University of London
IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY
Department of Mineral Resources Engineering

Geophysical and television logging trials in horizontal boreholes for probing ahead of tunnels

by

Graham West BA FGS

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ABSTRACT

GEOPHYSICAL AND TELEVISION LOGGING TRIALS IN HORIZONTAL BOREHOLES FOR PROBING AHEAD OF TUNNELS

GRAHAM WEST BA FGS

Trials of geophysical and television logging in a horizontal borehole have been made with the object of assessing their potentiality for use in probing ahead of tunnels.

The first borehole that was logged was drilled horizontally through an assembly of concrete blocks designed to simulate rocks of different types and strengths and arranged to simulate different joint characteristics. The commercially-available geophysical logging methods tested were gamma-gamma (long and short spacing), natural gamma, neutron-neutron, neutron-gamma, self potential and resistivity. A commercially-available borehole television camera was also tested.

A new ultrasonic velocity logger was designed and used; it does not require a liquid-filled hole in which to operate, but is mechanically coupled to the borehole wall. An attempt was made to derive the strength from the velocity measurements obtained with the logger.

The second borehole that was logged was drilled horizontally through oolitic limestone in a disused underground stone quarry. The methods used were the ultrasonic velocity logger and the borehole television camera.

The main conclusions of the trials were:

1. Of the geophysical logging methods, only the gamma-gamma (long and short spacing) method would seem to be useful in probing ahead of tunnels. It provided a good overall measure of the density of the material and an indication of the presence of open joints. However the tool requires considerable modification before it could be used in horizontal boreholes for probing ahead.

2. The borehole television camera was most successful in showing the presence of joints, cavities and other features. Existing equipment could be used in probing ahead with little modification.

3. The prototype ultrasonic velocity logger was easy to use in a horizontal borehole and could readily be developed for use in routine probing ahead. It can provide a general indication of rock strength.

ACKNOWLEDGEMENTS

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The work described in this thesis formed part of the research programme of the Rock Mechanics Section of the Imperial College of Science and Technology and of the Tunnels and Underground Pipes Division of the Transport and Road Research Laboratory.

CONTENTS

CONTENTS (CONTINUED)

CONTENTS (CONTINUED)

PAGE

CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

NOTATION

Symbols are defined when they first occur. The following have been used:

C_p	Compressional wave velocity
C_s	Shear wave velocity
C_o	Compressive strength
λ, G	Lamé's parameters
ν	Dynamic Poisson's ratio
E	Dynamic Young's modulus
e	Base of natural logarithms
ρ	Density
A, B, C, D	Constants
N, N_o	Count rates at detector and source of gamma-gamma logger
S	Spacing between detector and source of gamma-gamma logger
α	Angle of dip of joint from horizontal
θ	Angle between strike of joint and borehole axis
d	Diameter of borehole
m, n	Horizontal distances along borehole
I_s	Point load strength index
I_d	Slake durability index

"Perhaps the greatest need at the present time is for the tunnelling engineer to be able to foresee, from his prospection of the ground, the nature and situation of difficulties before these occur. Drilling and sampling techniques have greatly improved but the areas calling for particular attention at the present day appear to be these:

(a) The capability of predicting the mass properties of rock from the information obtained by boreholes or otherwise, to provide reliable information for excavation and lining as well as for design

(b) The capability of using more precise geophysical methods for relating ground structure along the full length of the tunnel to that revealed by boreholes

(c) Improvements in the prediction of conditions ahead of a tunnel face by probing and geophysical methods."

A. M. Muir Wood (1976)

CHAPTER 1

INTRODUCTION

However good the site investigation, tunnel construction remains an uncertain and sometimes dangerous operation. In order to reduce uncertainty of ground conditions ahead of the face and to give advance warning of hazards, probing ahead of tunnels is sometimes practised. The probing may be undertaken over a short distance ahead of the tunnel face say at each change of shift, or over a longer distance ahead of the face say at weekly intervals.

Current British attitudes to probing ahead of tunnels may be exemplified by the Channel Tunnel and the Kielder Aqueduct Tunnels. During the driving of the British section of the Channel Tunnel Phase 2 works, probing ahead of the tunnel face was undertaken by the use of two open-hole rotary drill rigs set up permanently in front of the shield just behind the cutting head. The drills probed 70m ahead of the face, and probing was carried out at 50m intervals - corresponding roughly to intervals of 24h. The main purpose of the probing was to intersect and thereby give advance warning of any water-bearing fissures in the chalk, particularly if these were in communication with the sea bed. Probe drilling ahead of the face in the Channel Tunnel was therefore to reduce the risk to both men and works and little use was made of any advance information on ground conditions that the drilling may have been able to provide. Probe drilling occupied 16 per cent of construction time, although it was considered that this could have been reduced with experience and with some simple improvements to the method of working (Morgan, Barratt and Tilley, 1977).

During the construction of the Kielder Aqueduct Tunnels, probing ahead of the tunnel face was not undertaken, no doubt because it was considered that the risk to men and machinery was negligible or so small as to be acceptable. In the event, up to the present time (June 1979) there have been no hazards encountered during tunnel driving, but one instance at least has occurred where probing ahead of the face would have been useful in predicting a change in ground conditions. This was at about chainage 2700m in the South Wear Drive where dolerite of the Little Whin Sill appeared in the face for a length of 360m of the tunnel drive (Berry and Brown, 1977). When the dolerite was first encountered it was not known for how long it would persist and eventually a borehole was sunk from the surface to give a spot indication of its position. One 50mm diameter forward probe was also drilled from the face. If forward probing had been practised routinely during the drive, advance information on the extent of the dolerite ahead of the face would have been continuously available. Probe drilling ahead of the face in the Kielder Tunnels was therefore not carried out because risks were considered to be low, but may well have proved useful in providing advance notice of a change in ground conditions.

Except in soft ground, probing ahead of the tunnel face will usually be by open-hole water-flush rotary drilling using a non-coring bit such as a drag bit or a rock roller bit depending on the hardness of the rock, because core drilling will take too much time.* To obtain maximum information from the drilling operation the drill should be instrumented (Brown and Phillips, 1977 and Brown and Barr, 1978), because the only information directly available on the ground ahead will be from examination of the drill cuttings carried back in the water return, and considerable research effort is currently being made to develop instrumented horizontal drilling systems for probing ahead of tunnels.

However, even a perfect instrumented horizontal drill will provide only limited information on conditions ahead of the face because of the small size of the borehole in relation to the size of the tunnel. For example, a single 50mm diameter borehole used to probe ahead of a 5m diameter tunnel will provide information on only 0.0001 per cent of the ground. The use of geophysical and television logging of the borehole will supplement the information available from instrumented drilling and may also provide information on ground conditions in a wider zone around the borehole itself. Moreover, it should be possible to log boreholes in this way very quickly once they have been drilled. The advantages of this approach have been discussed by the Building Research Establishment/Transport and Road Research Laboratory Working Party on Probing Ahead for Tunnels (1975), by O'Reilly (1977) and by Brown and Phillips (1977). Also, Tomlinson (1977) has pointed out that non-coring drilling methods are often unable to differentiate between

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* Non-coring rotary drilling is about three times as fast as core drilling.

hard and soft ground and that there is therefore a need for the development of in-hole geophysical equipment to be used in conjunction with non-coring drills to make good this deficiency when probing ahead of tunnels. As part of an integrated set of recommendations for research on probing ahead, the BRE/TRRL Working Party considered that work on in-hole logging techniques should be put in hand and encouraged by all possible means. Muir Wood (1976) has stated that improvements in the prediction of conditions ahead of a tunnel face by probing and geophysical methods is one of the most pressing needs for present day tunnelling (see page 12). Scott et al (1968), after finding good correlations between construction parameters and geophysical measurements made along the walls of a tunnel, suggested that geophysical measurements made in probe holes drilled ahead of the working face could be used to predict construction conditions in advance of the tunnel.

In a review of future needs in site investigation for tunnels, Underwood (1970) strongly advocated the development of horizontal drilling ahead of the face using a fast-cutting bit which would be followed by geophysical and photographic logging of the borehole. He envisaged that the drilling and logging would be a combined operation and gave an artist's impression of a proposed system to be used with a full-face tunnelling machine. In a comprehensive review of horizontal drilling for tunnel site investigation, Ash, Russell and Rommel (1974) discussed the possibility of using geophysical and other borehole logging techniques to log the completed borehole. They listed the methods available and touched on some of the difficulties that might be encountered in trying to apply these methods in a horizontal borehole.

In order to gain acceptance for use in probing ahead of tunnels, geophysical borehole logging methods would have to produce results that were interpretable to the tunnel engineer in meaningful and useful terms. In this context, much of the advice given in respect of surface geophysics for site investigation for roads (West and Dumbleton, 1975) is applicable to borehole geophysics for probing ahead of tunnels. The borehole logs would also have to be capable of being interpreted quickly enough for the engineer to have the results before commencement of tunnel driving through the section of ground to which they related.

