application, so it was not tested.

Principle:

The electrical properties of the rock (quartzites, shales and lavas) are probably sufficiently different from those of the grout to allow a radio wave reflection at a grout-rock interface. The steel tendon presents a strongly reflective interface, against either grout, air or rock. By using a radar wavelength small enough (about 10 mm in rock, implying frequencies of around 10 GHz) to "see" the borehole, grout and tendon as a target, reflections would in principle be detected and a GPR image built up that would allow the length of the tendon to be determined. With greater care, the degree of grout coverage might also be measurable. For these purposes it would be necessary to place the directional antenna against the rock surface at an oblique angle to the tendon, and aim the antenna towards the tendon. A skilled operator would be required to take and interpret the measurements.

Shortcomings:

The principal problem is one of range and resolution. Based on CSIR: Mining Technology's experience with GPR in mining, the most advanced GPR systems currently available (provided that they could be made to operate at these very high frequencies), would probably only have a penetrating range in these rock types of a few tens of centimetres. This would be insufficient to measure tendons of typically 2 m and longer. Even if the tendon was measured from an adjacent, empty tendon borehole by means of a suitable borehole GPR antenna, the target distance is likely to be uncomfortably large. By reducing the frequency the range could be extended sufficiently to measure the length of the tendon, but in this case the resolution would probably be insufficient to detect the presence or absence of the grout. In either case, the reflections from the tendon steel would probably swamp the nearby and smaller reflections from the grout-rock interface.

The geometry of the problem also creates difficulties. When using an antenna on the surface of the tunnel wall, the oblique incidence angle will result in most of the energy that is reflected off the tendon or borehole being directed away from the receiving antenna. In addition, the tendon constitutes a very small linear target in a mass of fractured rock, where each fracture surface will present as a strong planar reflector and the target reflections may well be masked by the fracture reflections. If mesh is present at the tunnel walls, reflections from this would be strong enough to completely obscure any useful reflections from within the tendon borehole. Most of these problems could be overcome by scanning the tendon from a nearby, roughly parallel borehole (the incidence angle would be more favourable in terms of both the tendon and the unwanted fracture reflections, and mesh would be more manageable), but the tendon would still present a small target.

Conclusion:

The GPR technique has too many shortcomings of a fundamental physical nature to warrant further attention in this application. This is unfortunate, because the technique would otherwise offer the advantages of a non-contact test method that could yield rapid measurement results.

3.3.2 The Tendon as an Antenna

As part of COMRO's earlier work on grouted tendon testing, a method was devised to measure the length of installed tendons by treating the tendon as a radio antenna and measuring its electrical length. The technique was developed to the stage of very basic experimental test equipment, which performed satisfactorily in the laboratory but not underground. In his later work, Agnew [18] re-evaluated the method on a more thorough theoretical basis, and concluded that the technique offered good potential for measuring the tendon length, but would not be able to provide information on the bond or grout quality. For this reason he chose not to explore this technique further.

Principle:

Provided that a ground plane is available at the tunnel wall around the tendon (mesh could act as such a ground plane), the tendon can be thought of as a monopole antenna buried in a relatively homogeneous half-space of rock. Such an antenna will resonate at a frequency inversely proportional to its electrical length, which is a function of the actual rod length and the electrical properties of the rock medium. Thus by measuring the resonant frequency of the tendon (using an RF impedance meter) it is possible to calculate the tendon length provided that the dielectric and conductivity characteristics of the rock mass are known. These characteristics could in turn be estimated according to the rock type, or could even be measured in situ.

Characteristics:

An attractive feature of this method is that the instrumentation is small and does not consume much power. Agnew provides a theoretical analysis of the technique, based on the work of electromagnetic geophysicists who used antennas buried in boreholes as a means of measuring rock electrical properties. From this analysis he proposed reasons why COMRO's initial underground experiments failed to produce meaningful results. He showed that the resonant frequency of the tendon when buried in rock would be considerably lower than that in air, so that the frequencies actually measured underground were probably from higher order resonances. He also suggested that the capacitive coupling method used in the COMRO equipment was not efficient or consistent enough to ensure repeatable results, and that not enough attention had been given to ensuring that an adequate ground plane was present. Agnew provides more detailed formulas for calculating the tendon length from the measured parameters, and suggests ways to improve the practical implementation of this measurement technique.

Shortcomings:

The principal shortcoming of the antenna technique is that it relies on a ground plane at the tunnel wall. Where there is mesh and lace, it is very important that the mesh is not electrically connected to the tendon, otherwise the technique will be useless. In practice, it might be difficult to break the electrical continuity that usually occurs between the tendon and elements attached to it, such as mesh and lace, without compromising the mechanical function of these attachments.

Where there is no mesh and lace, the instrument itself would have to provide a ground plane, which should ideally be of similar dimensions to that of the tendon. This would be impractical, so a smaller, less efficient ground plane would probably have to be used. The orientation of the ground plane may also present some difficulties (extent unknown), for example if the tendon is not installed perpendicular to the tunnel wall, and particularly where tendons are installed in the corners between the hanging- and sidewalls.

Finally, if the tendon is broken inside the borehole, the resonance characteristics would change and it is not clear what the effect of this would be on the length measurement. Likewise, the effect of adjacent tendons was not considered by Agnew. While this effect is not known at present, it is suspected that it could be significant.

Conclusion:

Despite its shortcomings, the antenna method still appears promising as a technique for measuring the installed length of grouted tendons; provided that the effects of a break in the tendon, and of adjacent tendons, can be determined and dealt with. Modeling and additional experimentation would be necessary to take the technique further.

3.3.3 Inductance

In considering a variety of techniques that might help to solve the problem, Agnew [18] evaluated an inductance method for measuring the length (only) of grouted tendons. He took this as far as basic laboratory tests before concluding that the technique was impractical.

Principle:

A small wire coil is wound on a tubular non-magnetic former that can be slipped over the exposed end of the grouted tendon (assuming a straight bar tendon type). The presence of the steel tendon acting as a core will cause the inductance of the coil to increase as the length of the tendon increases. By measuring the inductance of the coil on the test tendon and comparing this with calibration tables from measurements of comparable reference tendons, the length of the tendon can be read off.

Characteristics:

The advantage of a magnetic approach such as this is that the results will be independent of the condition of the surrounding rock (provided that the rock is non-magnetic, which is valid in most cases on South African deep level mines). On the other hand, the method would be sensitive to the presence of peripheral iron-containing elements in the vicinity of the tendon's outer end, such as washers, nuts, lacing cable and mesh.

Agnew made a coil of length 25 mm that fitted closely over the shank of a straight bar tendon with diameter 22 mm and length 1,8 m. Starting from a reference position with the outer end of the coil aligned flush with the outer end of the tendon, he measured the inductance of the coil as it was pushed further onto the tendon shank in increments of 1 mm. He repeated these measurements after shortening the tendon from the other end by 10 per cent and then by 90 per cent. The results are illustrated in Fig. 13.

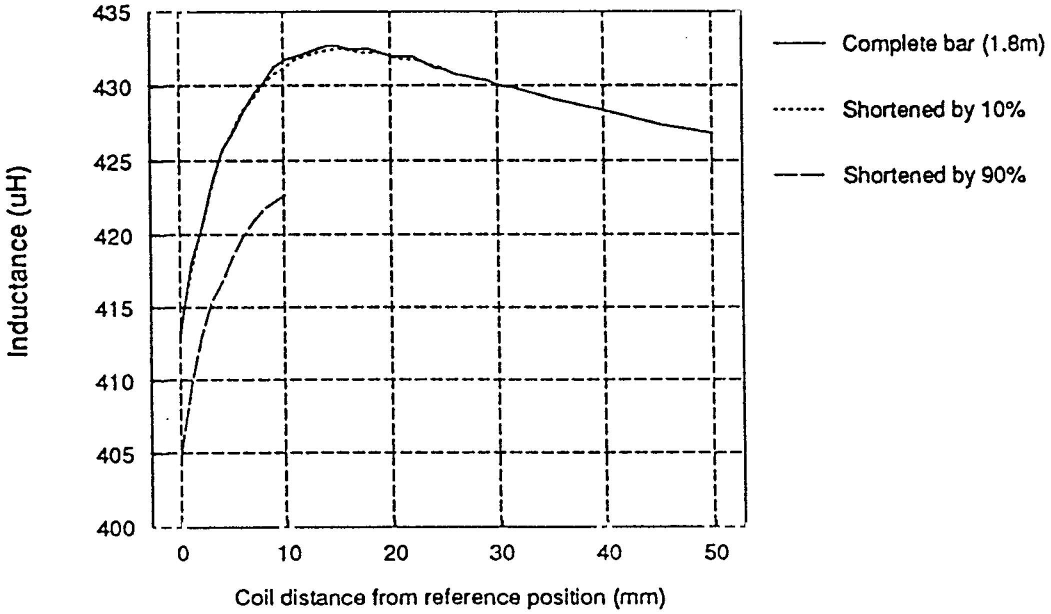

Figure 13. Measured inductance vs. coil placement for three tendon lengths in a laboratory test of the inductance technique (after Agnew [18])

As can be seen, the results show that the inductance is rather insensitive to effects at the end of the tendon furthest from the coil (a 10 per cent reduction in tendon length caused a reduction of inductance of only one part in a thousand), but very sensitive to effects at the coil-end of the tendon (a shift of the coil on the shank by as little as 1 mm also produced an inductance change of one part in a thousand).

Shortcomings:

The distortion in sensitivity of the inductance due to variations near the exposed end of the tendon, relative to variations along the rest of the tendon, is a serious problem. For example, in Agnew's tests it was found that individual ripples due to a thread cut into the exposed end of the tendon caused as much variation on the inductance as cutting off 10 per cent of the tendon from its far end. This implies that not only would washers, nuts, lacing cable and mesh pose a serious problem, but so would manufacturing tolerances in the surface profiles of rebar tendons. Further, if longer and thinner tendons are to be tested (e.g. 3 m long 16 mm diameter rebars), the required resolution of an inductance measuring technique would need to be at least one part in 10^5.

Conclusion:

It would be possible to reduce the sensitivity of the technique to the exposed end of the tendon relative to that of the buried part, by either allowing a greater air gap between the coil and the tendon core, or by using two coils mounted at right angles to the tendon axis on either side of it and measuring the mutual inductance between these coils as a function of tendon length. However, both of these methods would still be very sensitive to minor variations in the peripheral steel components near the exposed end of the tendon, so it is concluded that the inductance method does not warrant further investigation.

3.3.4 Other Electromagnetic Techniques

In the course of the present project, a short article was encountered that dealt with tendon corrosion problems in bridges constructed using the "grout-duct post-tensioned method" [31]. In this method, steel strands passing through ducts in the concrete beams are tensioned after the concrete has hardened. The strands are then grouted in position to seal them in. Around the world, thousands of bridges have been built using prestressed concrete prepared this way, and in a few cases the bridges have collapsed owing to failure of the tendons, following corrosion at anchorage points or at voids within the grout column. The article described the need to inspect old bridges to detect the possible presence of these defects.

There are obvious similarities between this problem and that of the present project. The conventional technique used to inspect such bridges is to locate the tendons using ground penetrating radar, and then drill into the ducts at various points to inspect the state of grouting and of the steel strands. Naturally it would be cheaper and easier to use a suitable non-destructive test method instead, and the article described two possibilities that were being pursued.

X-rays:

One of these is an X-ray based technique developed in France and dubbed the "Scorpion" method because it uses a vehicle with a hydraulic arm that reaches under the bridge to enable X-rays to be passed through the structure. It is claimed that the resulting images can be interpreted to detect grouting problems. Unfortunately, the method relies on lateral access to opposite sides of the tendon, so it could not be applied to the present problem unless adjacent boreholes were available on either side of each tendon to be tested, sufficiently closely spaced to allow X-rays to penetrate the intervening rock. It would also be necessary to construct an X-ray source suitable for insertion in a borehole.

RIMT:

The other technique described is known as RIMT, a Swiss / German development that passes an electrical impulse down the tendon strand from one end. The developers claimed that the reflected signal could be interpreted to indicate corrosion. The 1992 article reports that "the results (were) still admitted to be inconclusive", and that the method "still (had) a long way to go" before it could become an established test technique. The test method was being offered in the United Kingdom by a company called Test Consult. Other than this article, no further information has been encountered about this technique. It is possible that development was terminated owing to lack of success. If the method has been successful, it would be relevant to the present problem, at least as far as detecting tendon corrosion is concerned.

3.4 Other Techniques

Finally, during COMRO's earlier work on the problem, the possibility of using thermal response was suggested as a means to measure the length and/or grout coupling of tendons. This was explored in theory by Agnew [18]. His evaluation indicated that the technique could conceivably provide the required information, but that the practical difficulties were too onerous. He therefore rejected the technique before any experiments were carried out.

Principle:

Two approaches to a thermal response testing technique were identified: a one-dimensional profile of temperature against time in response to a known heat source applied to the tendon; and a two-dimensional profile of temperature against both time and distance from the tendon, also in response to a known heat source applied to the exposed end of the tendon.

If a heat source with a constant rate of heat transfer is applied to the exposed end of a grouted tendon, and the tendon's temperature is measured somewhere near the exposed end, the temperature response should resemble the curve sketched in Fig. 14 (equivalently, if a constant temperature source is applied to the end of the tendon and the rate of heat flow into the tendon is measured, a different curve would be obtained that would embody the same information). The shape of this curve would depend on both the length of the tendon and the degree of coupling (i.e. grout coverage) between the tendon and the infinite heat sink formed by the surrounding rock, which has a higher specific heat capacity and a lower conductivity than the tendon. With a knowledge of the conductivity and specific heat capacity of the three materials, it would be possible to model the thermal system and hence interpret the curves - although using the one-dimensional approach, it may not be possible to distinguish between a short, well-grouted tendon and a long poorly-grouted one.

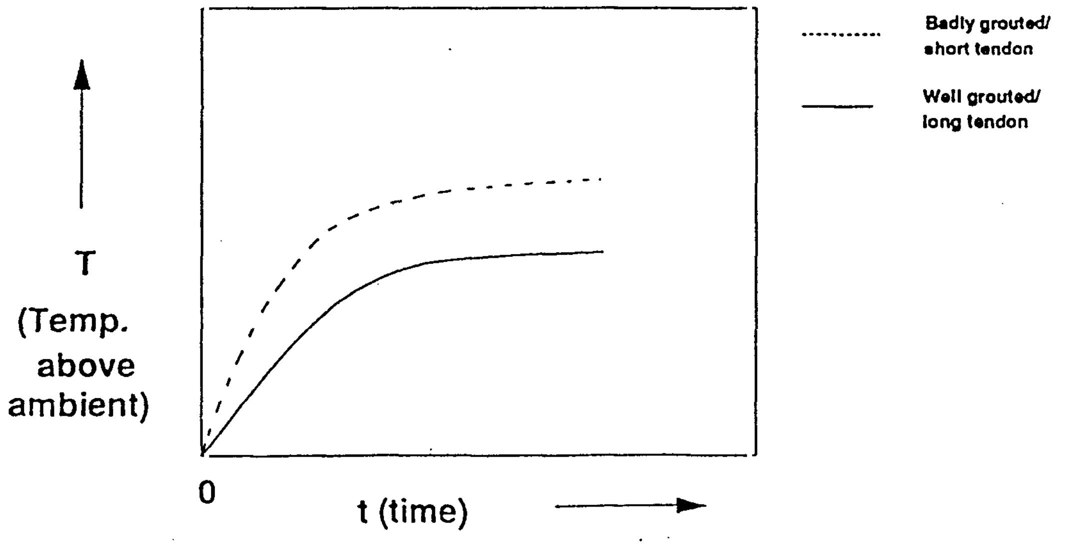

Figure 14. Sketch of temperature response curve illustrating the fixed heat source principle (after Agnew [18])

In the two-dimensional approach, a fixed temperature heat source could be coupled to the free end of the tendon and the effect on the surrounding rock (through the tendon and grout) could be measured by taking temperature readings at the rock surface at various distances in a straight line away from the tendon. The predicted response with distance is sketched in Fig. 15. This could be measured with a single temperature probe that was moved from place to place, with an array of temperature probes, or even with an infrared camera. The response would also be measured as a function of time, and the two-dimensional data thus obtained should, in theory, provide enough information to determine both the length and the grouting quality of the tendon.