An alternative to probing ahead of tunnels during construction that has been proposed is to drive a horizontal borehole along the proposed tunnel axis from the tunnel portals or from shafts sunk for the purpose at intervals along the tunnel line at the site investigation stage (Ward, 1975 and BRE/TRRL Working Party, 1975). The advantage of this technique is that it frees the horizontal drilling operation from the constraints of lack of space and shortage of time imposed by the tunnel construction operations, but the disadvantages are that the tunnel line and level have to be chosen before the site investigation has been completed, and that it may require the sinking of shafts which will be costly if the tunnel is deep. However, any techniques that are useful for logging horizontal boreholes for probing ahead will be equally applicable to pre-tunnelling horizontal drilling.

Considerable research is being carried out into horizontal long hole drilling in order to establish the practicability of pre-tunnelling site investigation by this means. The Jacobs Associates (1972), Ash, Russell and Rommel (1974) and Harding, Rubin and Still (1975) have studied methods both for drilling long horizontal boreholes and for controlling their direction. Following an extensive review of existing horizontal drilling methods and case histories of their application, Ash, Russell and Rommel (1974) concluded that the equipment and technology exists for drilling small diameter horizontal holes up to 1600m long in materials having compressive strengths up to $55MN/m^2$.

The Rock Mechanics Section of the Imperial College of Science and Technology and the Tunnels and Underground Pipes Division of the Transport and Road Research Laboratory, working together, have conducted a series of trials of instrumented horizontal drilling with a view to developing a system for probing ahead of tunnels either before or during construction. This work included trials of geophysical and television logging devices, aimed at assessing their potentiality when used in horizontal boreholes for probing ahead of tunnels; this thesis describes these trials and reports their results.

CHAPTER 2

GEOPHYSICAL BOREHOLE LOGGING METHODS

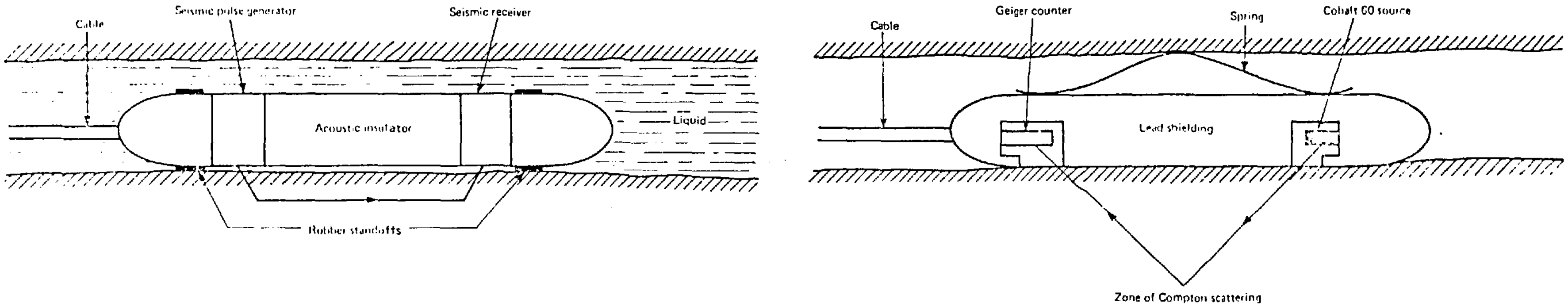
Geophysical borehole logging methods were developed specifically for logging deep vertical boreholes sunk in the course of exploration for petroleum, and the instruments and techniques reflect the special needs of this application. These are the identification of geological formations, particularly potential reservoir rocks and the determination of their porosity and permeability and the nature of the fluids present. The methods used include seismic, electrical, radioactive, magnetic, thermal and gravity measurements; very often they are most effectively used in combination.

All geophysical logging devices consist basically of a tool, sometimes called a sonde, which is lowered down the borehole on a cable and a recording system at the surface. With some tools, because of the long cable run, the measurement is not conducted to the surface in its original form but is converted into a more conveniently transmitted signal. The borehole log is a graph in which the geophysical measurement is plotted against depth in the borehole.

A brief description of those geophysical methods that seem to offer most promise for logging horizontal boreholes for probing ahead purposes will now be given; the following account concentrates on the principles involved rather than on the technical details. More information is given by Telford et al (1976).

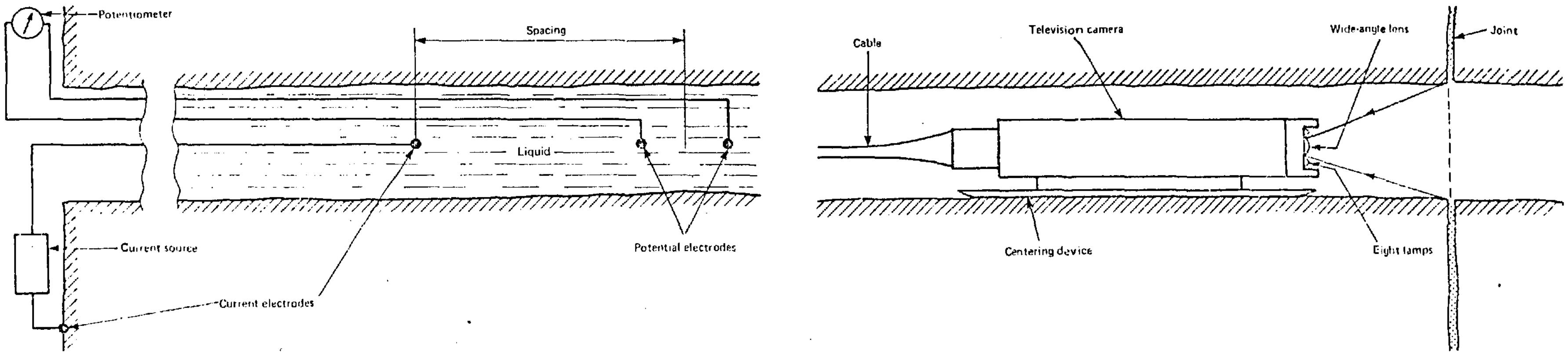
2.1 Seismic methods

The seismic velocity logger, Figure 1a, consists essentially of a tool containing a seismic pulse generator at one end and a receiver at the other, separated by acoustic insulating material. The travel time for a seismic pulse to travel the known distance through the rock is measured. Most seismic loggers measure only the first arrival which is usually that of the compressional wave (P-wave) but some loggers can measure the shear wave (S-wave) arrival as well. Seismic loggers must be operated in a liquid-filled hole to provide a coupling for the signal between the generator and receiver and the rock surrounding the borehole. Civil engineering applications of seismic logging in vertical boreholes have been described. Kennett (1971) has described the use of a down-hole seismic tool known as the 3-D velocity logger to determine the compressional wave velocity and the shear wave velocity of the rock. From these measurements, together with the bulk density of the rock which must be determined with another logging device, Young's modulus, the bulk modulus, the shear modulus and Poisson's ratio of the rock can be calculated. It should be noted, however, that the 3-D velocity logger requires a hole of at least 75mm diameter and the minimum distance between transmitter and receiver is 305mm. Allard and Grenet (1972) have described a similar apparatus and give examples of its application. Cratchley _et al_ (1976) describe the use of the 3-D velocity logger in the investigation of a tunnel site.



(a) VELOCITY LOGGER

(b) GAMMA–GAMMA LOGGER



(c) RESISTIVITY LOGGER

(d) BOREHOLE TELEVISION CAMERA

Fig. 1 GEOPHYSICAL BOREHOLE LOGGING TOOLS

An acoustical logging device known as the Seisviewer has been described by Myung and Baltosser (1972). This consists of a cable-suspended rotating downhole scanning tool which produces an acoustical picture of the borehole wall resembling a simplified television picture. The amplitude of the signal returned from the borehole wall depends on its acoustical impedance and fractured or highly disturbed zones are recognised by a poor signal or no reflected signal. The Seisviewer needs to be operated in a liquid-filled hole but can be used in holes down to 50mm in diameter.

A recent development has been an acoustic borehole logging system that does not require a liquid-filled borehole in which to operate. This tool utilises hydraulic pistons to force the transducer holders into direct contact with the borehole wall (King et al, 1978). The apparatus can therefore be used in both liquid-filled and dry boreholes orientated in any direction. As well as measuring the compressional wave velocity, it can also measure the shear wave velocity provided that the shear wave arrival can be recognised on the oscilloscope trace. Its main application has been in determining the presence and degree of fracturing of the rock mass in mines and in mining exploration. The tool is designed for use in 48mm diameter boreholes. The transducer spacing is 300mm.