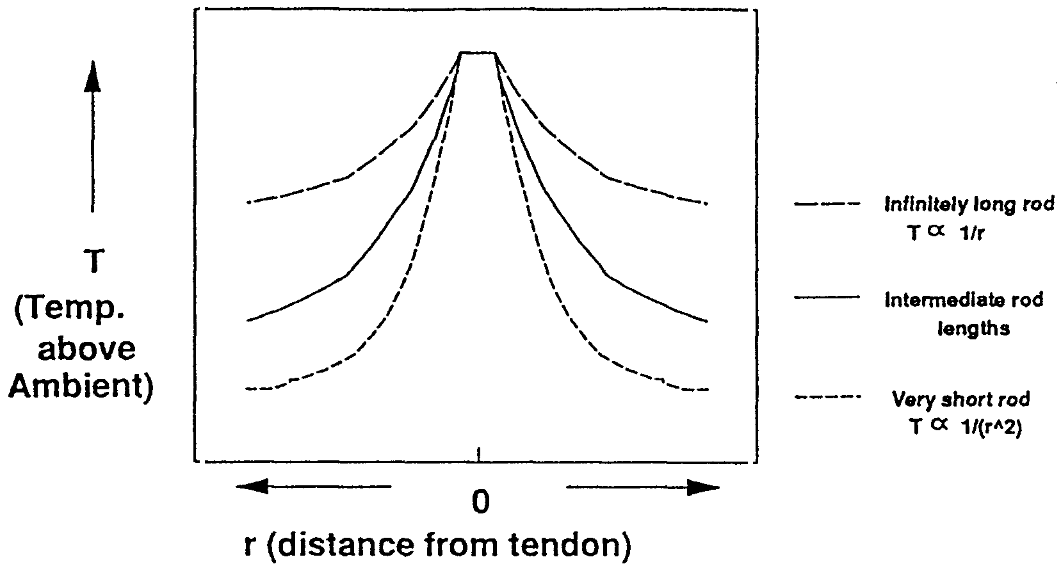

Figure 15. Sketch of temperature profile with distance (after Agnew [18])

Characteristics:

As with many of the techniques discussed, careful calibration would be required. A series of test tendons would need to be installed, covering the most important installation variations. These would have to be carefully measured and used for comparison purposes.

Shortcomings:

Agnew calculated that to use the two-dimensional temperature profile method on a 2 m tendon, assuming that it was necessary to be able to detect a temperature rise of at least 0,5 degrees Celsius on the rock surface at a distance of 2 m from the tendon, would require a heat source of at least 40 kW applied for a period of at least 10 minutes. Even if this calculation overestimates the required power source by an order of magnitude, this amount of energy would be impractical to apply underground and certainly would not be portable. In the one-dimensional method, the heat required would probably be significantly less, but the time required to make the measurement would be about the same.

The thermal effects of cracks in the rock, of mesh and lace or shotcrete, of tendons not installed perpendicular to the walls of the tunnel, and of variations in the ambient temperature of the tunnel during the measurement, could complicate the technique to the point of unusability.

Finally, the method cannot be considered non-intrusive as the high temperatures that would occur during testing, particularly near the exposed end of the tendon, could cause material property changes to the grout and/or damage the grout-steel bond. The "thermal shock" may destroy an effective tendon installation which is under significant stress.

Conclusion:

A thermal technique could conceivably provide the required information about tendon length and grouting effectiveness. To explore the concept further, it would probably be necessary to use computational finite element modeling (FEM) of the thermal system, and conduct a series of laboratory experiments on a scaled-down physical model of the system.

However, this is not recommended as the practical difficulties of the technique in the mine are too great. With improvements in technology, more sensitive temperature sensors could allow smaller amounts of heating power to be used, and together with more compact heat sources, the portability problem could conceivably be overcome. However, the temperature levels are still likely to be too high to prevent damage to the grout-steel bond. Also, the amount of time required for each measurement depends upon physical constants and is not likely to be reduced with advancing technology.

No other "special" techniques were identified, other than those which would require a modification to the design of the tendon or installation process (these are discussed in Chapter 5).

3.5 Concluding Remarks

A summary of all the techniques reviewed is presented in Table 4. From that list the following conclusions can be drawn:

- acoustic techniques can provide a closer fundamental link to the problem of grouting effectiveness, but are generally not good for shepherd's crooks or cable bolts;
- electromagnetic techniques are generally not troubled by shepherd's crooks or cable bolts, but can only at best provide an indirect measure of grouting effectiveness;

- there has not been a shortage of innovative ideas applied, looking at the problem from both the perspective of "tendon outwards" (most of the techniques) and "rock environment inwards" (Acoustic imaging, Ground penetrating radar, X-rays);

- the problem is a difficult one, and where success has been achieved, it has taken a great deal of time and effort.

Further to the last point, in retrospect it appears that at its termination, the COMRO, Wits and Mattek work had reached a stage (of being overwhelmed by the number of variables involved in the field problem, as opposed to the laboratory problem) that the Boltometer developers must have reached some time before. It is speculated that a further five years of dedicated development could have yielded an instrument of equivalent performance to the Boltometer, but better suited to the South African deep mining problem. On the other hand, the benefit of being able to learn fully from the Boltometer experience at the beginning of the South African effort, had this been possible, could have resulted in a solution with less effort than that already applied.

Table 4. RATED SUMMARY OF TECHNIQUES REVIEWED FOR TESTING TENDON GROUTING EFFECTIVENESS

Technique	Ref. (*)	Maturity (#)	Measure Length?	Measure Grout?	Penetration (m)	Shepherd's crooks? (+)	Cable (+) tendons?	Mesh, lace, washers? (+)	Remarks
Boltometer	3.2.1	Product - 10 years	Usually	Yes	1,5 - 5,0	No	No	Can cause problems	Closest to solution. No shepherd's crooks. Washers, lace, mesh sometimes a problem.
Mattek: CTFM	3.2.2	Abandoned	Sometimes	Not in practice	about 2,0	No	No	-	Too many spurious, unpredictable reflections to measure grout effectively.
Agnew: Pulse Attenuation	3.2.3	Lab tested	Usually	Don't know	about 2,0	Don't know	No	Don't know	Lab tests were reasonably promising, but much work still required to prove concept.
COMRO: Blow and Ring Down	3.2.4	Abandoned	No	Not in practice	-	-	-	-	Technique was fundamentally inadequate.
USBM: RBBT	3.2.5	Abandoned	No	Not consistently	about 3,0	Never tried	No	Don't know	Technique was also inadequate. Could not measure length.
USBM: Sonic Bolt Load	3.2.6	Product - 8 years	Yes	No	0,5 -2,4	Probably No	No	Probably Yes	Cannot measure grouting quality, but can measure bolt load and length.
Acoustic Imaging	3.2.7	Rejected	Probably Yes	Probably No	Anything - ideally	Yes	Yes - ideally	Yes - ideally	Never tried because serious problems predicted in penetrating cracks in rock.
AE/MS with Pull Test	3.2.7	New idea	Don't know	Don't know	Don't know	Probably Yes	Probably Yes	Probably Yes	New idea, still requires theoretical evaluation. Could be destructive.
Ground Penetrating Radar	3.3.1	Rejected	Probably Yes	Probably No	Depends on resolution	Yes	Yes	Mesh is a big problem	Never tried in practice because insufficient range / resolution predicted and poor angle.
Antenna	3.3.2	Lab tested	Usually	No	> 5,0 m	Yes	Yes	May be a problem	Technique is promising. Some questions must still be answered by experiment.
Inductance	3.3.3	Lab tested	Sometimes	No	about 3,0	Yes - with modifications	Yes - with modificat'ns	Probably a problem	Very sensitive to conditions near bolt outer end: impractical.
X-rays	3.3.4	New idea	Yes - ideally	Yes - ideally	Anything - ideally	Yes	Yes	Yes	Impractical because would need extra holes, high power and borehole X-ray transmitter?
RIMT	3.3.4	Under development?	Yes - presumably	Yes - presumably	Probably > 5,0 m	Don't know	Don't know	Don't know	No further information: was development abandoned?
Thermal	3.4	Rejected	Yes	Yes	Don't know	Yes	Yes	Probably a problem	High power heat source required, long test time, could damage grout bond.

NOTES: (*) Refer to section of this report.

(#) Maturity: how far has this technique been developed?

Abandoned	= development abandoned after lab and field tests
Rejected	= concept rejected after theoretical evaluation
New idea	= not yet thoroughly evaluated theoretically.

(+) Would the technique work with shepherd's crooks, cable tendons, and mesh, lace and washers?

4 ASSESSMENT OF THE POSSIBILITY OF IMPROVING EXISTING DEVELOPMENTS

The most promising of the techniques or developments reviewed in Chapter 3 are judged according to two criteria; their closeness at present to an acceptable solution to the problem defined in Chapter 2, and their amenability to further improvement. Referring to Table 4, the following are the techniques judged worthy of further consideration and the actions that could be taken in that regard, in order of most to least promising:

1. The Boltometer. This development is the nearest match to a solution. However, its scope for further development appears limited. See section 4.1.

2. RIMT. Further information should be obtained regarding the state of this development, which could potentially measure tendon length as well as grout quality in situ. The technique should first be assessed theoretically and then a judgement made on whether to proceed further.

3. The pulse attenuation method (Agnew). This development is still far from a solution, but showed some promise. By incorporating shear wave modes and focussing attention on the problem of coupling sufficient acoustic energy into and out of shepherd's crook tendons, a solution could possibly result. This would most likely require a few man-years of work and some significant experimental operating costs. Such a programme of work should take into account the possibility to save time and effort by working in collaboration with the developers of the Boltometer.

4. The US Bureau of Mines ultrasonic bolt load tester. This instrument can measure bolt length in short, pre-prepared tendons, but it cannot measure grout effectiveness. With suitable modifications, it *may* be able to measure the installed lengths of cement grouted bolts up to the desired 3 m length, without pre-installation preparation. In addition, its ability to measure load in-situ would be useful to geomechanics practitioners. Steblay, the leader of this development, has indicated his willingness to proceed with the development, subject to the availability of his time and the necessary equipment. An existing instrument could be tested on South African mines to assess its potential. The cost involved would probably amount to a few man-months of effort plus sub-contracting costs of a few tens of thousands of rands.

5. The antenna method. This technique could probably measure bolt lengths, but it cannot measure grout effectiveness. Further development and field testing would be required to assess whether it can indeed reliably measure tendon lengths. The cost and time required to do this would be of the same order as discussed in point 4 above.

6. Acoustic emission / microseismicity method. The principles of this potential technique have not yet been carefully thought through and tested for validity. A theoretical study of feasibility would be required.

7. X-rays. The possibility of scaling-down this technique so that it could provide a solution in South African mine conditions needs to be explored on paper, including the need for two nearby boreholes and a high-power X-ray source that can be mounted within a borehole.

The possibilities listed above should not be seen as the only ways to proceed. A great deal of progress could also be made by modifying the problem slightly, as discussed in Chapter 5.

4.1 Boltometer

In the course of this project, a representative of CSIR: Mining Technology visited Geodynamik AB in Sweden to discuss the Boltometer and its potential for development as a solution to the present problem. The following points can be made:

- Usability - the latest model of the instrument was demonstrated at an underground nuclear waste storage site near Stockholm. It was not difficult to use and seemed to be effective.

- Shepherd's crooks - Thurner at Geodynamik is fully aware of the benefits that would result if the Boltometer could test these tendons, and has been thinking about the problem for some time, but to date he does not see any possibilities for a solution.

- Inability to test grouted cables - it appears that no acoustic technique is likely to be suitable for these, because the multiple wires and air voids lead to an acoustic response that is too complex to make sense of.

- Inadequate penetration range with well-grouted bolts - it would be possible to increase the penetration somewhat, by improving the instrument's dynamic range.

- Highly fractured rock - it was learned that Geodynamik has little experience operating the Boltometer in highly fractured rock, but where it was tested in these conditions, the instrument did not appear to work very well.

- Applications - it was learned that the Boltometer is actively used in Chinese coal mines, and discussions were taking place with a view to having the instrument manufactured in China. If this went ahead, larger volumes of the instrument would be produced and the price would come down.

> Interest had also been expressed by the British coal mining industry in a possible intrinsically safe model; Geodynamik believes that intrinsic safety is quite feasible. However, the biggest market for the instrument in its present form is the civil (as opposed to mining) tunneling community, especially in Europe.

There is scope for improvement in the Boltometer, but this is not likely to solve the most important problem (shepherd's crooks). The most meaningful improvement that can be envisaged at this stage would be to increase the instrument's penetration range. This could be tackled by increasing the power or improving the coupling of the acoustic excitation source; and/or increasing the sensitivity of the echo sensor and its electronics. Other improvements that could be considered (although these have not been discussed in detail with Geodynamik) would relate to the interpretation of the Boltometer recordings and the reliability of tendon quality classification. For example, in Mattek's 1991 final report [19], suggestions were made for future work using a Boltometer-like approach. Improved interpretation and classification of readings could possibly be obtained by measuring the loss of each individual mode of shear wave propagation, or by applying neural network techniques to the problem. These suggestions were speculative, and it is not clear that they should be pursued.

However, the first requirement for assessing whether improvements to the Boltometer should be pursued, would be to test the existing instrument under local conditions. Only after such a test would it be possible to meaningfully plan any future development concerning the instrument.

5 CONCLUSION AND RECOMMENDATIONS

Concerning the problem of developing a technique for testing the effectiveness of grouted tendon installations in situ, the first aim of this project was to critically review past local and international research work, in an attempt to understand why the techniques contemplated did not achieve the desired result.

To achieve this it was considered necessary to first understand and define the problem clearly. It is believed that the material in Chapter 2 represents the most complete analysis of this problem, particularly as it applies to South African gold and platinum mines, that has yet been attempted. An obvious deficiency in the problem description is the lack of quantitative data to define the *extent* of tendon grouting quality problems in South African mines (this matter is discussed further below). From an engineering perspective, Section 2.4.1 and Table 2 list the technical requirements which should be met by any proposed solution technique.

The review itself, in Chapter 3, considered 14 techniques or potential techniques, as summarised in Table 4. The physical principles involved in these were mostly acoustic or electromagnetic. The acoustic principle offers promise in that sound waves are directly influenced by mechanical coupling, which lies at the heart of the problem of grouting effectiveness. On the other hand, acoustic techniques generally would experience difficulties with shepherd's crooks and cable tendons. In contrast, electromagnetic techniques could in principle measure the length of tendons of any construction; but the measurement of grouting effectiveness using these techniques, where possible at all, is indirect at best.

The techniques reviewed represent a variety of approaches to the problem; mostly "looking outwards" from the tendon towards the surrounding rock mass, but also "looking inwards" from the perspective of the surrounding rock. The latter approach embodies the imaging techniques such as acoustic or seismic imaging, ground penetrating radar, or X-rays. It is significant that to date no serious experimental efforts have been made to test imaging techniques on this problem - instead the techniques were all rejected on theoretical assessment because of the restricted geometrical access, and the high probability that fractures in the surrounding rock mass would interfere too much with data from the vicinity of the tendon itself.

None of the techniques reviewed represents a solution at present, although the Boltometer is nearest to one. It was apparent that partial successes, where achieved, had come at the price of much dedicated effort. A comment from Agnew [18] illustrates the challenge: "The main difficulty in the rock anchor tester problem is not creating the electronics and acoustics which give a detectable echo pulse. It is dealing with the *variety* (and variability) of conditions which occurs in mines". As described in Section

2.4.4, the number of variables that need to be taken into account is too large to permit measurement of all of these simultaneously, so to obtain meaningful results it is necessary to reduce the problem by controlling as many parameters as possible. Hence the approach to calibrate instruments against rock type, grout type, tendon type and length.

The second aim of the project was to assess the possibility of improving existing developments. Chapter 4 lists all the techniques reviewed that showed at least some promise of possible success, and the development approach that would be needed to take these techniques further. The order of the list reflects the authors' assessment of relative attractiveness.

In summary, none of these approaches offers the promise of a rapid solution. Whilst the Boltometer is nearest, it appears to offer no possibility for improvement in the area of most concern - the need to test shepherd's crooks. And, while the Boltometer offers promise for measuring straight bar tendons in South African gold and platinum mines, this must be tested before too much confidence is placed in even the basic capabilities of this instrument with respect to the present problem. Of particular concern is the question of how well the Boltometer can work in the highly fractured rock environment of the deeper mines.

All of the other techniques that could be pursued further (with the exception of the RIMT technique, where there is a need to obtain further information), either require extensive development or else represent a partial solution at best.