2.2 Radioactive methods

The gamma-gamma logger, Figure 1b, consists essentially of a tool containing a source of gamma rays, usually cobalt-60, at one end and a detector, usually a Geiger counter or scintillation counter, at the other, separated by lead shielding. The tool is spring loaded against the borehole wall. The gamma rays from the source interact with electrons in the atoms in the rock, mainly by Compton scattering*. The detected gamma ray intensity is a negative exponential function of rock density, given by $N = N_o e^{-CS\rho}$ where N and N_o are the counting rates at the detector and source respectively, S is the spacing between source and detector, ρ is the density and C is a constant (Lynch, 1962). However, in practice a calibration is usually made in materials of known density. The tool investigates to a depth of about 150mm with most of the signal coming from the first 75mm of rock. In civil engineering applications, the gamma-gamma logger is used to determine the bulk density of the rock. This is also required to calculate the elastic moduli from the compressional and shear wave velocities obtained by use of the 3-D velocity logger as discussed in Section 2.1.

The natural gamma logger consists essentially of a tool containing a gamma ray detector, either a Geiger counter or a scintillation counter. The detector measures the gamma radiation arising from any naturally radioactive elements in the surrounding rock. The principal naturally occurring radioactive elements, potassium-40 and uranium and thorium isotopes, originate in granitic igneous rocks, but by the process of weathering, erosion, transport and deposition find their way into sedimentary rocks where they

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* Named after Arthur H Compton the American physicist who studied the effect in 1924.

tend to become concentrated in clays and shales. Because in oil well logging it is mainly sedimentary rocks that are studied, the natural gamma logger is used as an indicator of clays and shales.

The neutron-neutron logger is similar to the gamma-gamma logger except that the tool contains a neutron source, e.g. radium-beryllium, and a neutron detector with a neutron shield between them. Hydrogen atoms present in substances such as water, oil or gas contained in the rock slow down and absorb the neutrons and in so doing reduce the neutron flux. Therefore in porous formations saturated with water the counting rate of the neutron detector is low and in low-porosity formations it is high. The neutron-gamma logger has a gamma ray detector in place of the neutron detector which detects the gamma rays produced when the neutrons are captured by the nuclei of hydrogen atoms. Therefore in saturated porous formations the counting rate of the gamma ray detector is high and in low-porosity formations it is low. Thus both the neutron-neutron and the neutron-gamma loggers measure mainly water content from which the porosity of the formation may be deduced. The depth of penetration of the neutrons is about 180 to 600mm depending inversely on the hydrogen content of the rock.

2.3 Electrical methods

Resistivity loggers include the 'three-electrode' device in which one current electrode and two potential electrodes are fixed in the tool (Figure 1c), the second current electrode being at the surface. The depth of investigation is equal to the spacing between the current electrode and the mid-point of the two potential electrodes. The focused-current device, sometimes called a 'laterolog', is a tool with either three or seven electrodes so arranged to cause the current from a central electrode to be focused into a thin disc-shaped sheet which penetrates up to 3m into the borehole walls; resolution can be down to 50mm. Direct or low-frequency alternating current is applied across the current electrodes and the potential is measured between the potential electrodes; the record is a plot of resistivity with depth. Because the minerals common in sedimentary rocks are generally non-conductors, and because porous sedimentary rocks usually contain water which is to some extent conductive, the resistivity logger is used to locate water-bearing porous sedimentary rocks which therefore exhibit relatively low resistivity.

The self-potential logger detects spontaneous ground potentials and consists essentially of a tool containing two electrodes at a small fixed spacing which are connected to a recording potentiometer. There are a number of causes of self potential in the ground (Telford et al, 1976), but in oil well logging the three main purposes for which the log is run are to locate the boundaries between shales and sandstones, to make correlations between wells and to determine the formation-water resistivity. Sometimes self potential and resistivity are logged simultaneously, both sets of electrodes being carried on the same tool.*

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*Self potential and resisitivity were the earliest geophysical techniques used in well logging, being first introduced by the Schlumbergers in 1928 and 1931.

Resistivity and self-potential tools must be operated in a liquid-filled hole because a conducting medium is required to couple the electrodes to the rock.

The Dipmeter is a resistivity tool which has three spring-loaded electrodes spaced 120 degrees apart around the borehole wall and also has an azimuth and inclination measuring system. When the tool crosses a stratum boundary having a change of resistivity, then the records from the three electrodes enable the apparent dip of the boundary to be calculated. From the azimuth and inclination records the true dip can then be calculated. The tool is designed for use in vertical boreholes of 90mm minimum diameter. A description of the Dipmeter and its application has been given by Pirson (1970).

2.4 Caliper logger

The caliper logger is a tool consisting of three spring-loaded extending arms equally spaced around a central tube. Radial movement of the outer ends of the arms is converted electrically to give a record of the borehole diameter. Used in its own right the caliper log is a guide to the competence of the rock in the borehole wall and to the presence of cavities, but the caliper log is also required for data reduction in several of the other geophysical logs (Schlumberger, 1972 a, b, c).

2.5 Borehole television camera

The borehole television camera consists of a stainless steel cylindrical tube housing a miniature closed-circuit television camera (Figure 1d). A cable leads to a camera control unit and television screen at the surface; various lengths of cable are available, up to a maximum length of 136m. Videotape recordings can be made if required. The camera incorporates a wide angle lens looking forward which can be focused from 20mm to infinity, and lighting is by small lamps arranged in a circle around the camera lens. An angled mirror attachment is available for radial scanning if required. The system was originally designed for the inspection of small internal diameter pipes and tubes, but has found application in the inspection of underground pipes and sewers (Lester *et al*, 1978) and of boreholes (Ward, 1971). Attewell and Farmer (1976) cite examples of the use of the borehole television camera for determining the spacing and orientation of joints in rock, and Obert and Duvall (1967) give brief descriptions of borehole television cameras that have been used. The borehole television camera is not strictly a geophysical method, but the description is included here for convenience.

The main types of geophysical borehole logging tools that might be adapted to probing ahead of tunnels have been reviewed by the BRE/TRRL Working Party (1975), by Brown and Phillips (1977) and, as part of a comprehensive review of all types of in-hole instrumentation for ground investigation, by

Barr (1977). However it should be noted that there are a number of practical difficulties that must be overcome before the geophysical borehole logging tools developed for well logging in the petroleum industry can be used for probing ahead of tunnels. All the existing tools are cable suspended being designed for use in vertical boreholes, some, especially the seismic loggers, require to be operated in liquid-filled holes, some are too large in diameter to operate in the size of hole envisaged for probing ahead and some have too coarse a resolving capability.

A recent development has been the application of geophysical well logging to coal exploration (Kowalski and Fertl, 1977). Boreholes sunk for coal exploration are frequently too small in diameter to take most logging tools used by the petroleum industry, but recently 'slimline' geophysical logging tools have been developed specifically for coal and mineral exploration (Reeves, 1976). Although small in diameter, the tools are cable suspended and some have to be operated in liquid-filled holes.

Scott and Sena (1973) have described a group of geophysical borehole logging techniques aimed at predicting geological and hydrological conditions ahead of tunnelling operations. The methods proposed were magnetic, resistance, density, caliper, temperature and acoustic logging. All the tools were cable suspended from a winch housed in a logging truck and the resistance and acoustic methods required a liquid-filled borehole. The whole system was designed for logging vertical boreholes drilled along the tunnel line from the surface ahead of excavation and not for use in horizontal boreholes.

Numerous examples of the borehole logs produced by the various geophysical methods can be found in the references cited, in geophysical textbooks (for example, Lynch, 1962 and Telford et al, 1976) and in the technical literature of geophysical firms (for example, Schlumberger, 1972b). A selection of borehole logs of those kinds likely to be useful in tunnelling ground investigation has been brought together by Barr (1977).

CHAPTER 3

LABORATORY TRIALS

The laboratory trials consisted of the logging of a 56mm diameter borehole drilled horizontally into blocks of concrete arranged in a manner to simulate different joint configurations. The purpose of the laboratory trials was to provide a means of carrying out the geophysical and television logging under controlled conditions on materials of known properties containing joints of known characteristics. It was considered that unless the methods could be shown to give useful results under laboratory conditions there was little likelihood of their proving useful in the field. Another purpose of the laboratory trials was to provide an opportunity of ascertaining any operational difficulties of using logging tools designed for vertical boreholes in a horizontal borehole.

3.1 Test assembly

The test assembly had two functions: the first was to provide a facility for the instrumented drilling trials and the second was to provide a facility for the geophysical and television logging trials.

The basic considerations when designing the test assembly were the need to provide blocks showing a range of geological type and strength and to arrange them in a manner to simulate the characteristics of jointed strata. These needs were met by casting blocks of concrete made from a number of aggregates and having mix designs giving different strengths. The blocks were fixed in the required array by embedding them in concrete, the whole assembly being supported by a concrete plinth at a convenient height for drilling into.

The aggregates used were flint, quartzite, gritstone, limestone, siltstone, dolerite and granite, and by using a constant coarse to fine aggregate ratio together with three different cement contents, blocks of three different strengths were made from each aggregate. Full details of the design and manufacture of the blocks, together with test results for the aggregates and concrete used are given in Appendix 1. The method of designating the concrete is also explained.