The final aim of this project was to recommend the most promising direction for future development that could finally lead to an acceptable method for measuring the quality of grouted tendon installations in situ.

The first recommendation arises from the assessment, namely to purchase a Boltometer and test it under local mining conditions. In its present form, the instrument promises useful application in mines where straight bar tendons are used. The test results would indicate whether, and in what way, any further improvement of the instrument should be considered. The Boltometer could also be used in coal mines, provided that the aforementioned non-spark method is used for preparing the tendon ends, and special exemption is obtained for each application[1].

Until such testing is done, it is not recommended to pursue any of the development approaches listed in chapter 4, other than to obtain further information on the potential of the "new" ideas mentioned in Chapter 3, such as RIMT or acoustic emission. Certainly it is not recommended to continue

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[1] Until such time as an intrinsically safe model of the instrument is produced.

development on any technique that would involve re-learning the lessons learned during the Boltometer's development.

The second recommendation arises from the finding that whilst the problem of inadequate grouted tendon installations is known to be significant, the extent of deficiencies is not well known. It is therefore recommended that a quantitative study is undertaken, where representative samples of installed tendons in gold and platinum mines are inspected by overcoring, in a similar way to the work performed by Thurner (see Appendix).

By modifying the statement of the problem slightly, it is possible to open a new way to proceed. If, instead of focussing on the need to *test existing* tendon installations, attention is rather focussed on the need to *improve future* tendon installations, a range of new possibilities present themselves - including the possibility of modifying the design of the tendon and installation process so that future grouted tendons become testable.

The third recommendation arises from this argument, namely to focus future research on improving the quality of future grouted tendon installations generally. This would require three distinct steps:

1. Identify the character and frequency of the quality problems - section 2.2.2 of this report makes a start by examining the types of problems that will be encountered, and the second recommendation above will address the remainder of this requirement.

2. Modify the design of the support system, the tendon, the grouting process, or all of these, in order to solve the most important quality problems encountered in the first step (this aspect is discussed further below).

3. Test the modified tendon and/or installation process to verify and quantify the quality improvement obtained. The Boltometer (if available - see first recommendation) could serve as a useful tool in this regard, because test installations could be designed in such a way as to ensure that the instrument is applicable.

To improve the quality of grouted tendon installations, a number of possible design or process modifications could be considered. For example, in terms of the type of tendon chosen, serious consideration should be given to unwaxed cone bolts, which only require good grouting at the inner end of the borehole to provide a guaranteed end-anchored tendon, at least. The quality of the grouting in the rest of the hole could then be considered as a bonus to provide the full column grouted property. In addition, every tenth or so cone bolt could be of the straight bar variety, which would be suitable for grout quality testing using the Boltometer, in favourable rock conditions.

But, assuming that grouting system manufacturers cannot radically improve the effectiveness of the grout emplacement process itself, perhaps the most striking improvements could be made by modifying the grouted tendon system design, in such a way that the condition of the grout can be inspected immediately after installation (and preferably also periodically thereafter). In this way, grouting quality problems could be detected and rectified before the support installation crew leaves the site.

This "design for testability" consideration should be an important part of any quality improvement project for grouted tendons, because even if the installation quality can be assured as optimum, the tendons will still be subject to deterioration over time. The ability to test the continuing effectiveness of the tendons after installation would allow tendons that have been damaged by fracture dilation or shear, resulting in possible corrosion or breaks, to be detected and replaced before a rock fall occurs.

There are a number of ways to design a grouted tendon so that it is easily testable; the chief difficulty being to keep the cost of the tendon down to a level which is acceptable. Some ideas from Agnew [18] include:

- using a hollow tendon of some kind (a small axial hole would permit the use of acoustic or other instruments which could measure the bond along the entire length of the tendon from the inside);
- using an "indicator wire" which runs along the length of the tendon and changes its properties depending upon whether it is covered with grout or not;
- fitting some device to the inner end of the tendon which aids in the detection of an end-echo by instruments such as the Boltometer.

As an example of the principle in a related field, Franke and Meyer [32] describe the use of copper wire sensors integrated into glass-fibre reinforced polymer (GRP) tendons used in reinforced concrete. By measuring the capacitance between the wires, breaks in the tendon can be detected and located, tendon elongation can be measured, and even water ingress can be detected (unfortunately this method is not applicable to steel tendons).

To conclude, admittedly the main approach recommended above does not satisfactorily address the need to screen the millions of grouted tendons already installed, in order to detect those that are ineffective. But it would address what should be done about those defective tendons, once they are discovered.

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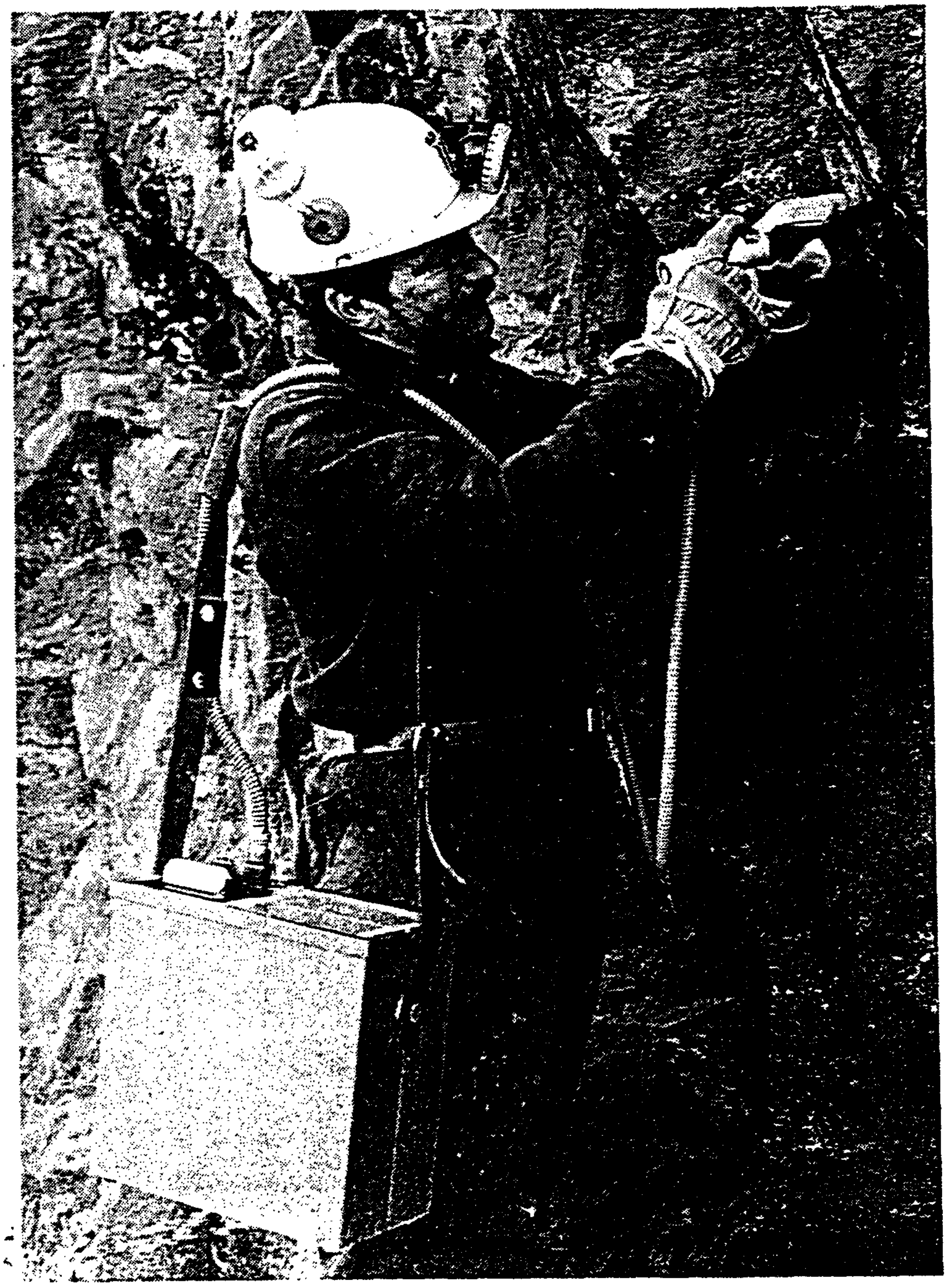
ROCK BOLTING - REFERENCE BANK

AMFO 84-0847
Final Report

Translated from the Swedish by B C Baur & Associates,
courtesy of CSIR : Division of Mining Technology, South Africa
Johannesburg, February 1996



Stockholm, February 1994

GEODYNAMIK AB

ROCK BOLTING - REFERENCE BANK

PREFACE

This report concludes ASF/AMFO project "Rock bolt - reference bank" and constitutes simultaneously a summary relating to the development of the Boltometer: the testing instrument for non-destructive testing of cement grouted rock bolts in-situ.

The primary purpose of project "Rock bolt - reference bank" was to increase the reliability of gauging the signal by defining the reasons for part echoes. The work on the project mainly comprised a comparison between recorded signals and rock bolts that were overcored or in some other way exposed.

For this purpose a large number of Boltometer signals were collected from logged bore hole cores and similar observations in a reference bank at KTH*. The result of these comparisons form the foundation for a simple "Gauging Bible". The reference bank at KTH was simultaneously intended as a generally accessible data bank where results from the Boltometer readings and borehole cores could be stored, analysed and statistically compared.

Geodynamik has during and after the project's development, at it's own cost, further developed the instrument's hard- and soft ware. Amongst other things the instrument has been modified for transferring of measured data to a PC and software has been developed for analysis and presentation of measured data on a PC.

Stockholm, February 1994
GEODYNAMIK

Heinz Thurner

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*Kungliga Tekniska Högskolan I Stockholm (Royal Technical University of Stockholm)

SUMMARY (Provided in English)

The Boltometer, an instrument for non-destructive testing of grouted rock bolts, has been in use since 1979. Comparative tests carried out under different conditions have made valuable contributions to the improvement of the instrument and a better understanding of bolting techniques in general. The instrument allows us to look into the rock and to detect otherwise invisible faults in the grouting and/or on the bolt stem.

The instrument provides access to two levels of information: either a quick estimation of the bolt function (insufficient, poor or good) on the LCD-display or documentation of the bolt conditions on the built-in printer unit. The documentation can be used for a more specific study of different wave echoes or be saved until a new measurement is taken, allowing comparison of the bolt condition on different occasions.

Contractors can now check rock bolting work as it is completed and provide the customer with evidence of a job well done. Now that unsatisfactorily grouted bolts can be detected, both the contractor and his customer can easily test the performance of the rock bolts installed.

Many customers wish to have new bolting work independently checked after it has been completed, besides have older bolting of unknown reliability monitored. This represents a vast new field for engineering consultants who can put the Boltometer to work providing a rock bolt quality-control service.

With a Boltometer at hand, underground workers have the chance to monitor and maintain the safety of their own working environment.

Field tests indicate there is a large discrepancy between the intended bolt product and the actual in-situ result, this gap can now be closed. The Boltometer will contribute to the evolution of improved bolts and bolting techniques. Manufacturers of rock bolts and bolt setting equipment can now check the performance of their products, detect any systematic faults, and determine which bolting method is best.

Finally, it must be stressed that the Boltometer is mainly designed to discover grouted rock bolts with insufficient function and not to specify bolts in good or perfect condition. This may limit the range of the instrument to a certain length of a well-grouted bolt. A fault will not be detected if it occurs on the inner part of a bolt with a certain length of perfect grouting.

SUMMARY (From the Swedish)

The Boltometer - an instrument for non-destructive testing of rock bolts *in situ* has been in use since 1979. Over this period valuable knowledge has been accumulated through both pure research projects and through practical measurements in mines and tunnels through rocks. Within the scope of the present project different bolts have been tested with the Boltometer after which they have been exposed or overcored. The comparison between the signals and the logging of the bolts, attachment and the surrounding rock formation has been accumulated in the reference bank. Results from the reference bank and Geodynamik's other experiences from measurements in different countries has formed the base for an interpretation "bible" and a number of general conclusions.

Based on this the project steering committee has arrived at the following, major conclusions:

- an unexpectedly large number of tested bolts show a signal which indicates defective function, i.e. that the grouting is considerably inferior to that expected;
- the aim of the Boltometer should be the detection of unsatisfactory bolts;
- a standardisation of the Boltometer as well as general gauging criteria will increase the instrument's reliability;
- a slight improvement in the bolting technique can increase its security considerably.

This means that the contractor can immediately check the function of the bolts and provide the client with proof of a satisfactory job. At the same time the contractor will quickly discover any systematic faults in the bolt installation technique and thus be able to take necessary preventative steps whilst work is in process.

The consultant can investigate and document both old and newly placed bolts and thus be able to issue a "quality assurance certificate".

All underground workers can now personally check safety in their work places.

Finally the manufacturers of bolt aggregate and bolt parts can test the function and reliability of their products, adapt them to different circumstances and furthermore, in an easier way, be able to demonstrate the function of the products to the user.

OBJECTIVE OF PROJECT

The main aim of the ASF project was partly to increase the safety of underground workers and partly to improve underground rock bolting work by:

- identifying poorly operative bolts in place of usage;
- revealing any systematic errors in the bolt installation technique;
- making underground workers aware of the fact that a test method exists - which should automatically promote better workmanship.

Furthermore the project aimed at improving the "Boltometer"' an instrument for non-destructive testing of rock bolts. The Boltometer was originally designed for the testing of loose fitting cement grouted bolts in-situ. During the operation of the project attempts were also made to use the instrument for the testing of other types of rock bolts, such as polyester grouted bolts, epoxy grouted bolts, Swellex and expanding bolts.

The "reference bank" portion of the project was primarily aimed at increasing the accuracy of the signal interpretation by defining the reason for the part-echo. The work of the project was therefore mainly concerned with a comparison between recorded signals and inspection of rock bolts that had been overcored or released by some other method, so as to be able to determine whether the part echo was caused by the bolt's bottom end, damage to the bolt, damage to the grouting or cracks in the surrounding rocks.

HISTORY

Rockfall is still the largest safety hazard in Swedish mines - in spite of extensive advances within the fields of e.g. bolting and gunniting.

In 1977 Norbert Krauland of Boliden Mineral AB put forward a request that Geodynamik AB should develop a process for testing of cement grouted rock bolts *in situ*. The idea was then to make use of Geodynamik AB's know-how within the seismic field to measure/test the effectiveness of bolts or bolt fixings.

After certain initial studies of different principles for generating shock waves in the bolts, basic research work was first carried out during 1077/78 followed by practical efforts with support from the Directorate of Technical Development (STU, now NUTEK) and the Workers Protection Directorate (ASS) to develop a suitable method to test rock bolts. In 1978 a patent application was made on a principle which since has formed the basis for the test method - i.e. the Boltometer principle.

In 1978 a notice of request was, for the first time, received from the Workers Protection Foundation (ASF now AMFO), simultaneously as a steering committee was established consisting of S.G.A. Bergman (BeFo), Sune Granström (Tyrens) and Lars Corp (Workers Protection Directorate).

During the year 1981-1983 the first test instruments were developed and manufactured under the name of "Boltometer Model 002." ASF's large project steering committee was started in 1982 in conjunction with a renewed notice of request which over the years included representatives of:

- Worker's Protection Foundation;
- Worker's Protection Directorate;
- Atlas Copco;
- BeFo;
- Boliden Mineral AB;
- Engineering Administration;
- GRAMCO;
- Hagconsult AB;
- University College of Otnäs, Finland;
- Royal Technical University of Stockholm (KTH),

- LKAB
- Stockholm's Street Planning Office;
- Swedish Mine Workers Union;
- Vattenfall.

During 1984/85 an improved version of the instrument was produced: "Boltometer model 011"

In 1985/86 the reference bank at KTH was started where the results from the controlled measurements on test and production bolts were stored together with samples from drilled-out or exposed bolts.

In 1991 the Boltometer measurements were introduced as an official testing method for subterranean constructions in Saudi Arabia. In conjunction with this the latest model "Boltometer model 011-S" was developed which can be attached to a PC for storing and analysing measurement data.

In connection with the specification for the tunnel work on the Grödinge railway it was stipulated by the Railways Department that the bolts in the Grödinge railway tunnels should be tested with the aid of the Boltometer. The test measurements were carried out by BERGAB.