After curing, the blocks were assembled on a concrete plinth in the array shown in Figure 2 and Plate 1. The array consisted of three sections. At one end was a series of blocks assembled together to give units of two blocks separated by different joint apertures, and at the other end was a series of blocks assembled together to give units of three blocks made from the same aggregate but having different strengths. The central section consisted of three pairs of blocks having joints set at different angles (70, 60 and 45 degrees) to the borehole direction; the spaces between the pairs of blocks being used to provide zones of gravel-sand-clay, clay of high plasticity, and weakly-cemented coarse

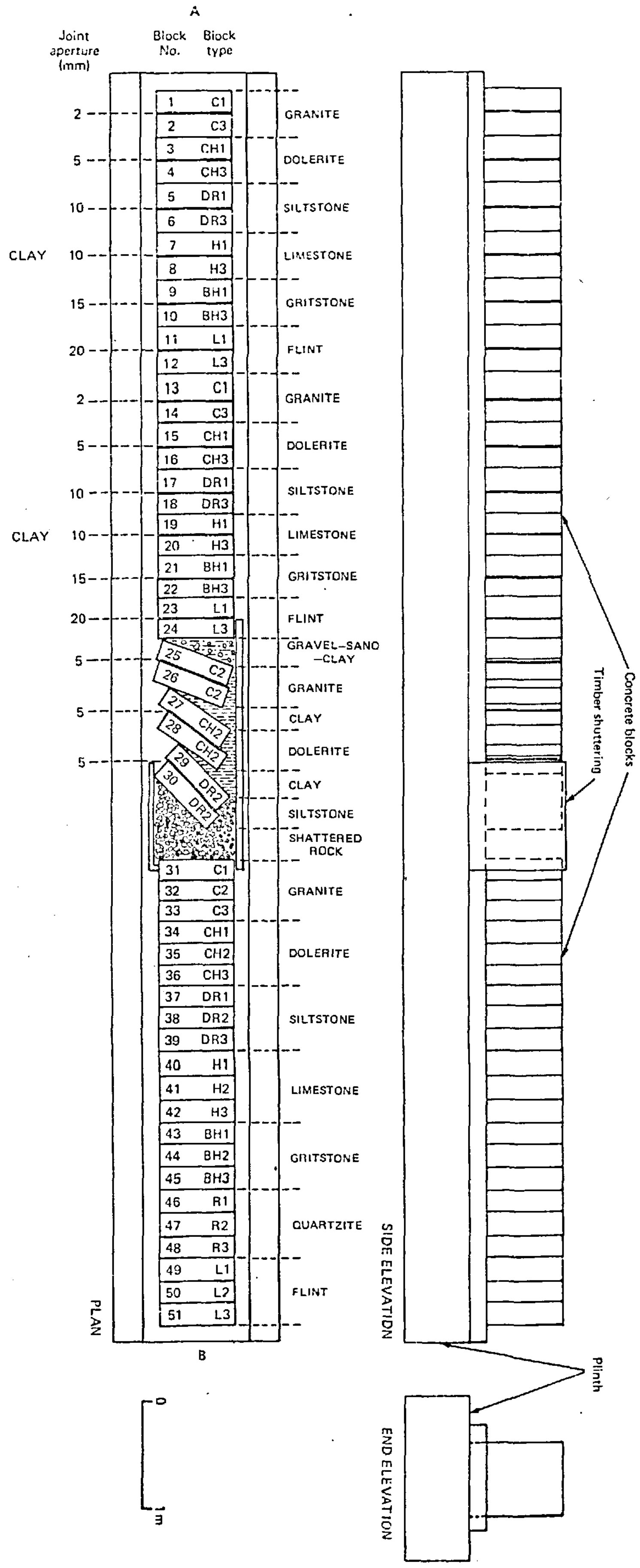

Fig. 2 ARRANGEMENT OF BLOCKS FOR LABORATORY TRIALS

PLATE 1 General view of assembly of blocks

limestone aggregate to simulate gravel-filled and clay-filled fissures and shattered rock respectively. The properties of these materials are given in Appendix 3. The sides and tops of the joints between the blocks were sealed with cement mortar and sealing strip, and the shuttering on both sides of the central section was left in place. After the blocks had been assembled on the plinth, seismic wave velocity measurements and Schmidt hammer tests were carried out on them; the results are given in Appendix 2.

The hole to be logged was drilled through the centre of the blocks down the longitudinal axis of the array from A to B (Figure 2). An Atlas Copco Craelius Diamec 250 hydraulically-driven diamond core-drilling rig was used. It was fitted with a 56mm diameter core barrel having an impregnated diamond bit and with 53mm diameter aluminium drill rods. The hole was water flushed and uncased.

The drilling rig was mounted in a specially made steel frame which was bolted to the floor about 0.5m in front of end A of the test assembly. The frame allowed the drilling rig to be adjusted for line and level so that it could be accurately positioned on the intended borehole axis before drilling. The frame also allowed the drilling rig to be quickly swung to one side after drilling to give unobstructed access to the borehole for the geophysical and television logging. Electrical power and mains water supplies for the drill were provided close at hand.

The Diamec 250 was used because it is a typical example of the kind of drilling rig that would be used in probing ahead of tunnels, and 56mm is the maximum diameter of hole that it is possible to drill with the rig. It should be noted that although core drilling was carried out for this trial, for probing ahead of tunnels core drilling would be too slow and a faster non-coring bit would be used. Periodically during drilling of the hole, core was extracted from the core barrel and placed in wooden core boxes according to standard practice. It was at once apparent that the condition of the core did not accurately reflect the condition of the array of blocks. The condition of the core was as follows:

Intact lengths of core :	19
Core broken in one place :	20
Core broken in two places :	5
Pieces of core and rubble :	4
Rubble only :	3

It can be seen that of the 51 blocks, only 19 are represented by intact lengths of core, the rest of the core indicating more broken material than in fact is present in the array. The probable reason for this was the inexperience of the driller and the condition of the drill. Also, double-tube core barrel was used which does not give such good core recovery as triple-tube core barrel. The density of the more intact cores, determined from measurements of their mass and dimensions, is given in Appendix 2.

It can be noted that the completed test assembly, consisting as it did of a set of concrete blocks of known properties traversed by a borehole, is somewhat similar to the calibration models described by Snodgrass (1976). However, these were concrete blocks with vertical boreholes of various diameters and were prepared for a different purpose, namely to provide a calibration facility for geophysical logging systems in routine use.

3.2 Method of logging

The method of carrying out the geophysical logging is shown in Figure 3 and Plate 2a. At each end of the assembly of blocks was placed a 3m length of 150mm diameter rigid PVC guttering which was closed at one end. The lengths of guttering were positioned on the borehole axis, being supported at the correct height on wooden trestles, and sealed to the faces of the end blocks with Plasticine. The purposes of the guttering were to support the geophysical logging tools and to provide a means of filling the borehole with water for those tools that had to be run in a water-filled hole. Hoses connected the guttering to the mains water supply. At one end of the assembly the drilling rig had to be swung to one side to allow the guttering to be placed in position (see Plate 2b) but this proved a very simple and quick operation.

The logging truck, which contained the cable winch (Plate 3a) and the instrumentation and recording equipment