PRINCIPLE

The principle pertaining to the Boltometer is quite simple. One transfers well defined elastic waves to the outer end of the bolt which propagate along the bolt and reflect off its inner end to return to the outer end of the bolt. In its forward and backwards passage through the bolt the waves are influenced by the bolt itself, but also by the grouting and to a certain extent by the surrounding rock.

To produce and couple these waves piezo-electrical crystals are used. These crystals consist of a ceramic material which, for this purpose, has suitable qualities: if one applies a voltage to the crystal the crystal expands proportionately to the electrical voltage. If pressure is applied to the crystal the material emits an electrical charge which can be utilised in measuring the distribution of pressure.

Elastic waves created with the help of these crystals can be of different types. In the simplest case the pressure wave is generated over the complete cross sectional area of the bolt and thus transmits itself as a so called compression wave (Compwave) concentrically through the bolt (Fig. 1). A "Flexural wave" is created by each half of the bolt being influenced individually and following one another (Fig 2).

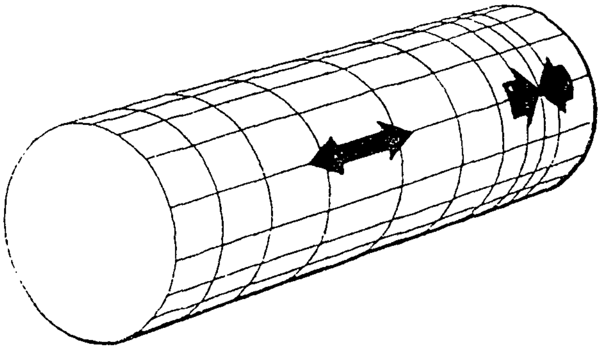

Figure 1 Compressional wave

By measuring the difference in time between generating the wave and receiving the reflected wave, the length of the bolt can be calculated, provided that the speed of the respective wave is known.

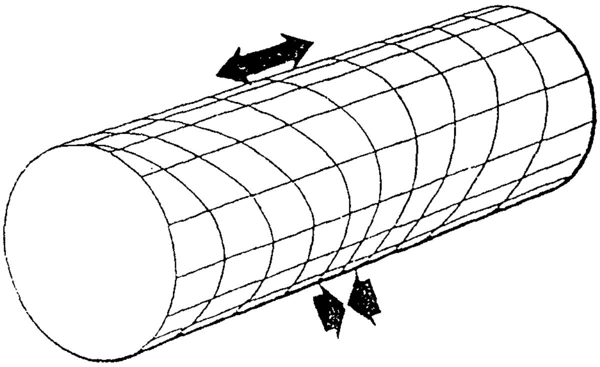

Figure 2 Flexural wave

If one analyses the time signature in the waves which have passed through the bolt and which have been recorded or registered from the bolts outer end one finds that the waves are influenced in different ways all relative to the condition of the bolt, the grout and the rock. In an undamaged well grouted bolt (Fig. 3) a great deal of the wave's energy is emitted to the surrounding rock because the contact with the rock is very good. Hence on the recording of the reflected wave a very small "echo" or no "echo" at all may be had from the inner end of the bolt.

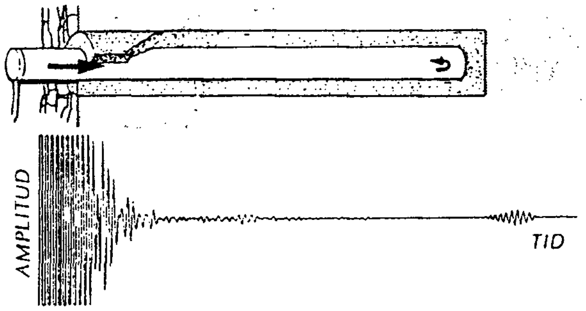

Figure 3 Undamaged well grouted bolt

If the grouting is of poor quality or if the grouting along a portion of the bolt is missing (Fig. 4) the wave's energy is less damped, resulting in a stronger echo.

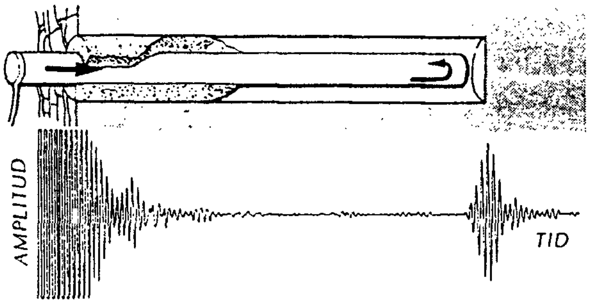

Figure 4 Defective grouting

The size of the echo (signal amplitude) thereby indicates the bolt's quality: a small echo = good quality; large echo = poor quality.

Damage to the bolt, i.e. a crack, rust formation or a heavy bending (Fig. 5) will create a partial echo which depending on the extent of the damage, can be distinguished more or less clearly in the measured signal.

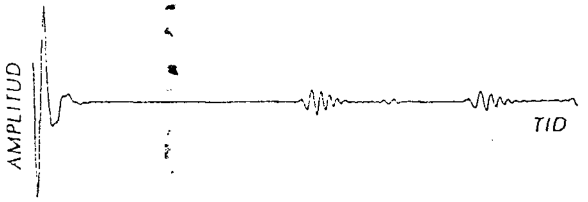

Figure 5 Defective bolt

The limit of the method is related to the penetration ability of the waves. 50 cm of satisfactory cement grouting will suffice to completely dampen the Compwave's energy. This means that a bolt which is grouted to > 50 cm will normally not give a Compwave echo from the bolt's bottom end.

The Flexwave, however, has a considerably larger penetration ability and can, depending on the type and quality of the grouting, make a penetration of 1,5 - 5 m through the cement grout.

The Boltometer's partially restricted penetration ability results in amongst other things that it can be difficult or impossible to differentiate between certain bolts that have been well grouted and others that have a reduced grouting quality.

The advantage of the method is the possibility of a quick, effective and reliable way of identifying bolts which have been poorly grouted, or damaged bolts, within restricted bolt lengths.

MEASURING EQUIPMENT

The Boltometer consists of the following main components:

- sensor;
- main control box;
- supporting equipment.

The sensor contains several piezo-electrical crystals (divided into 4 sections), four light-emitting diodes (which indicate contact between the end of the bolt and the four different sectors of the sensor) as well as a push button for starting the measuring procedure.

The main control box consists of a panel, electronics for generating, receiving and analysing the signals, as well as rechargeable batteries.

The first Boltometer (model 002, Fig. 6) only showed the length of the bolt and an indication of its class. The instrument could however be provided with a mini-oscilloscope for a more detailed study of the measured signal trace. For recording the complete signal trace one could either attach a special printer or a separate memory oscilloscope with computer diskette drive.

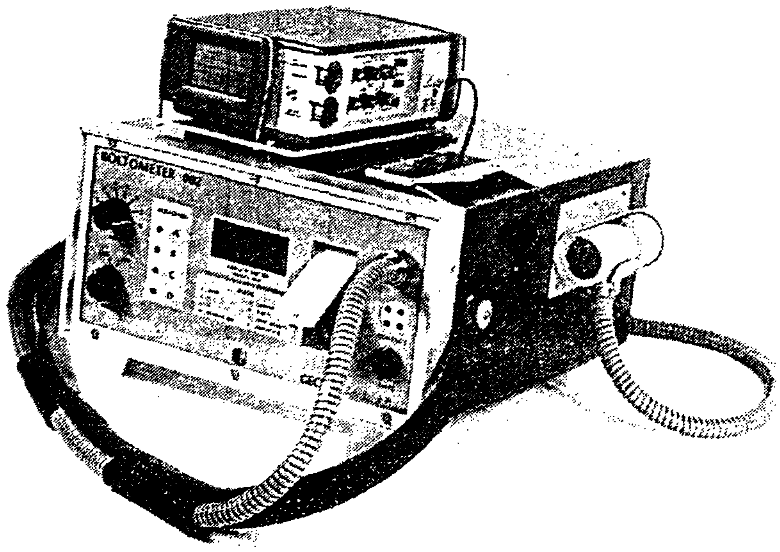

Figure 6 Boltmeter model 002

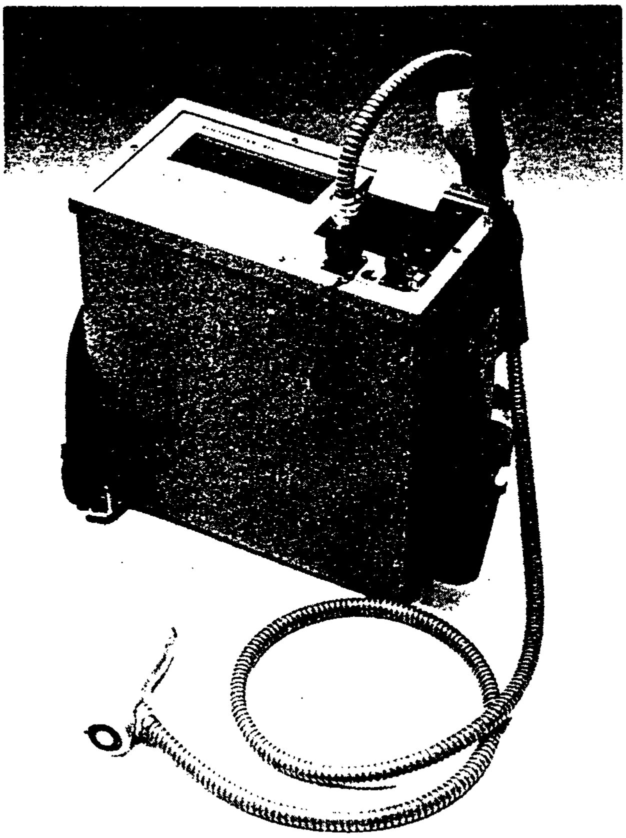

Figure 7 Boltometer model 011

Figure 7 shows the next Boltometer model (model 011) which was improved in some important ways:

- the signal is shown for both types of waves on a built-in LCD;
- all parameter adjustment is carried out through software via commands from the keyboard on the instrument panel;
- the signals can be hard-copied directly on a built-in matrix printer;
- the sensor cable has been fitted with a connector which allows for exchange of the sensor, and also allows for a possible extension of the sensor cable.

So as to receive the best possible quality of the signal, the outer end of the bolt must have a plane surface (see Fig. 8).

Finally the quality of the signal has been improved considerably:

- clearer signal (better signal/background noise)
- possibility of measuring on shorter bolts (the duration of the excitation signal has been reduced)
- the original signal in the Boltometer can be amplified 5 times, and it can furthermore - with the aid of an external adaptor - dampen the signal 50 times.

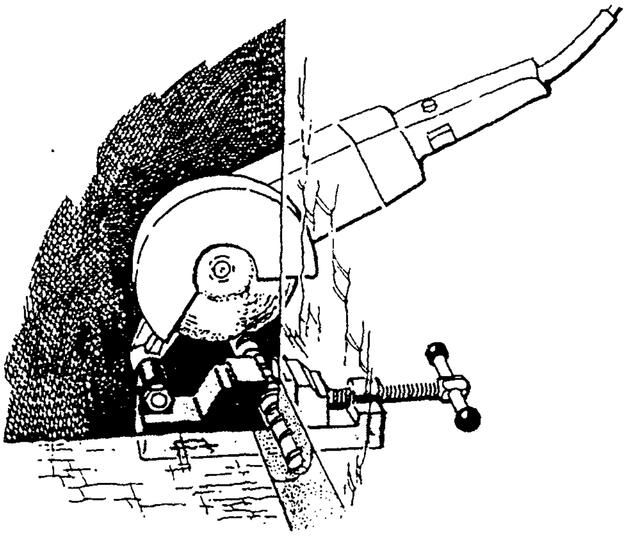

Figure 8 Cutting/grinding machine

REFERENCE BOLTS

When a Boltometer is delivered certain parameters (principally the Compwave and Flexwave seismic velocity and pulse frequency) are preset by means of the pre-delivery test applied to each instrument. The pre-delivery test is carried out on approximately 2 m long bolts of rebar with a diameter of 25 mm cement grouted into 38 mm diameter boreholes drilled into fairly solid granite.

Should the instrument be used under deviating circumstances - i.e. with smaller or larger bolts and/or borehole diameters, poorer rock or alternative grouting material - the preset parameters may need to be adjusted relative to existing conditions. This is done simply and most reliably with the aid of reference bolts.

The aim of the reference bolt is to determine under existing conditions in certain mine or underground works:

1. The measurement range of the Boltometer (penetration ability)
2. Classification limits for relative area of investigation.

For this purpose one should select from the works a suitable rock area of average quality with respect to frequency of cracks etc: within this section of the rock a number of holes are drilled using standard drill equipment and having a variety of lengths (1,0-2,5 m increasing by 0,25 m for bolt lengths of approximately 2,0 m). It is suggested that two holes are drilled of each length together with four extra holes of standard length. One of every two holes are drilled downwards at an angle.

A standard bolt is fixed into each hole drilled (standard diameter, standard drill equipment, cement grouting with standard water/cement ratio). The above mentioned four extra holes are intended for bolts with only 40 cm depth of grouting from the surface of the rock. This simulated inferior grouting is achieved by either placing a manchett around the bolt or by filling the inner portion of the hole with Styrofoam.

All bolts are chopped off 10 cm outside the rock surface: the exact length of each bolt is noted. If the cutting off does not finish off in an absolutely level plane the end of the bolt is ground flat.

If required a number of special test bolts are placed as follows:

- bolt with machine lathed groove (10 mm wide and 1 mm deep).
- bolt with machine lathed groove (10 mm wide and 3 mm deep).
- bolt with thread, washer and nut, if such bolts are used.

The reference bolts used are then tested and the signals are printed out as shown in the following.

CALIBRATING OF THE BOLTOMETER

Before the Boltometer is put into use one follows the schedule "starting up the instrument" according to the manual. The instrument's internal clock and calendar etc are then adjusted accordingly.

The first step in adapting the Boltometer to conditions which differ from conditions as tested on delivery (see chapter on "Reference Bolts") is the calibration of the instrument. For this purpose one of the reference bolts is chosen with a minimum length of 1,5 m and well grouted.

The velocity of the two types of waves are preset at the factory according to the following:

- Flexwave 3 000 m/s
- Compwave 4 520 m/s

A measurement is carried out on the bolt and the indicated bolt length is read either on the display or on the printout ("Indicated length of bolt" achieved by extending the front portion of the end echo to the zero-line).

The correct Flexwave velocity is obtained as the actual length of the bolt divided by the measured length of the bolt multiplied by the set Flexwave speed. The Flexwave speed previously set in the Boltometer is then corrected and a check measurement is carried out.

To adjust the Compwave velocity a check measurement is carried out on a well grouted bolt, with a total grout length of < 0,5 m. Correcting the Compwave speed is then carried out similarly to correcting the Flexwave speed.

On delivery the Boltometer's pulse frequencies are preset as follows:

- Flexwave 30 kHz
- Compwave 50 kHz

To adapt the Boltometer's pulse frequency to existing conditions a number of measurements are carried out with varying frequencies for both types of waves (Flexwave: from 20 kHz, Compwave: from 40 kHz).

On a reference bolt of known length (> 1,5 m) a number of test measurements are carried out with the sensor in different positions (twisted around the central axis until the largest possible end echo has been achieved). The signals are printed out, and a note is made of the amplitude of the largest end echo for each frequency. Increase the frequency for both types of waves by 4 kHz until the maximum frequency has been achieved (Flexwave: 40 kHz, Compwave: 60 kHz).

The largest end echo for the respective type of wave gives the optimum pulse frequency for this type of wave. After adjustment of optimum frequency for both types of waves, a check measurement is carried out.

In order to create boundaries for the different classes of function, all the reference bolts are documented in accordance with above instructions for optimising the measured signal. The maximum measuring length of the instrument - i.e. longest measurable grout length - corresponds to the length of the reference bolt with the smallest Flexwave echo. If cement grout with a low water/cement ratio is used it is possible that a maximum measuring length must be interpolated from measurement of different reference bolts. If cement grout with a high water/cement ratio is used it could happen that the maximum length must be extrapolated using the signals from reference bolts, i.e. the ability to penetrate can be greater than the length of the reference bolts.

The dividing line between Class A and Class B is created by making the limiting line 1 for the Flexwave slightly higher than that of the Flexwave echo from the bolt end for the bolt which corresponds with local requirements for "well grouted bolt". If the Flex-wave-echo is missing from all the reference bolts the limiting line 1 is raised slightly higher than the background noise. If the longest reference bolt produces an echo which corresponds with the bolt's correct length the limiting line 1 is raised slightly higher than this echo. A reference bolt should always be available which is slightly longer than the standard bolt so that one is able to interpolate the amplitude of the end echo for the standard bolt.

The limiting line between Class B and Class C is created by placing the limiting line 2 for the Flexwave at a position which corresponds to the position of the limiting line 1 plus 50%.

The limiting line between Class C and Class D is created by placing the limiting line for the Compwave at a position which corresponds to the Compwave echo for a bolt having less than 30 cm of good grouting.

For shorter bolts the position of the limiting line must be programmed according to a special procedure. Note that the limiting lines are only disclosed in the case of amplification/attenuation ratio 1:1.

MEASURING IN THE FIELD

A test measurement of a certain rock bolt can be carried out in two different ways:

1. Quick estimation, where the intention is to determine as soon as possible whether the bolt in question is damaged or has defective grouting (primarily along the outer part)
2. Comprehensive testing, where the intention is to document the bolt installation as accurately as possible.

For quick estimation it suffices to hold the sensor only once against the plane outer end of the bolt and estimate the function and/or length of the bolt by either using the reading from the "bolt class" meter (A = satisfactory function, B = reduced, C = defective, D = insufficient) or by roughly estimating the signal on the LCD display (no echo = satisfactory function, occasional echo = defective, several powerful echoes = insufficient function).

In comprehensive testing, one follows and more conclusive measuring procedure in order to obtain more accurate results. To begin with an optimal contact must be created between the sensor and the bolt end; i.e. the bolt end must be carefully levelled by cutting or grinding and a certain amount of contact paste or acoustic gel applied. Secondly the optimum measuring signals should be attained by repeated measurements with the sensor in different positions as per following.

At the start of the measurement process the largest signal amplification ratio is set on the LCD display, i.e. 5:1. Thereafter one presses the sensor gently against the end of the bolt and centres with the aid of the four sensor LEDs (representing the four sectors of the sensor). When all four diodes are lit an automatic measurement is recorded. If no echoes are discernible on either the Flex- or Compwave signal the sensor is turned 30 degrees and the measurement is repeated. If the sensor has been turned to five different positions with amplification of 5:1 and no echo has been observed, the grouting of the bolt is of good quality and one may assume that no damage has occurred to the bolt or the grouting, throughout the length of the bolt which corresponds to the maximum measuring length (according to the reference bolts).

If an echo can be detected on either of the signals one endeavours to get the highest possible echo in the Flexwave signal by using the sensor to measure in different positions (turning at 30 degrees at a time). Document the signal with the highest Flexwave echo on the printer.

Strong and frequent Flexwave echoes often indicate poor grouting of the bolt in question. If the total complete grouting length is less than 50 cm a Compwave end echo can most likely be observed. In such cases one should try to measure and record the largest possible Compwave end echo.

THE "GAUGING BIBLE"

The main aim of the project in question was to increase the reliability in signal gauging by defining the reasons for the part echo. For this purpose a large number of documented signal recordings were compared with samples from overcored or exposed bolts. The results of these comparisons - together with experiences from earlier investigated bolts (with known grouting conditions) - form the basis for the "Gauging Bible" as shown below.

After the completion of each measurement the signal results are tabulated for both the Flex and Comp waves in the Boltometer's internal memory and are shown in the display panel (LCD display), see Fig. 9. Signal results may also be printed out on the internal matrix printer, see the example in Fig. 10, or be transferred to an external data memory storage unit (for later analysis and/or documentation).

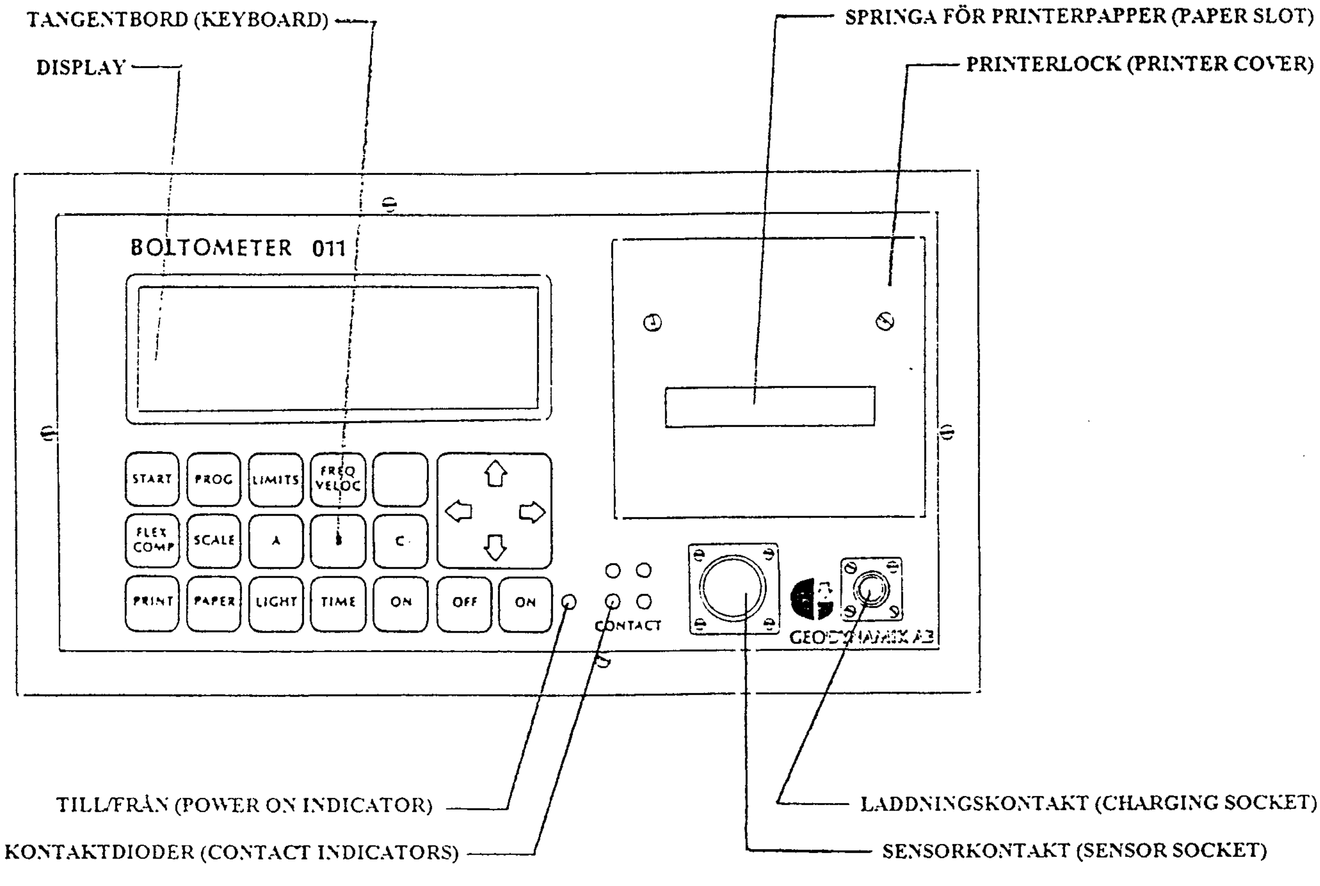

Figure 9 Boltometer front panel

Signal results are shown in the form of a graph (rectified signal) as per Fig. 10 onward. The vertical axis of the graph shows the signal amplitude from 0-255 (dimensionless units). The horizontal axis shows the bolt length in metres. (The seismic time interval has been recalculated to metres using the preset seismic velocity for the respective wave type.) During each measurement one recording is made for the Compwave and one for the Flexwave. Adjacent to the signal results the date and time of the measurement, contact test, class of bolt and the distance measuring internal (0-4, 1-5, 2-6, etc.) are tabulated.

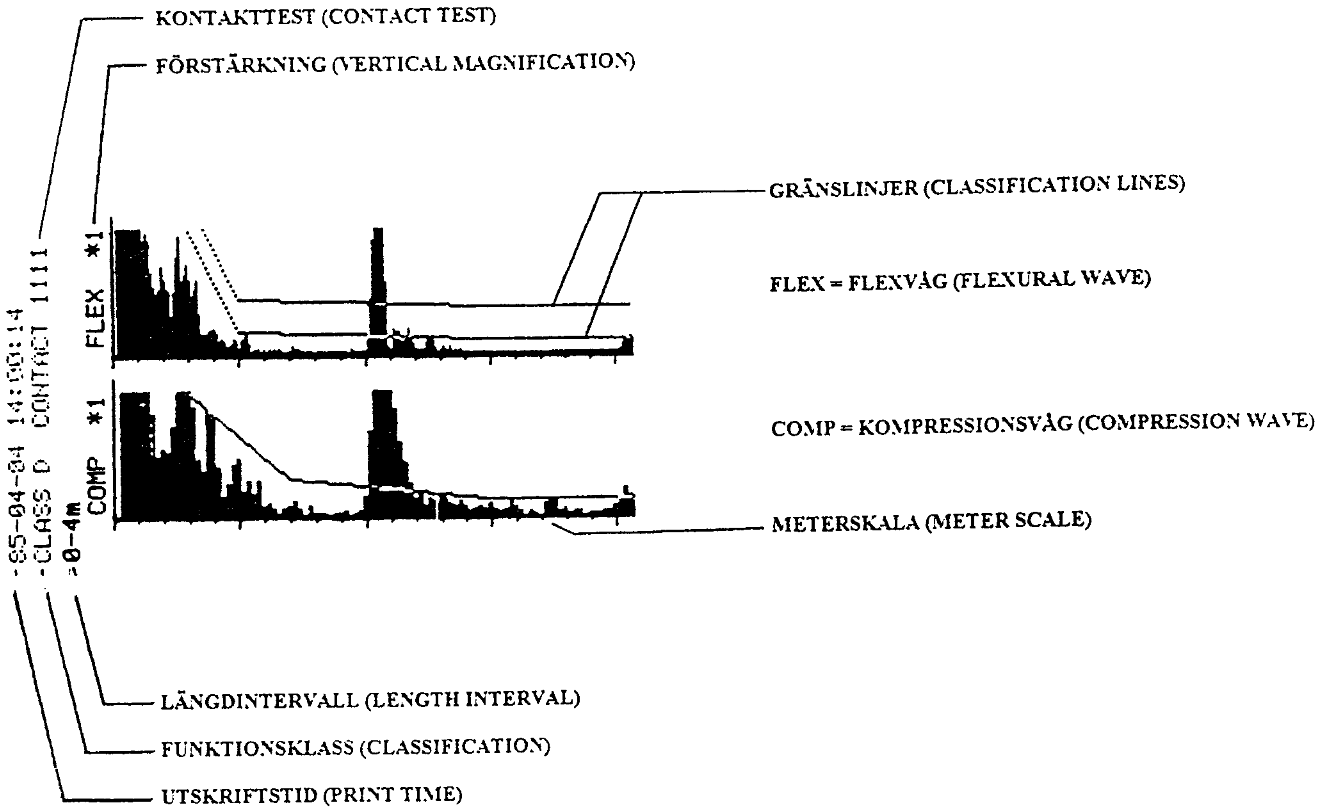

Figure 10 Hard copy from Boltometer printer

Fig. 11 shows the signal results from a 4,8 m long bolt of very high quality (signal results from the reference bank, plotted after storage on an external data memory machine).

The first part of the signal reproduces the signal transferred to the bolt (excitation signal, overdriven) caused by the fact that the receiving crystals in the sensor are influenced when the respective measured wave passes the sensor. After this partial transmit signal the actual received signal follows which in Fig. 11 shows only some minimal part echoes in the beginning, after which the signal consists only of background noise.

The signal results in Fig. 11 represents a bolt of such high quality that the Boltometer's total measuring energy is transferred to the surrounding rocks, leaving no echoes whatsoever from the bolt's bottom end.

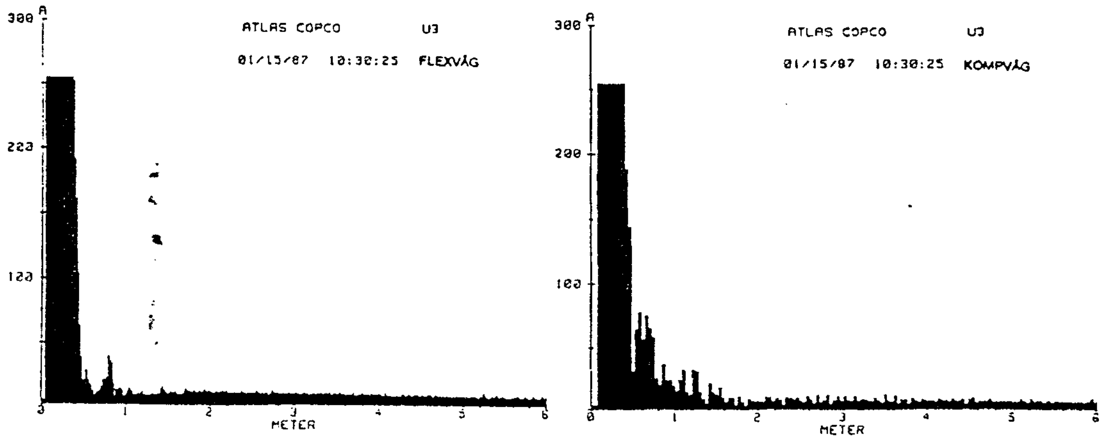

Figure 11 Signal from a high quality bolt

Fig. 12 shows the opposite, namely the signal results from a bolt with very poor quality.

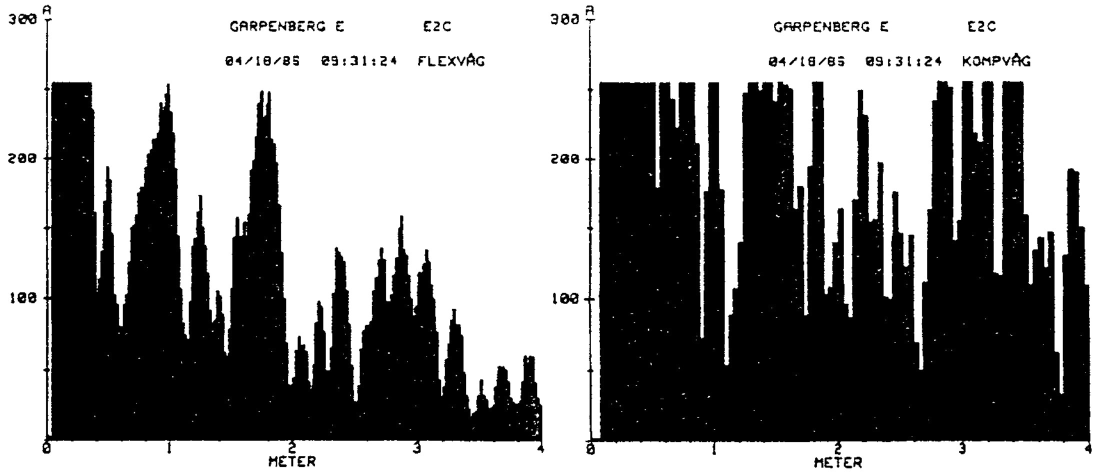

Figure 12 Signal from a badly grouted bolt

The results for both types of waves show strong (overdriven) part echoes. The grouting of this bolt is very defective, on the verge of disintegration. Part echo is possibly caused by:

- the grouting starting approximately 50 cm from the bolt's outer end;
- fragments from the grouting and/or
- damage to the actual bolt.

Because of the inferior quality of the bolt which, amongst other things, creates multiple echoes, it is very difficult to gauge the length of the bolt. A bolt with such a signal can often be loosened, especially if one hits the outer end of the bolt with a sledge hammer.

The bolt in Fig. 13 is 1,5 m long and cement grouted throughout its total length. Because of the good grouting no echo is received in the Compwave signal. In the Flexwave signal however the end echo is very distinct even if its amplitude is considerably lower than that of the bolt in Fig. 12. The part echo prior to the end echo is caused by a crack in the rock approximately 1,2 m from the bolt's outer end (seen by overcoring). The reason for part echoes beyond the end echo is unknown; these could have been caused by the transmission of the wave from the bolt across the grouting to the bottom of the drilled hole.