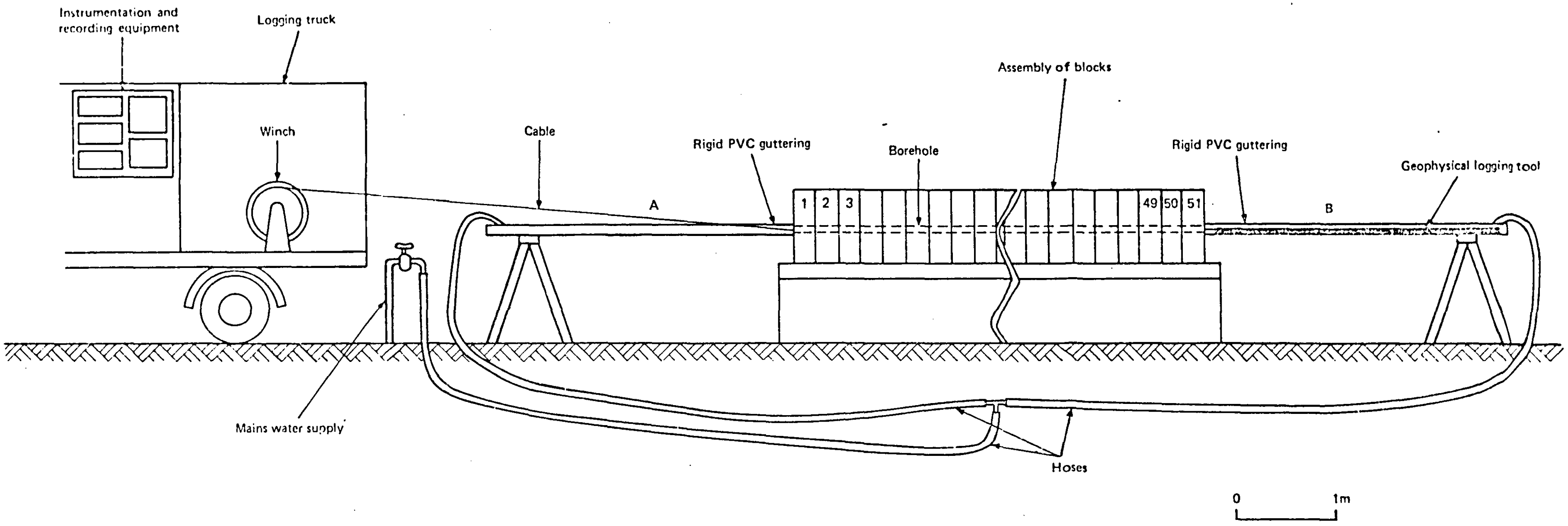

Fig. 3 METHOD OF CARRYING OUT GEOPHYSICAL LOGGING

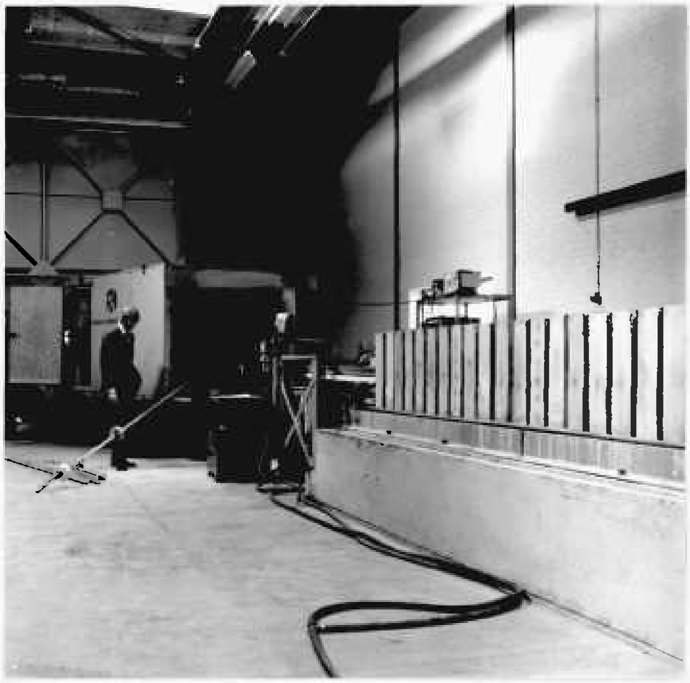

PLATE 2a Geophysical logging truck in position

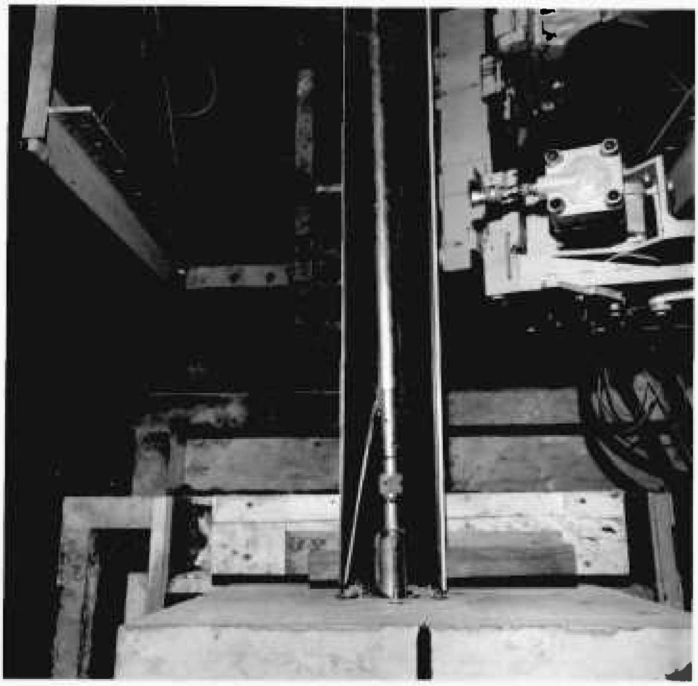

PLATE 2b Combination tool emerging from borehole at end A

PLATE 3a Interior of logging truck showing winch

PLATE 3b Interior of logging truck showing instrumentation

(Plate 3b), was positioned at one end of the assembly as shown in Figure 3, and the method of operating all the geophysical logging tools was as follows. Drain rods were pushed through the borehole from B to A, the cable was attached and then pulled through from A to B. The cable was detached from the drain rods and attached to the tool which was placed in the guttering at B. The tool was then winched through the borehole from B to A while geophysical logging was carried out. Plate 2b shows a tool emerging from the borehole at end A. The tool was then detached from the cable and the process was repeated for each of the different tools in turn. The tools that could be used in a dry hole were run first; the borehole was then filled with water and the tools that required a water-filled hole were run. The sources for the radioactive logging tools were kept in shielded containers and only attached to the tools just before they were winched into the borehole.

The 'slimline' tools used were about 3m long and 48mm in diameter, and weighed about 20 kg. All the logging was done at a speed of 2.5 m/minute. No difficulties were encountered with the logging except that BPB's sonic velocity tool was too large in diameter to fit into the borehole with its standoffs (see Figure 1a) fitted, and would not operate with the standoffs removed.

The method of carrying out the logging as described above would be feasible for logging horizontal boreholes driven between shafts, but could not, of course, be practised in a horizontal borehole driven from a tunnel face because access to end B would not be available. Therefore a trial was made with one of the tools to see if the tool with cable attached could be advanced along the borehole by pushing it with drain rods from end A. It proved very difficult to push the long heavy tool along the borehole and this poses an operational problem which will be returned to later (see Section 3.9).

3.3 Combination tool: natural gamma, gamma-gamma and caliper

The first tool to be run in the hole was a combination tool which recorded natural gamma, gamma-gamma and caliper logs simultaneously. The gamma ray source was caesium-137 of strength 100 millicuries* and the gamma ray detector was a scintillation counter. The caliper was a single arm, motor-driven from the side of the tool (the caliper arm can be seen, having just emerged from the borehole, in Plate 2b). The depth of investigation of the gamma-gamma logger is about 150 to 300mm and that of the natural gamma logger is about 300mm. The gamma-gamma logger produces two logs, a long spacing density log having a fairly coarse resolution of about 0.5m and a short spacing density log having a finer resolution of about 150mm. The purpose of the long spacing log is to measure the density of the formation being logged, and as well as giving a log scaled in normalised count/s, a calibration of density in Mg/m^3 is provided. The purpose

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* 1 curie = radioactivity of 1 g of radium = 3.7×10^{10} count/s.

of the short spacing log is to detect thin beds or seams and the log is scaled in normalised count/s only. The natural gamma log is scaled in count/s. The combination tool was run in a dry hole.

3.4 Neutron-neutron tool

The neutron-neutron tool had an americium-beryllium neutron source of strength 1 curie and a helium-3 neutron detector; the source to detector spacing was 0.5m. The depth of investigation depends on the amount of hydrogen in the rock, being least in porous saturated rock. The log is scaled in normalised count/s. The tool was run in a dry hole.

3.5 Neutron-gamma tool

The neutron-gamma tool used the same americium-beryllium neutron source as the neutron-neutron tool and the gamma ray detector was a scintillation counter. The source to detector spacing was 0.25m and, as for the neutron-neutron tool, the depth of investigation depends on the amount of hydrogen in the rock. The log is scaled in normalised count/s. The tool was run in a water-filled hole.

3.6 Resistivity and self-potential tool

Resistivity and self-potential were logged together with the same tool. Resistivity was not measured using the three-electrode or laterolog systems described in Section 2.3 and which are commonly used in well logging, but the earlier and now less common single-electrode method. This was done because it was considered by BPB that the single-electrode method was more suited to the measurement of the resistivity of the test array than other methods. With the single-electrode method, because of the long distance over which the resistivity is measured, the resistivity of the rock that is measured is the apparent resistivity rather than the true resistivity (Telford et al, 1976). The tool consisted of a single electrode. Another electrode was attached to the plinth at end A and measurement of the resistance was made by passing a 0.3mA alternating current between the electrodes and recording the potential across them while the tool was winched along the borehole. The resulting log is scaled in ohms; because of this it should, strictly speaking, be called a resistance log.* The same electrodes on the tool and plinth were used to record self potential simultaneously with the resistivity measurement. A filter in the instrumentation was used to prevent the alternating current used for the resistivity logging from affecting the direct current self-potential logging. The self-potential log is scaled in mV.

3.7 Borehole television camera

The borehole was logged with the Rees 60 Borehole Television Camera System. This consisted of a 51mm diameter, 200mm long miniature television camera with built-in illumination, a camera control unit, a television

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* Because BPB refer to the tool and the log as resistivity this practice will be followed here.

monitor, a videotape recorder and 15m of cable (Plate 4a). The system gave a 625-line black-and-white picture. The camera had two interchangeable heads, one for looking forward (Plate 4b) and another with a rotatable mirror inclined at 45 degrees to the camera axis for looking sideways (Plate 5a). The forward-looking head had eight small lamps fitted in a circle around the camera lens (see Figure 1d) and the side-scanning head had a single large lamp fitted in front of the mirror housing. The levels of illumination together with the focus of the camera lens and the rotation of the mirror were all controlled from the camera control unit.

The control unit, the monitor and the recorder were set up at end A of the borehole and the camera was firmly attached to the end of a drain rod. A surveyor's measuring tape, graduated to 0.01m, was attached to the camera. The camera together with its cable was then advanced down the borehole from A to B using drain rods (Plate 5b). Still photographs were taken of the monitor screen when required, and the whole passage down the hole was recorded on videotape. Runs were first made with the camera looking forward; the side-scanning head was then fitted and particular sections of the borehole wall were examined. The scale of the picture on the monitor screen was calibrated by photographing a sheet of graph paper placed around the borehole wall. Because of the small difference between the borehole diameter (56mm) and the camera diameter (51mm), the centering device (see Figure 1d) could not be used.

PLATE 4a Borehole television camera, television monitor, videotape recorder and control unit

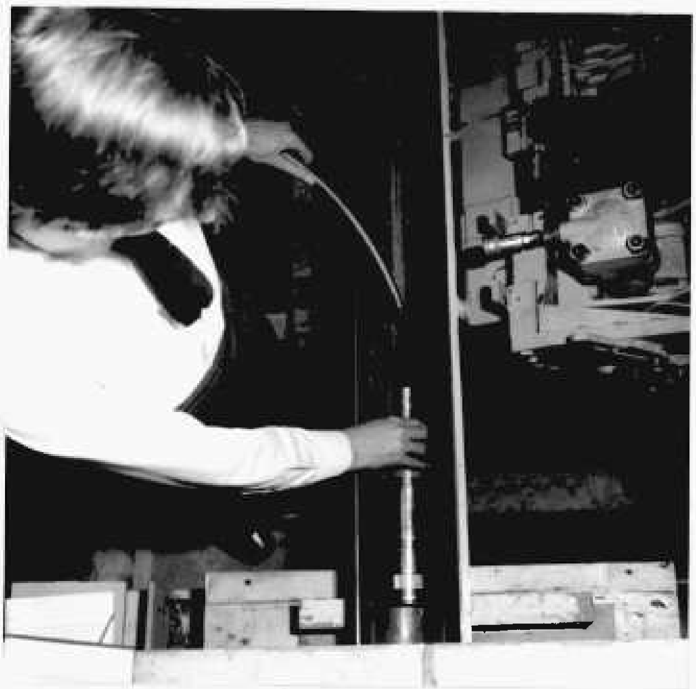

PLATE 4b Borehole television camera fitted with forward-looking head

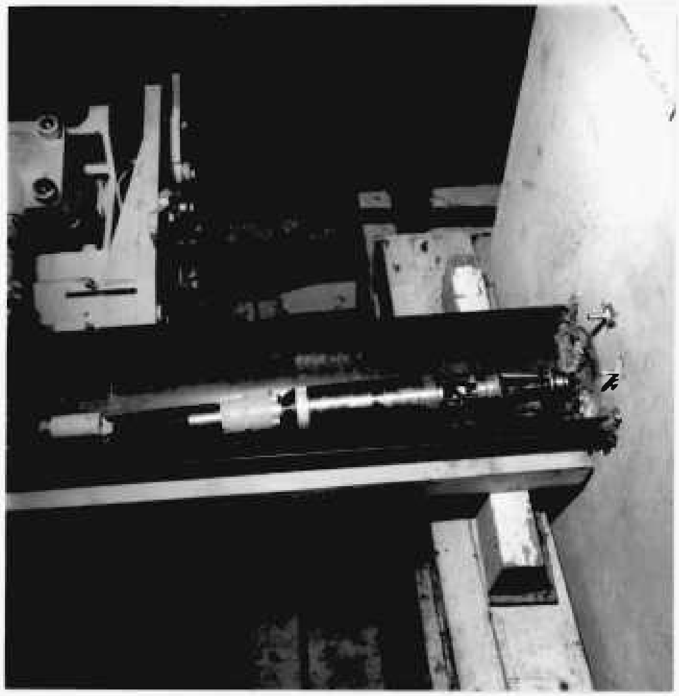

PLATE 5a Borehole television camera fitted with side-scanning head

PLATE 5b Introducing camera into borehole at end A

The accuracy of measurement of the position of joints along the borehole made with the borehole television camera was assessed. Joints along the borehole appeared as circles on the television screen with the camera looking forward. Measurement of the position of every joint in the test assembly, including the three inclined joints, was made by noting the reading on the measuring tape when the circular image of the joint was of a given size on the monitor screen. The distance of a joint in front of the camera when the circle was of the given size on the screen was also determined. This distance was added to the measuring tape readings to give the true position along the borehole of all the joints. The actual positions of all the joints were then determined by direct measurement along the centreline of the top of the test assembly. The positions were compared and the results were as follows:

No difference	:	17 joints
Difference of 0.01m	:	24 joints
Difference of 0.02m	:	5 joints

It can be seen that of the 46 joints, 41 have had their position determined to 0.01m or less. This accuracy is similar to the precision of direct measurement of joint spacing using the scanline technique (Priest and Hudson, 1976) used in tunnel site investigation and monitoring.

3.8 Ultrasonic velocity tool

It will be recalled from Section 3.2 that BPB's sonic velocity tool was too large in diameter to log the borehole, and as far as could be ascertained there is no velocity tool available in Britain to log a 56mm diameter borehole.

A velocity tool was therefore developed specifically to log a 56mm diameter borehole. It consisted of two ceramic piezoelectric transducers of natural frequency 82kHz mounted in stainless steel cases fitted with brass pads having the same radius of curvature as the borehole wall. The transducers were mounted 140mm apart in a Delrin holder which was tapered at either end to facilitate easy passage along the borehole. Delrin was selected because it is a tough plastic material with an ultrasonic wave velocity of less than 2000 m/s, a value less than most rocks. The transducer spacing was made 140mm so that the velocities of individual blocks in the test assembly could be measured with the tool. The transducers were decoupled from each other by fitting them in floating mountings using rubber gaskets. A mechanical lever arrangement enabled the transducers to be pressed into contact with the borehole wall when tension was applied to the end of a cord passing out of the borehole; no grease or other coupling medium was used. The tool is shown in Figure 4 and Plate 6a. One of the transducers, the transmitter, was connected by coaxial cable to a pulse generator having a pulse repetition rate of ten per second. The other transducer, the receiver, was connected by coaxial cable to a cathode ray oscilloscope. A connection between the pulse generator and the oscilloscope allowed the initiation of a pulse from the pulse generator to trigger the sweep of the oscilloscope.

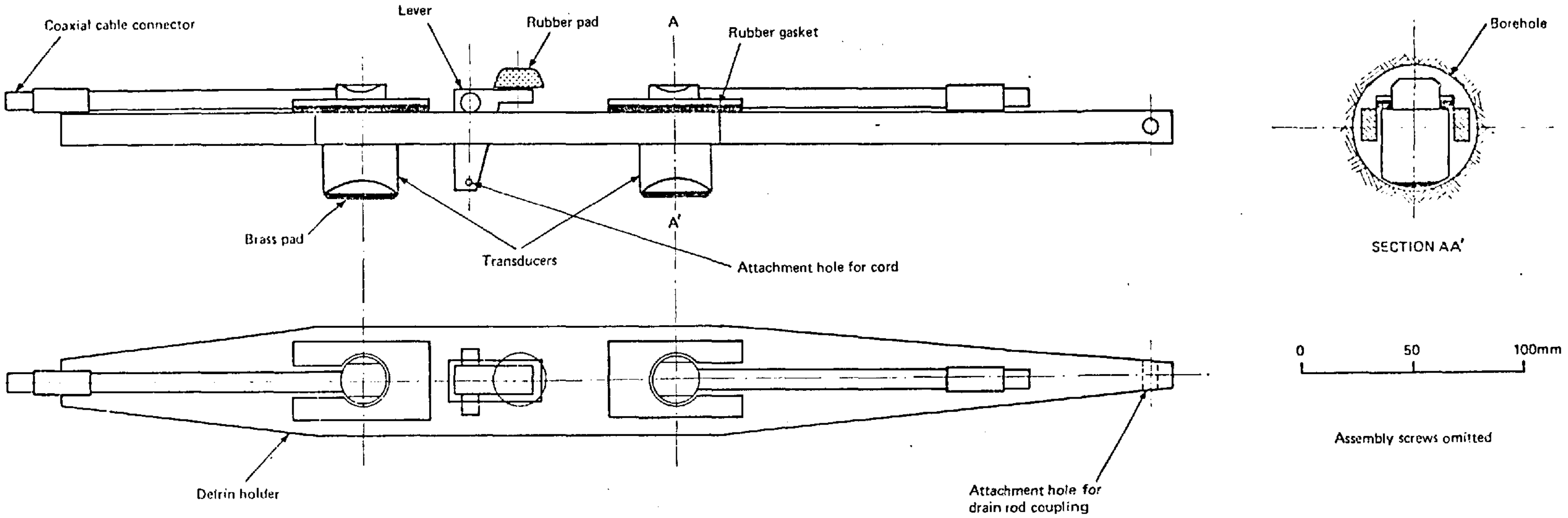

Fig. 4 ULTRASONIC VELOCITY TOOL

PLATE 6a Ultrasonic velocity tool

PLATE 6b Ultrasonic velocity logging of borehole at end B

The transit time for the pulse to travel between the transmitter and the receiver was then measured from the time scale on the cathode ray tube, by noting the position of the first arrival in the wave train detected by the receiver. Although the signal was small, there was little noise and it was found that the transmit time was readable to 1 μs on the oscilloscope screen.