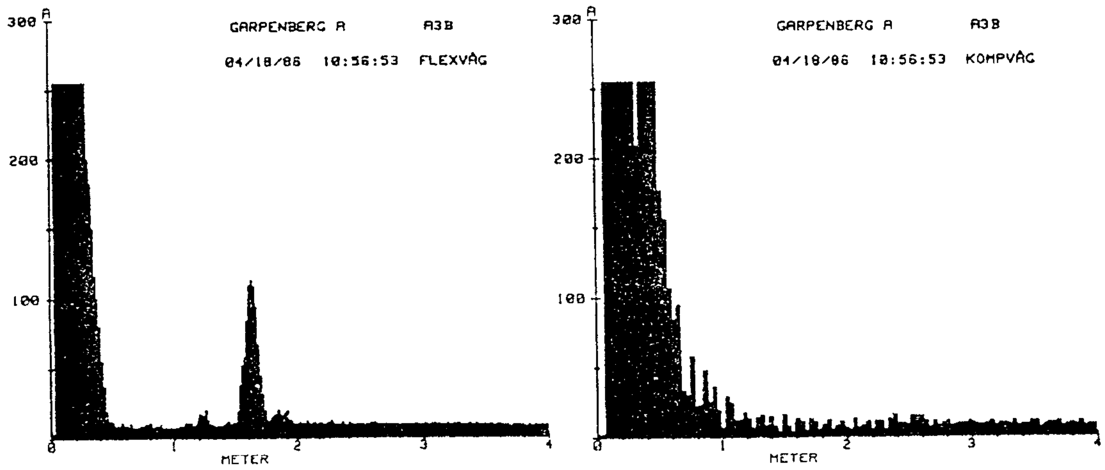

Figure 13 Signal from a 1,5 m long well grouted bolt

The signals in Fig. 14 show a 2,0 m long bolt with satisfactory cement grouting for an approximate distance of 20 cm (Test bolt in Atlas Copco mine at Nacka).

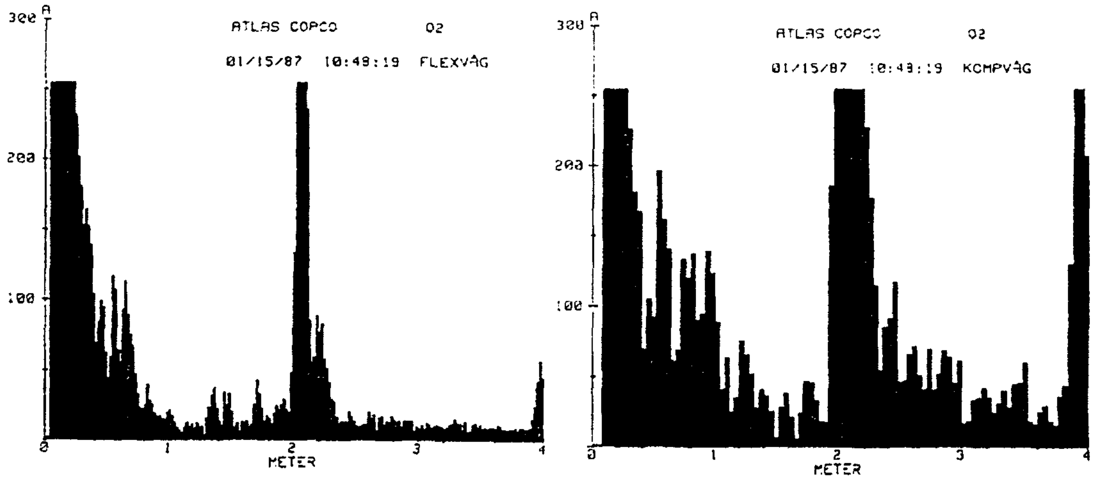

Figure 14 Signal from a 20 cm grouted bolt

The short grouting signifies that a large part of both types of wave energy is reflected from the bolt's inner end, sufficient to reveal a further echo (the end echo at 2,0 m has a multiple at 4,0 m). This bolt cannot be loosened and a pull-test with a jack will prove excellent bearing strength of the bolt (20 cm good grouting of a rebar bolt is sufficient to support a 16 ton tensile force: with more force the bolt will break on the outside of the rock face).

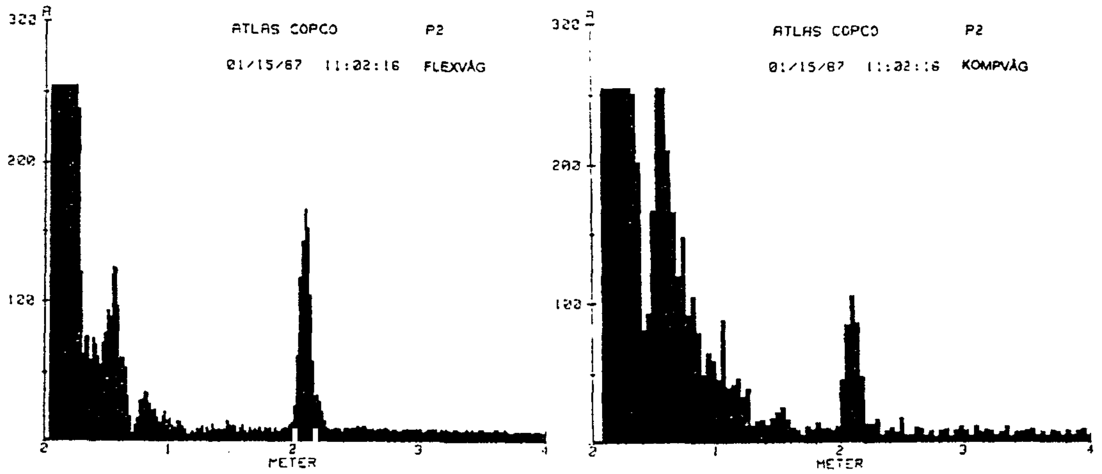

Figure 15 Signal from a 40 cm grouted bolt

In Fig. 15 the signal results are shown from a 2,0 m long bolt with 40 cm of satisfactory cement grouting (test bolt, Atlas Copco mine at Nacka).

The Flexwave still gives a strong end echo with a small multiple. On the other hand the end echo from the Compwave is significantly smaller. The echo at 0,4 m in the Compwave result is derived from the start of the grouting which is located 40 cm from the outer end of the bolt. The echo at 3,0 m (?) is caused by the fact that the strong Flexwave cuts in (can easily be checked by a comparison of conditions between the two types of waves, particularly seismic velocity).

The signals in Fig. 16 show a 2,0 m long bolt with 60 cm of satisfactory grouting. The Flexwave still gives a significant end echo with high amplitude (overdriven), the multiple, however, has practically vanished. On the other hand the Compwave end echo has now become very small. The grouting for this bolt starts 0,3 m from the bolt's outer end, which also can be read on the signal result. Echoes between 0,7 and 1,6 m are multiples from the first echo in the Compwave (same distance, regularly decreasing amplitudes).

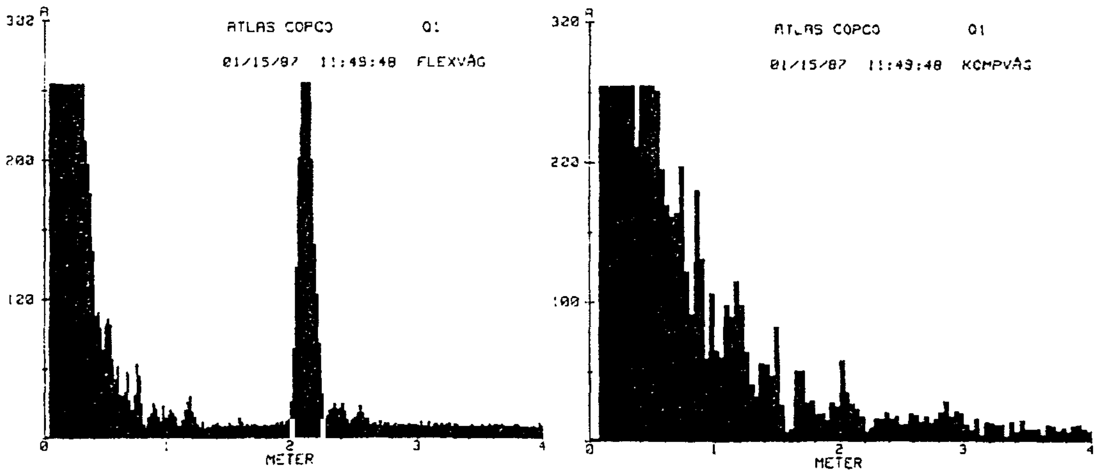

Figure 16 Signal from a 60 cm grouted bolt

Fig. 17 shows a 2,6 m long and approximate 1,0 m bottom grouted bolt (which was overcored). Even in this signal result one sees an obvious marking of the outer end of the bolt at 2,6 m. The part echo ahead of the end-echo indicates discontinuations of both Flex and Comp waves. This discontinuation becomes most apparent in the Compwave signal. Compwave echoes at 0,9 m and 1,6 m indicate that the grouting for 1,6 m is very poor (only local) and even after that not of especially high quality: in other words, a certain grouting at 0,9 m after which bottom grouting from 1,6 m to the end of the bolt.

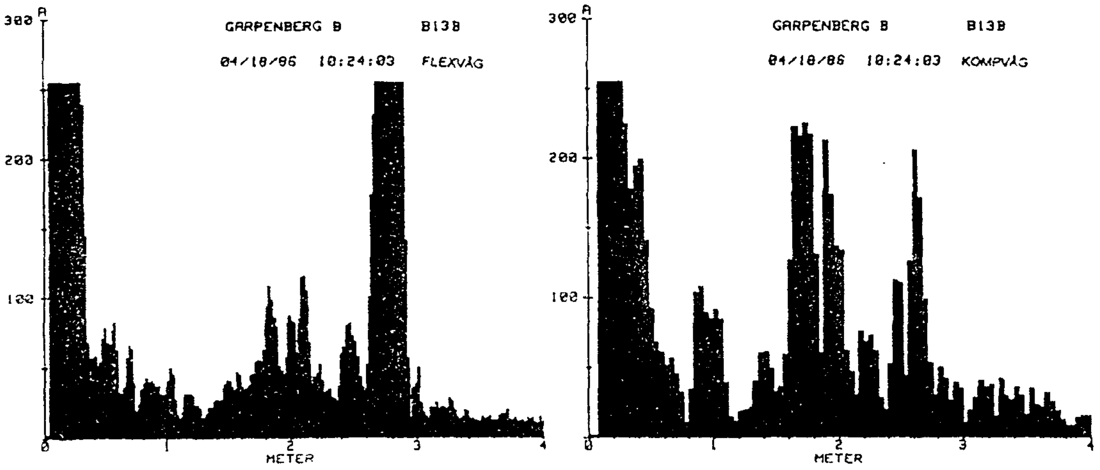

Figure 17 Signal from a 1,0 m grouted bolt

On an astonishingly large number of bolts that were overcored or in some other way exposed, one could see small or larger hollows in the grouting. Fig. 18 shows the signal results for such a bolt. The Compwave shows marked part echoes between 0,5 m and 1,4 m, but no end echo. The Flexwave has certain part echoes at the beginning of the record, as well as a double end echo. From the core of the overcored bolt a great number of air bubbles were seen, especially between 0,7 and 1,2 m.

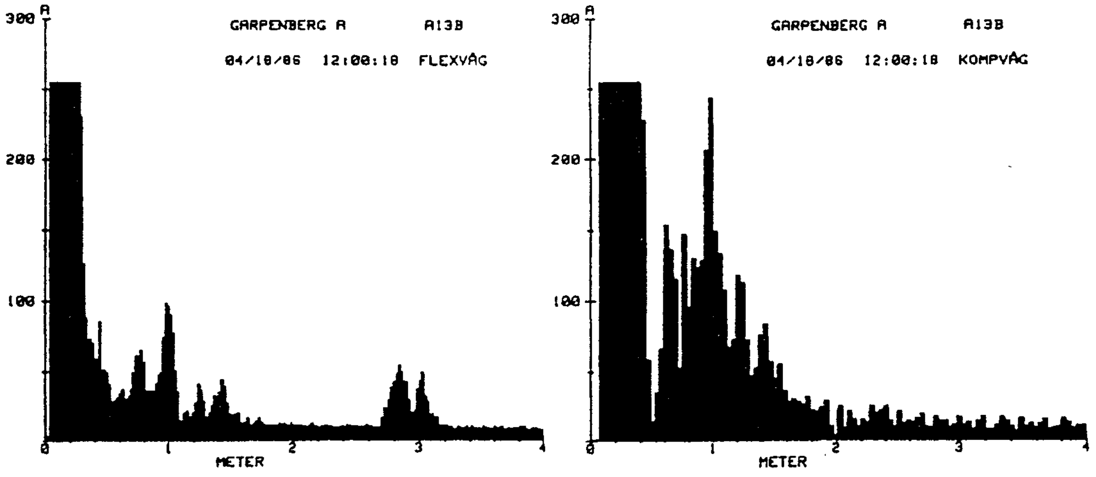

Figure 18 Signal from a bolt with air bubbles in grouting

A further frequently occurring observation showed that the grouting of the bolts only partly fills the holes. An example is seen in Fig. 19. In the case of both the Comp- and Flexwave the sound level in the signal apparently attenuates with distance, apparently indicating the grouting which successively fills the overcored hole around the bolt.

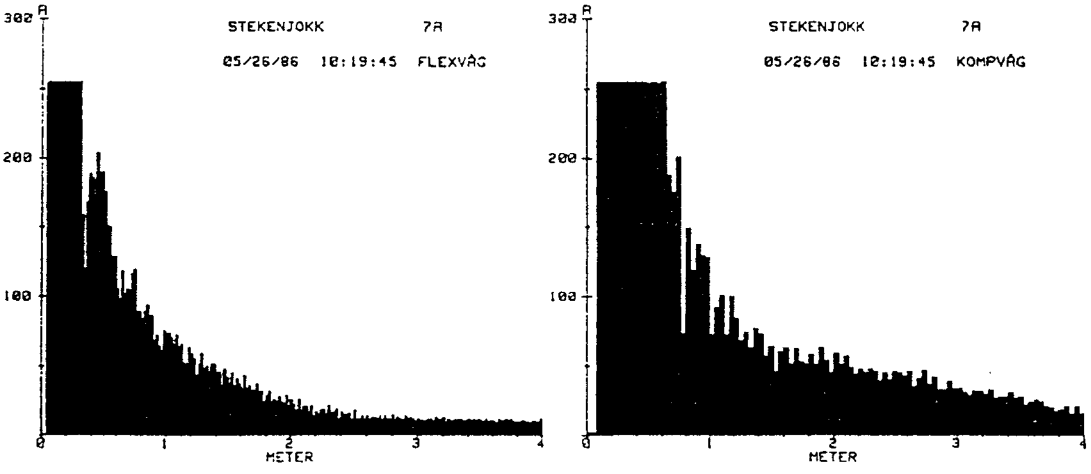

Figure 19 Signal from a bolt in a partly filled hole

Fig. 20 shows an example of a satisfactorily grouted 2,7 m long bolt. The Compwave echo indicates that the grouting first started at approximately 0,5 m (in reality 0,4 m) and in the Flexwave signal results one can see the end echo and a well grouted bolt. At a low water : cement ratio (< 0,3) it can be presumed that no end echo had appeared.

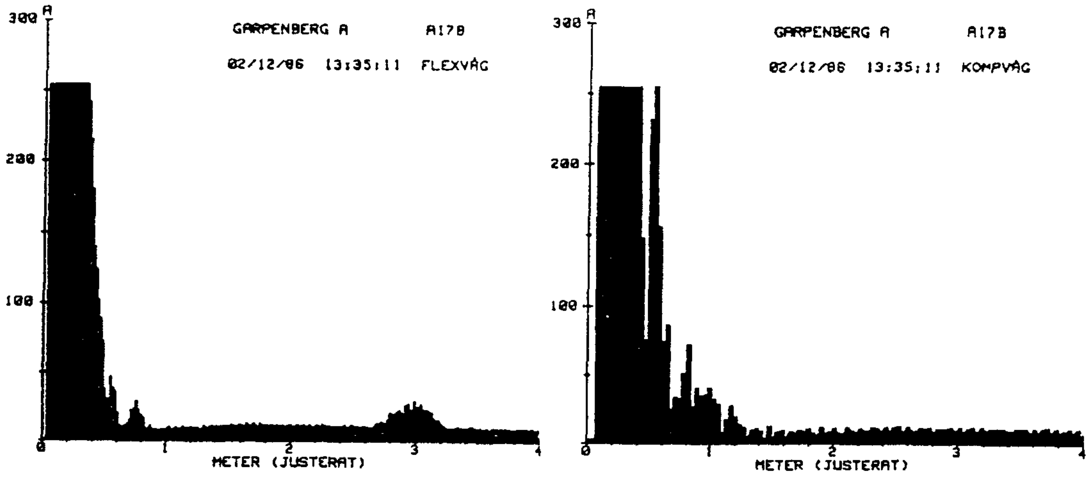

Figure 20 Signal from a 2,7 m well grouted bolt

Finally, Fig. 21 illustrates a damaged bolt. The bolt is 2,2 m long and at 1,4 m has an "artificial defect" i.e. a saw cut through half the diameter. Otherwise the bolt was well grouted. The Compwave does not penetrate 1,4 m of good grouting, hence no echo is found in its signal result. In the Flexwave record, on the other hand, one detects both the echo from the damage as well as from the bolt's bottom end.