The pulse generator and oscilloscope were positioned at one end of the array and logging was carried out by attaching drain rods to the tool and advancing it along the borehole so that the transducers were positioned within each block in turn (Plate 6b). When the position had been selected, tension was applied to the cord to bring the transducers into close contact with the borehole wall, the tension being increased until a consistent minimum transit time was obtained. It was found that if the transducers were positioned on either side of a joint between two blocks no signal could be detected by the receiver.

The repeatability of the readings with the ultrasonic velocity logger was assessed. Measurements of the transit time for each of the blocks were made as the tool was passed down the borehole in one direction and these were then repeated, without consulting the first set of readings, as the tool was brought back along the borehole in the other direction. The pairs of readings for the blocks were compared and the results were as follows:

No difference : 23 pairs of readings
Difference of 1 μs : 21 pairs of readings
Difference of 2 μs : 6 pairs of readings
Difference of 3 μs : 1 pair of readings

It can be seen that 44 of the 51 pairs of readings have a difference of 1 μs or less. To give an idea of the effect of a difference of 1 μs on the velocity, the following example is given:

Transit time 40 μs, velocity 3500 m/s
Transit time 41 μs, velocity 3415 m/s

It can be seen that the difference in velocity, 85 m/s, is small in relation to the velocity, being about 2.5 per cent. For the blocks where a difference in transit time was observed, the mean value was used for compiling the velocity log.

The ultrasonic velocity tool has its transducers mounted in the indirect configuration as defined by the British Standards Institution (1974). The velocities measured by the tool are therefore indirect velocities and a correction has to be applied to obtain the direct velocity. The velocities obtained with the tool were compared with the direct velocities for the blocks listed in Table 5 of Appendix 2 giving a correction factor of 1.05, and this was used in compiling the velocity log.

Because it is the transit time of the first arrival that is measured with this tool, the property of the rock measured is the compressional wave (P-wave) velocity because these are the fastest waves (Dobrin, 1960).

As far as it is known this tool is the first to utilise ultrasonic velocity measurement in a borehole logger although ultrasonic velocity measurements in a tunnel have been made before (Hudson, Jones and New, 1979).

3.9 Operational observations

None of BPB's geophysical logging tools could be used for logging horizontal boreholes for probing ahead of tunnels without modification. The most important need would be to replace the cable suspension with a method of advancing the tools using drill rods or drain rods whilst still accommodating the electrical leads. It would also be an advantage if the tools were shorter and lighter (see Section 3.2), and were fitted in a casing having no projections or sharp edges that can catch on joints in the rock. Another difficulty that would have to be overcome when using logging tools containing radioactive sources would be to provide a method of shielding the source in the event of the tool becoming jammed in the hole; at the present if this occurred the tool would become a hazard to subsequent tunnelling operations. The instrumentation and recording system would need to be housed more suitably for use in a tunnel than in the logging truck shown in Plate 2a. Radioactive logging methods used in tunnels would have to conform to the appropriate safety standards (Department of Employment and Productivity, 1969 and Statutory Instruments, 1969). Radioactive logging methods could not be used in compressed air tunnels because of the danger of the ionising radiation causing 'the bends' to the operators and possibly the workforce (Jackson, 1975). In a tunnel it might prove difficult to provide a liquid-filled horizontal borehole for those geophysical logging tools that require a liquid-filled hole in which to operate.

The borehole television camera could be readily adapted to log horizontal boreholes. It is short and light and was easily advanced along the borehole with drain rods. Stones in the borehole liable to cause jamming could be seen in advance and cleared if necessary. The monitor, control unit and videotape recorder would take up little room in a tunnel. The recommended maximum cable length of 136m is more than adequate for logging the 100m long holes envisaged for probing ahead of the face.

The ultrasonic velocity tool is, of course, a prototype. It has however demonstrated the feasibility of making in-borehole velocity measurements by mechanically coupling the transducers to the borehole wall instead of using a liquid-filled hole to provide the coupling as do the velocity tools used for well logging. It has also showed that a velocity tool can be made small enough to operate in a 56mm diameter borehole. The prototype tool described here could be readily developed into a tool that could be used for routine probing ahead.

The geophysical logging tools, the borehole television camera and the ultrasonic velocity tool all require an electrical power supply, but this should be available in most tunnels. However, in tunnels subject to the Coal and Other Mines (Electricity) Regulations 1956 including Amendment Regulations 1967, 1974, special safeguards are necessary to eliminate accidents caused by explosion or fire (Carver _et al_, 1976), and to comply with these any borehole logging equipment would have to be made either intrinsically safe or flameproof.

CHAPTER 4

ANALYSIS OF RESULTS OF LABORATORY TRIALS

In well logging the objectives are the location of rocks containing hydrocarbons, either oil or gas or coal, the identification of suitable reservoir rocks, usually sandstones, the identification of unsuitable reservoir rocks, usually shales, and the correlation of strata in adjacent boreholes so that the geological structure can be determined. For these purposes the methods of analysis of the logs are often qualitative, displacements of the record from the baseline being known from experience to be indicative of particular factors or conditions. On the other hand, since the advent of the computer, quantitative methods have been developed to make detailed analysis of the porosity and lithological composition of sediments (Schlumberger, 1972a,b,c). The principles and practice of well log analysis for formation evaluation in petroleum exploration are described by Lynch (1962). More recently well log analysis has been developed to give information on wider geological topics, such as the sedimentational history of a region and this approach has been described by Pirson (1970).

For probing ahead of tunnels the needs are completely different. Whilst general geological information is of some interest, the prime needs of the tunnel engineer are for information on the mechanical properties of the rock material and the presence and condition of joints, together with advance warning of hazards such as water-bearing deposits of sand and gravel and zones of shattered rock (BRE/TRRL Working Party, 1975). The compressive strength is the particular mechanical property of the rock material that is used to predict the likely penetration rate of a tunnelling machine (Robbins, 1976). The mean joint spacing is used to predict the likely primary support requirements (Bieniawski, 1973). In this Chapter the geophysical logs obtained will therefore be analysed by comparing each log with the known properties of the array to see how far each log satisfies the needs of the tunnel engineer. This will enable an assessment to be made of the usefulness of the various methods for the logging of horizontal boreholes drilled in rock for probing ahead of tunnels.

For the geophysical logging done with BPB's equipment, the logs supplied by the firm consisted only of graphs of the logger reading against distance along the borehole. The annotations on the logs and all the interpretations were made by the author.

4.1 Gamma-gamma logs

It will be recalled that the gamma-gamma tool produces two logs; a long spacing density log and a short spacing density log. On both logs high density is shown by a low count rate at the detector. The long spacing density log is shown in Figure 5. Two very large peaks, at C and D, indicate areas in the array of very low density. In fact peak C corresponds to the gravel-sand-clay which had a measured density of 1.87 Mg/m^3 and peak D corresponds to the shattered rock zone which had a measured density of 1.39 Mg/m^3 (see Appendix 3). A small peak at E indicates an area of slightly lower density, and coincides with blocks 10 and 11 which in fact are of slightly lower density than most in the array. The long spacing density log, with its coarse resolution of 0.5m does not, of course, indicate the density of individual blocks. Furthermore, it can be seen that the core densities (shown by solid circles on the log) are in general a little higher than the density curve determined by the gamma-gamma long spacing density tool. However, the log indicates that the general level of the density of the blocks is 2.3 Mg/m^3 which is in reasonable agreement with their mean measured density of 2.33 Mg/m^3 (see Appendix 2).