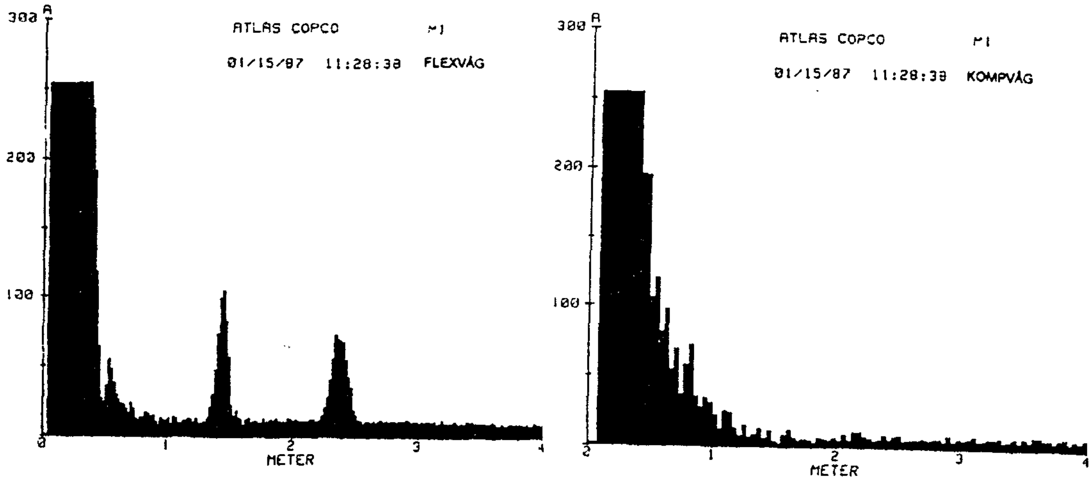

Figure 21 Signal from a defective bolt

TEST BOLTS

Since the Boltometer project started a large quantity of test bolts have been installed, tested and exposed or overcored.

The first test bolts were installed in 1978 in a rock cavern at Ugglevikskällan in Stockholm. The bolts were fixed vertically downwards in the floor of the cavern and simulated varying functional attributes - from fully satisfactory cement grouting to a loose bolt (Fig. 22).

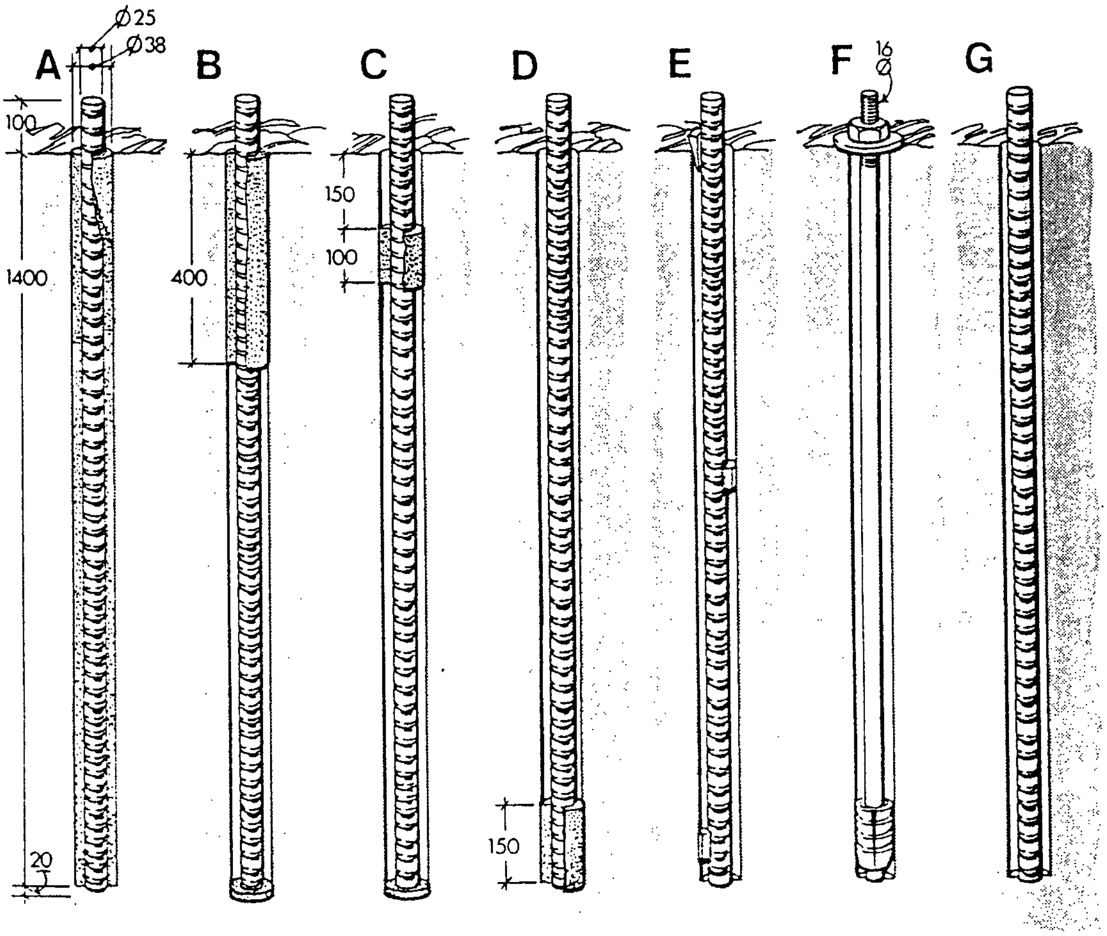

Figure 22 Test bolts at Ugglevikskällan

In 1979 a large number of test bolts were fitted at Atlas Copco's test mine at Nacka (Table 1). Over and above the more academic test bolts with cement grouting of varying quality and length, groups of standard production bolts were also fitted. The standard bolts included amongst others Cembolts, Kiruna bolts, SN-bolts, expander bolts and resin grouted bolts.

All the bolts were carefully documented with respect to length, method of installation and observations before and after installation. Most of these bolts are still in position in the test mine and are used for calibrating and checking of the Boltometer.

Since then in several mines and underground construction sites in Sweden and Finland, bolts have been overcored for testing with the Boltometer for the purpose of comparing the Boltometer measurements with accomplished results. Such evaluations were, for example, carried out by:

- Vattenfall at Grundforsen, Umluspen, Vietas, Harsprånget and Forsmark;
- Boliden Mineral AB in mines at Renström and Garpenberg;
- Hagconsult in the Bolmen tunnel;
- Otnäs Technical College in Finland.

Within the scope of AMF's "Reference Bank" project, a number of special test bolts were also installed in Mineral AB's mines in Garpenberg (see Chapter "Reference Bank") of which a large portion have been drilled out.

No.	Type of Bolt	Bolt Material	Dia. mm	Length mm	Preparation	Fixing	Fixing Material
3	sample bolt	rebar steel	25	2250	-	fully grouted	cement grout
3	sample bolt	rebar steel	25	2250	greased bolt	fully grouted	cement grout
3	sample bolt	rebar steel	25	2250	greased drill hole	fully grouted	cement grout
3	sample bolt	rebar steel	25	1500	-	fully grouted	cement grout
3	sample bolt	rebar steel	25	2250	half cut bolt	fully grouted	cement grout
3	sample bolt	rebar steel	25	2250	bottom end cut at angle	fully grouted	cement grout
3	sample bolt	rebar steel	25	2250	-	20 cm grouting	cement grout
3	sample bolt	rebar steel	25	2250	-	40 cm grouting	cement grout
3	sample bolt	rebar steel	25	2250	-	60 cm grouting	cement grout
3	sample bolt	rebar steel	25	2250	-	80 cm grouting	cement grout
3	sample bolt	rebar steel	25	2250	-	Two x 50 cm grouting	cement grout
3	sample bolt	rebar steel	25	2250	-	50 cm bottom grouting	cement grout
3	sample bolt	rebar steel	25	5000	-	fully grouted	cement grout
3	Strömnes	smooth steel	19	2250	-	steel expander	-
3	Farex	smooth steel	16	2250	-	plastic expander	-
3	Celtite	rebar steel	20	2250	-	fully grouted	Polyester
3	Celtite	rebar steel	20	2250	-	60 cm bottom grouted	Polyester
6	Perfo bolt	rebar steel	20	2350	-	fully grouted	cement grout
6	SN - bolt	rebar steel	25	2000	-	fully grouted	cement grout
6	Kiruna bolt	rebar steel	20	2300	-	fully grouted wedge expander	cement grout

Table 1 : Test bolts in Atlas Copco's test mine

PRODUCTION BOLTS

The Boltometer has been used over the years for the testing of different types of bolts with varying grouting methods and in different types of rock formation.

The following types of bolts have been tested:

- SN-bolt with w:c ratio varying from 0,28 to 0,5 with bolt diameter varying from 16 mm to 32 mm;
- Kiruna bolt;
- Perfo bolt;
- Cembolt bolt;
- Polyester grouted bolts (type Celtite);
- Epoxy grouted bolts of the SIG type;
- Thermoplastic grouted bolts;
- Pretensioned bolts (bottom grouted bolts and expander bolts);
- Swellex bolts.

In Sweden the tested production bolts were mainly installed in granite (for example Atlas Copco's mine at Nacka; electric generating plants at Granforsen, Umluspen, Forsmark) or in sulphide ore and surrounding rock (Boliden mines). The Boltometer has been used under many varying circumstances in different countries such as Canada, Chile, China, Finland, France, Germany, India, Japan, Norway, Pakistan, Saudi-Arabia, South Africa and Taiwan.

In addition to Geodynamik AB's for-own-use Boltometers there are today, in Sweden, four Boltometers in production use (Hagconsult AB: model 002, Vattenfall: model 002, LKAB: model 011, BERGAB: model 011).

REFERENCE BANK

The project under consideration was intended to lead to a more reliable test instrument and improved methods of interpreting the tests of rock bolts. The main idea was therefore to create a reference bank, where recorded signals, logs and bore-hole core samples and interpretation results are collected. The Reference Bank is official and will serve as a basis for research and development in bolting techniques.

In the first stage of the project one of Geodynamik AB's new Boltometer model 011 instruments was fitted with hardware for the attachment of a micro computer (EPSON HX20) for the collection of measured data.

In consultation with the project's steering committee the mines of Boliden Mineral AB in Garpenberg were selected as a testing area. At the same time the project work was organized to run parallel with the GRAMCO project at Stekenjokk. A great deal of importance was placed on a comprehensive and thorough documentation of these test bolts. Prior to the placing of the bolts in the Garpenberg test areas, which had been selected for geological sections with or without active movement, a geologist, (Kurt Wichman, Thyrens) familiar with the conditions in the mine, visited the test areas and gave a geological/rock mechanics verdict on the condition and existing stress state of the rock. His opinions were conveyed to the reference bank.

Boliden then drilled a hole as suggested by the steering committee. Kurt Wichman reviewed the conditions of the drilled hole and as suggested, the test bolts were installed with varying w:c ratios and bolt lengths. A number of Cembolts were also installed. Personnel from Geodynamik and from the Water Hydraulics Institution recorded the placing of the bolts and tested both the test bolts and a number of production bolts. Signals were recorded on the micro computer for transfer to the reference bank at KTH. Testing with the Boltometer was repeated after 2 and 6 months.

After plotting and assessing the signals, and with consideration to the signals' information value, 8 bolts out of 10 were finally overcored.

Complete drill cores were cut into 50 cm long pieces which were finally split. A portion of the core could be logged without cutting or splitting. Basic results were transferred to the reference bank.

The reference bank was located at the Water Hydraulics Institution, KTH. The Institution's computer was an HP9836 with requisite peripherals . To assist the reference bank the computer was supplied with interface and software for:

- transferring measured data from the micro computer or diskettes;
- value estimation of the signal;
- input and storage of data concerning bore hole layers, core logging and general observations;
- plotting signals and results from the core logging.

Within the scope of the GRAMCO project 18 bolts were in the meantime installed in the Stekenjokk mine. These were also tested with the Boltometer; the signals were stored on the micro computer and transferred to the reference bank. Instead of drilling them out it was decided to release the bolts with the aid of explosives in the drill holes between the bolts (which were placed in a pillar). Results from the visual inspection of the uncovered bolts were listed and transferred to the reference bank.

Normally the result from a Boltometer recording is documented on a paper printout from the built-in mini-printer in the form of a simple signal plot with bolt class etc; see the example in Fig. 23. If required such a measurement can be repeated at certain time intervals to ascertain if the bolt's condition has been altered or not.

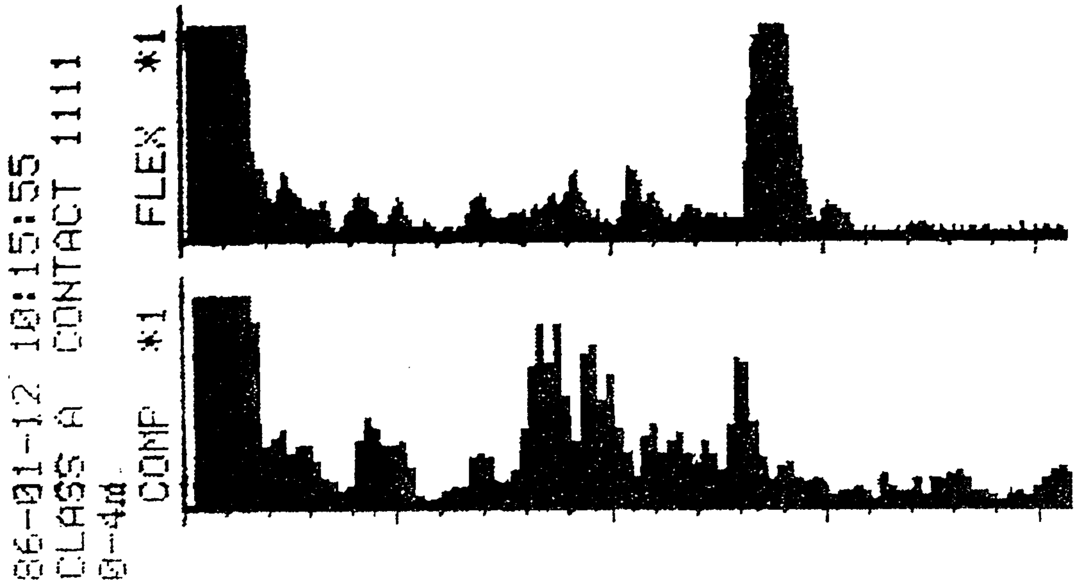

Figure 23 Documentation of Boltometer recording

If the Boltometer signal has been transferred to the reference bank one can get a tabulated form of tested bolts having certain basic data such as bolt numbers and the time of storage, see example in Table 2.

FILE NAME PRO	TYPE	REC/FILE	BYTE/REC	ADDRESS
D5A0743	BDAT	7	256	17
D5B0747	BDAT	7	256	25
D5C0754	BDAT	7	256	33
G22A0805	BDAT	7	256	41
G22B0810	BDAT	7	256	49
G22C0816	BDAT	7	256	57
E2A0916	BDAT	7	256	65
E2B0922	BDAT	7	256	73
E2C0931	BDAT	7	256	81
PARAMETER	BDAT	273	256	89
B13A1021	BDAT	7	256	363
B13B1024	BDAT	7	256	371
B13C1027	BDAT	7	256	379
B12A1037	BDAT	7	256	387
B12B1041	BDAT	7	256	395
B12C1047	BDAT	7	256	403
A3A1053	BDAT	7	256	411
A3B1056	BDAT	7	256	419
A3C1100	BDAT	7	256	427
A19A1107	BDAT	7	256	435
A19B1110	BDAT	7	256	443
A221226	BDAT	7	256	451
A23A1137	BDAT	7	256	459
A23B1140	BDAT	7	256	467
A26A1144	BDAT	7	256	475
A26B1147	BDAT	7	256	483
A10A1150	BDAT	7	256	491
A10B1153	BDAT	7	256	499
A13A1156	BDAT	7	256	507
A13B1200	BDAT	7	256	515
A30A1203	BDAT	7	256	523
A30B1206	BDAT	7	256	531
A211212	BDAT	7	256	539
A01A1359	BDAT	7	256	547
A01B1402	BDAT	7	256	555
A16A1822	BDAT	7	256	563
A16B1824	BDAT	7	256	571
A07A1739	BDAT	7	256	579
A07B1741	BDAT	7	256	587

Table 2: A sample from the list of bolt test results stored on the reference bank diskettes

In the reference bank, Boltometer signals are stored with greater resolution so that one can make a detailed analysis of the signals and, for example, make a closer study of the sighal around a bolt section where an extracted core sample shows a break in the grouting or in the surrounding rock formation. The stored signals can be plotted in their original form on the institution's computer. See example in Fig. 24.

The reference bank (as at February 1994) contains data on 87 bolts as well as logging from 8 overcored and 18 exposed bolts.

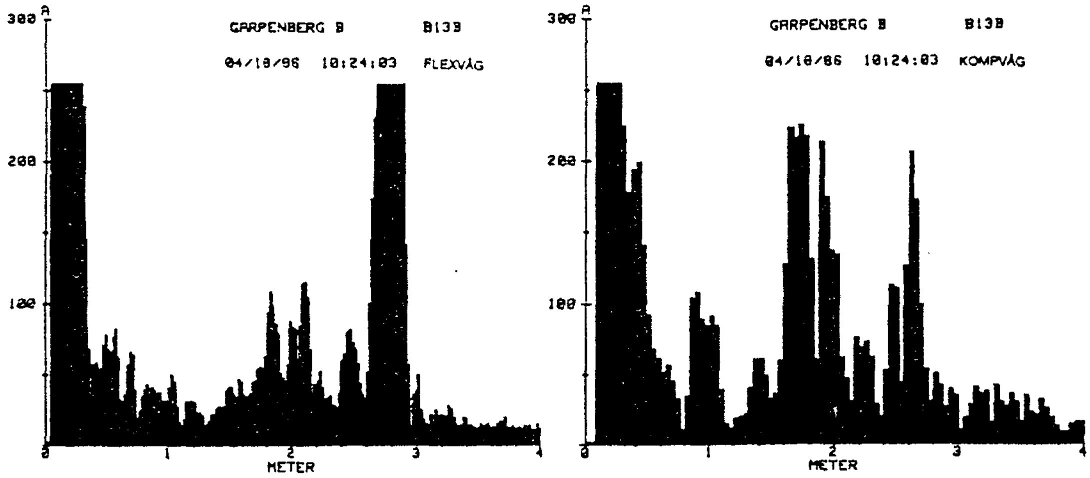

Figure 24 Signal from the reference bank

Simultaneously with the recorded signals, as in the previous case, results from a core logging, or other bolt investigation, can be stored in the reference bank, see example in Fig. 25.

NAME OF BOLT:	13
SITE OF MEASUREMENT:	B : Southern level 300 in the roof
DATE:	85/10/01
TIME:	01:05:02
TYPE OF BOLT:	Rebar with nut
ROCK TYPE:	
CRACKS IN BOLT:	
ROCK STRENGTHENING:	Actual bolt itself
CORE LOG OBSERVATIONS:	
HOLE LENGTH:	
HOLE DIAMETER:	
HOLE DIRECTION:	
FRACTURES IN HOLE:	
BOLT LENGTH:	
BOLT DIAMETER:	20 mm
FREE BOLT LENGTH:	
SURFACE CHARACTERISTICS:	
BOLT FIXING:	Bolt fixed by Boliden. Not fully grouted
OBSERVATIONS RE FIXING:	
GROUTING:	
INNER END OF BOLT:	
TREATMENT OF BOLT END:	Grinding with GEO equipment
MEASURING PRECAUTIONS:	Normal measuring
GENERAL OBSERVATIONS:	
CONTROL DRILLING:	
ADDITIONAL DRILLING:	

Figure 25 Record of an overcored bolt

INFLUENCING FACTORS (On Boltometer Performance)

The Boltometer signals, core samples and other observations connected with installation and testing of bolts which have been stored in the reference bank, have been evaluated and have, in conjunction with Geodynamik AB's experience from measurements in different countries, given valuable information about the function of grouted bolts as well as faults and/or improvement possibilities in the installation and testing of bolts.

However, it has been shown that there are several different factors which individually, or in combination, can influence the function of the bolt and the Boltometer:

- the condition of the end of the bolt
- geometry
- the bolt
- the bolt's contact with the rock
- fixing of the bolt (type of bolt)
- surrounding rock.

The condition of the end of the bolt is of major importance for testing. Amongst other things the planarity of the bolt end is the decisive factor for transferring the measuring impulses from the Boltometer sensor to the bolt as well as the reflected waves from the bolt to the sensor. The transfer can, to a certain degree, be improved by applying a thin layer of contact paste or grease to the end of the bolt. Burring and similar unevenness on the end of the bolt can make it impossible to take measurements; on the other hand pitting in the bolt end or a thread on the exposed portion of the bolt has little or no negative effect on the measurement. If the bolt end is encased in a thick layer of gunite/shotcrete which furthermore may be provided with reinforcing mesh or wire lacing - the measuring pulse energy can to a large extent disappear into the rock instead of transferring into the bolt. This naturally reduces penetration ability; i.e. the Boltometer's range. The biggest obstruction to a satisfactory test of grouted bolts is however caused by a nut and washer at the end of the bolt. It is therefore recommended that the nut and washer are removed before measurements are made.

Geometry i.e.: the diameters of the bolt and the bore hole, is of some importance when measuring. The Boltometer is designed for bolts having a diameter of 25 mm. In practice it has been found that bolts with a diameter of < 17 mm are not suitable for testing with a Boltometer; this means that no types of cable bolt can be tested. Bolts with diameter > 30 mm require a special sensor. The diameter of the bore hole is of primary importance with cement grouted bolts when the diameter of the hole is > 1,5 times the bolt diameter. If the hole diameter increases with distance from the hole collar - which can happen when the bore crown "jerks around" - the measuring results are frequently worsened. (The bore hole is not filled with grouting material.)

The bolt as such i.e. the steel shaft of it, only influences the measuring results if there is discontinuity in the material. These discontinuities can occur in the original bolt (cracks in the material) or develop later (rust, bending/shearing). In principle a part echo is received from all conspicuous discontinuities in the bolt; the stronger the discontinuity the stronger the part echo. This means that cracks as radial rust formation give obvious part echoes (in water carrying cracks in the rock formation where the grouting material has been washed away and the bolt has been attacked). It is surprising that even tangential rust attacks - which can be quite shallow - can cause part echoes. If the bolt has been bent or buckled as a result of rock displacement then even this can be the cause of a part echo provided that the radius of the bend is small (in which case the grouting has cracked up and the bolt pressed up against the bore hole wall). Pre-tensioned bolts, both grouted and ungrouted, have been tested in certain countries, but the Boltometer is not suitable for measuring the pre-stressed grade of such bolts.

The bolt's contact with the rock surface can influence the measured results in several ways. Under extreme circumstances the whole length of the bolt lies against the wall of the drilled hole, on the other hand, if the bolt is bent so as not to slip out of the drilled hole during grouting, a conspicuous contact surface will be found due to the "bending". In both instances air pockets are easily formed where the bolt lies up against the rock which create part echoes which are difficult to analyse. An important influencing factor in the measurement results is the contact of the inner end of the bolt with the rock at the bottom of the hole. If the end of the bolt has good contact with the rock at the bottom of the drilled hole a great portion of the measuring pulse energy is transferred to the rock which partially or totally prevents one from observing a reflection from the bolt's bottom end. Optimal measuring results are obtained in the reverse condition, i.e. when there is an air pocket between the inner end of the bolt and the bottom of the drilled hole, in which case the largest possible reflection is obtained and therewith a presumption for, amongst other things, a determination of the length of the bolt. With respect to the installation of the bolt, one can benefit from this phenomenon by first pressing the bolt against the bottom of the drilled hole and then carefully withdrawing it a few centimetres (thereby creating an artificial air pocket between the bolt's inner end and the bottom of the drilled hole).

The fixing of the bolt and also the type of bolt used is of great importance for the measurement results. The Boltometer was originally developed for testing cement grouted bolts, but, over the years, bolts with other types of grouting material have been tested, such as polyester, epoxy and thermoplastic.

With regard to cement grouted bolts **(SN bolt, Cembolt and Perfo bolt)** it has been proven that the water : cement (w:c) ratio is of decisive importance. A high water : cement count (0,5: highly diluted cement paste) allows for a good penetration ability (end echoes have been received from bolts with 4,9 m length) whilst a low water : cement count (0,28: very stiff cement/water mix) reduces the penetration ability (in extreme cases the maximum length of the bolt has been 1,5 m). Should there be no grouting material around the outer end of the bolt or if the grouting only covers a portion within the immediate area of the bolt (often the case with horizontally placed bolts) then this is most evident in the measuring signal. If, however, the bolt is well grouted in its outer section and the grout is missing in its inner part, then it is difficult and in certain instances impossible to get a reading from the measuring signal. Larger air pockets in the cement grouting have been observed to cause part echoes. A relatively large part of mainly older SN bolts had spiral formed air pockets enclosed in the grouting and/or drill hole, the diameter of which increased towards the bottom end.

Among the resin grouted bolts the penetration ability is best for **polyester grouted bolts** (end echoes have been received from approximately 10 m long bolts); on the other hand the penetration ability for both **epoxy and thermoplastic grouted bolts** is limited to approximately 1 m. One can however with the aid of the Boltometer reliably separate those bolts where one of the two resin components is missing - which implies that the grouting has not hardened and consequently the bolt's function is non-existent. Furthermore the casings of the cartridges (and also partly from the Cembolt cartridges) create quite distinct part echoes which implies that one can quite simply read from the measuring signal the number of spent cartridges.

Over the years a number of tension bolts (**Kiruna bolts, expander bolts, bottom grouted bolts**) have been tested with the Boltometer. The Kiruna bolt is an expander-fitted, cement grouted bolt which has been used, amongst other places, in LKAB's mines. The expander in the expander bolt can be made of steel (Strömnes) or of resin (Farex). The grouting material in bottom grouted bolts can consist of cement or resin. All pre-stressed bolts are supplied with a washer and nut which has a negative influence on Boltometer measurements in that a great deal of the measuring energy is transferred, through the washer, to the rock formation.

Even **Swellex bolts** have been tested with the aid of the Boltometer. However it proved difficult to create sufficiently good contact between the Boltometer's sensor and the outer end of the bolt, in order to get a reliable reading from the Boltometer signal to determine if the Swellex bolt has good or bad contact with the rock.

The influence of the **surrounding rocks** on the function of the bolt is quite difficult to assess through the Boltometer's measuring signal. Should the surrounding rock formation have more or less similar qualities as the grouting (soft rock) it can become impossible to get part or end echoes (all energy from the measuring pulses disappears into the rock formation). This makes it difficult/impossible to gauge whether the signal refers to a fully functioning bolt or to a bolt which is quite loose fitting in a soft rock formation. Simultaneously the study of bore hole cores and released bolts has shown that on the one hand large cracks in the rock formation did not give a part echo, and on the other hand very fine cracks created distinct part echoes.

One of the aims of this project was to create a "Gauging Bible" for practical use. The "Gauging Bible" described in a separate chapter illustrates, with the help of records from the reference bank, certain characteristic signals which have been assessed by comparing the details of the signal with the details from the core log or from bolts released in some other way. In practice often a **variety of factors work in conjunction** which means that the Boltometer signal is generally quite complex and therefore more difficult to gauge than the rather clear examples suggested by the "Gauging Bible". It is important to note however, that a measured signal with part echoes always relates to a physical reason - which theoretically reduces the function of the bolt - and also that a measured signal without part echoes guarantees that the bolt, up to a certain distance from the outer end, has a fully satisfactory function.

GENERAL CONCLUSIONS

An instrument for non-destructive *in situ* testing of cement grouted rock bolts had previously been developed within the scope of earlier projects funded by STU and ASF. The main purpose of the present project was the establishment of a reference bank, where recorded signals, logging of borehole cores, rock mechanics reports and general observations could be collected. The stored information is authoritative and forms the basis for future research and development concerning rock bolting techniques.

Comparison between the stored signals from the tests with the Boltometer and other results - in other words, observations before, during and after installing the bolt as well as logging of the core and a visual appraisement of uncovered bolts - have created a basis for the following conclusions:

1. A method and an instrument have been developed for non-destructive testing of rock bolts and this is now in use in many countries.

2. The Boltometer can be used for testing of old bolts (for determining/documenting the lengths and function of bolts) as well as for newly installed bolts (for determining/documenting incorrect installation, incorrect curing of the grouting material, or bolts that are too short).

3. The Boltometer provides two testing levels:

   a. a quick estimation of the function of the bolt (insufficient, defective or good).
   b. documentation of the bolt's condition (analysis/determination of partial echoes, gradual time dependent changes etc; by comparing measurements carried out on different occasions).

4. The method and the instrument have the following advantages:

   - the method is the only established non-destructive method for *in-situ* testing of rock bolts;
   - the method allows for a "quick look into the rock" so that any damage to the bolt or any striking defects in the grouting can quickly and reliably be picked up provided that the damage/defect appears in the outer part of the bolt;
   - poor grouting, the total length of which reaches 0,5 m - 0,6 m, can be reliably indicated (Compwave echo). It is important to point out that pull-out tests using a hydraulic jack are limited to a length 20 cm of satisfactory grouting; if the grout length is longer the bolt is pulled off outside the rock face. Furthermore the pull-out test is considered a destructive test .

5. The method and the instrument have the following limits:

   - if the bolt's outer end is well grouted it can be difficult and in certain cases impossible to determine the function of the bolt and/or the grouting along its inner part. The limit of the Boltometer's penetration range varies depending on the quality of the grouting and the bolt as well as the bore hole diameter, from 1,5 m - 5,0 m in well grouted installations. A free length of bolt without the surrounding grout does not limit the range.
   - a detailed or reliable measured result requires the bolt's outer end to be planar (cut and/or ground). The best contact is achieved by using contact paste or grease between the sensor and the end of the bolt.
   - the Boltometer in its present form and with the requirement for cutting and grinding of the end of the bolt, may not be used in coal mines due to the danger of sparks.
   - the Boltometer in its present form is suitable for application to cement grouted bolts having a diameter of 18-32 mm, other dimensions or grouting materials can aggravate the interpretation of the signal.

6. The following systematic faults in bolting techniques have been documented with the aid of the Boltometer:

    - the appearance of large air bubbles in the cement grout;
    - grouting which has not set after 2-3 weeks or has not set at all;
    - bolts which are too short (extreme cases: 0,5 m long bolts in 2,25 m deep bore holes; 0,2 m long bolts in a cement patch on the outside of the rock without a bore hole);
    - insufficiently grouted holes, especially since the bolt's outer part is frequently not surrounded with grout;
    - certain drilled cores (with bolt, grout and surrounding rock) indicated that the diameter of the bore hole in the bottom of the hole was very much larger than in the outer portion of the hole, which may be the reason why there was too little grout along the bolt;
    - in the case of certain horizontal or slightly tilted bolts, the grout fills the hole gradually; occasionally the grout only filled a small portion of the drilled hole's diameter;
    - older bolts may have lost a large portion of the cement grout which obviously had been washed away by water in the borehole or through fissures which intersect the bore hole; rust damage has sometimes been observed in the signal in the form of a partial echo;
    - if the grout is used in cartridge form (Cembolt, Celtite), the cartridge cases are frequently collected in lumps, resulting in poor or non existent grouting, in certain cases around portions of the bolt containing cartridge case material. As part echoes of the cartridge case material are often visible on the Boltometer signal, one can easily determine the number of cartridges used.

If one summarises the experience from the reference bank and GRAMCO projects together with production measurements in several countries, one has to come to the conclusion that up to 50% of all tested bolts did not have the expected function, and that the quality of a portion of the bolts was surprisingly inferior.

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