It is concluded that the long spacing density log gives a very good indication of the general density of the array and shows clearly the two regions in the central section where the density is very low. The short spacing density log is shown in Figure 6. Very low densities are indicated at C and D, corresponding to the shattered rock zone and the gravel-sand-clay respectively. A peak at E also occurs at the same position as peak E on the long spacing density log (Figure 5). Peaks at F and G correspond to the two clay-filled regions in the central section of the array. Peaks a, b, c, d, e, f, g, h, i, j, E, k and

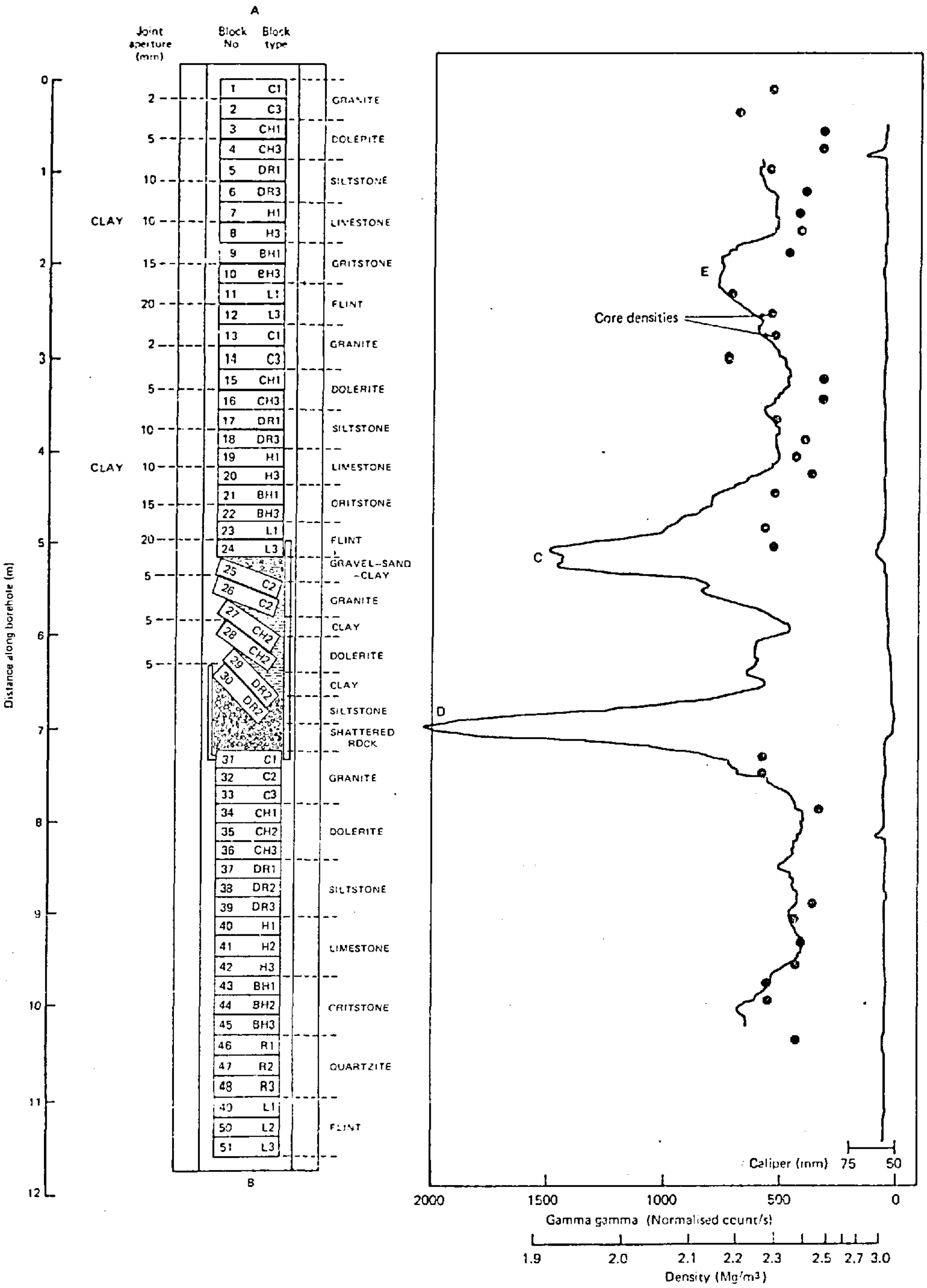

Fig. 5 GAMMA–GAMMA (LONG SPACING DENSITY) LOG

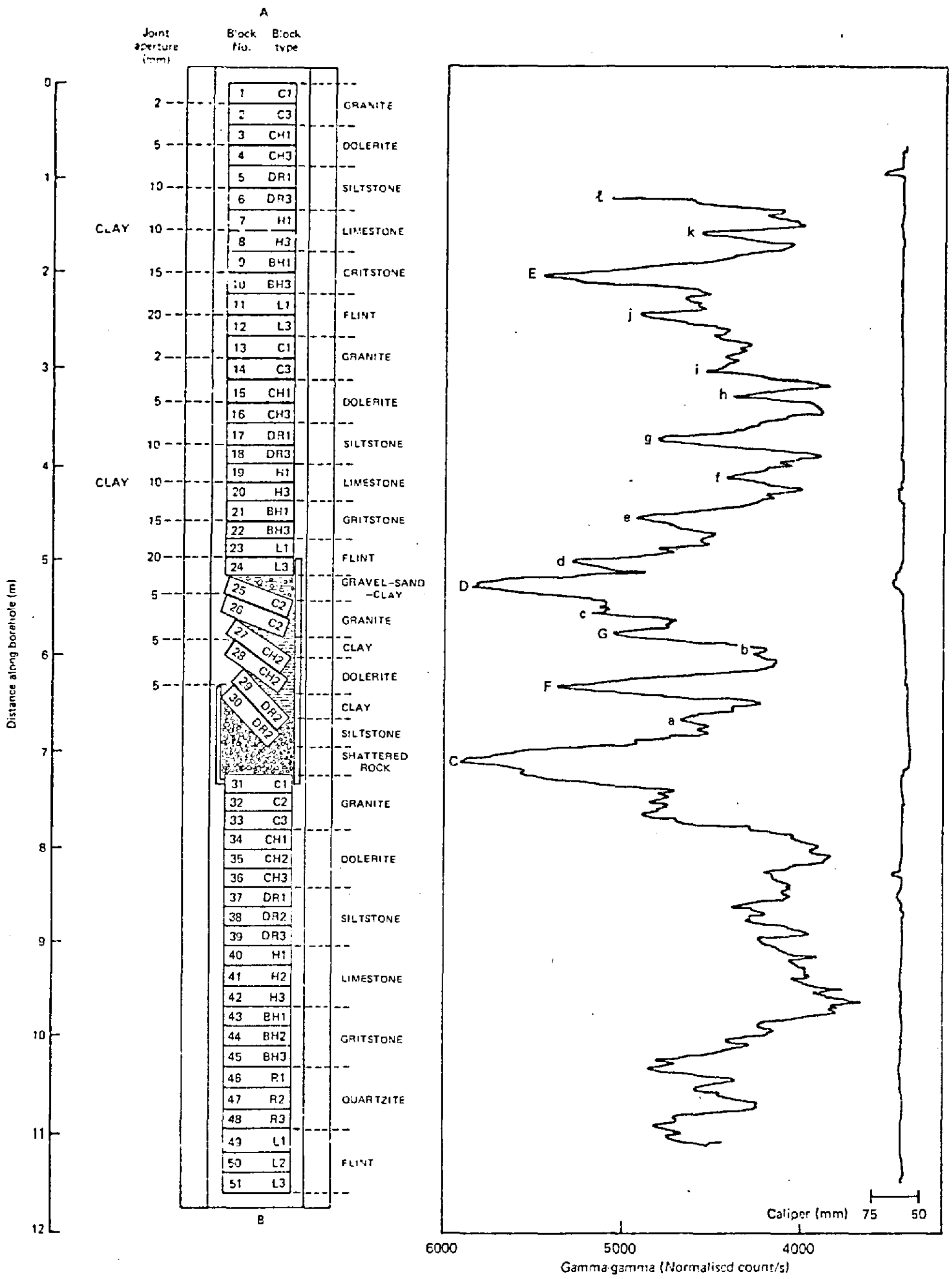

Fig. 6 GAMMA–GAMMA (SHORT SPACING DENSITY) LOG

1 correspond to open joints between blocks in the array. However, some peaks of comparable size occur in the section of blocks having all closed joints (end B), and this casts some doubt on the use of this log as an indicator of open joints.

Taken together, the two density logs have given a good indication of the array; the long spacing log has given an accurate measure of the overall density of the blocks and has indicated the two regions of low density in the central section of the array, while the short spacing log has indicated the presence of all the open joints between blocks — although not unequivocally.

4.2 Caliper log

In well logging it is customary to show the caliper log alongside the density log so that any major change in borehole diameter can be taken into account when interpreting the density log. The caliper log is therefore shown in Figures 5 and 6. It can be seen that the borehole is of constant diameter except for a slight variation when passing through the central section of the array. A peak at the junction of blocks 35 and 36 and another peak at the junction of blocks 4 and 5 may be due to overbreak when drilling the borehole.

4.3 Natural gamma log

The natural gamma log of the borehole is shown in

Figure 7. High natural radioactivity is shown by a high count rate at the detector. There are four main peaks on the log, at C, D, E and F, where the natural gamma radiation exceeds 60 count/s. These four peaks are all for sections of the array occupied by siltstone blocks, and the high levels of gamma radiation must arise from the clay in the siltstone. There are seven smaller peaks of gamma radiation at about 40 to 50 count/s and these are for granite and gritstone blocks. Granite is well known to be a source of natural gamma radiation (see Section 2.2) but the high count for the gritstone is probably due to the presence of some clay in the rock. The lowest levels of gamma radiation, 10 to 20 count/s, occur in flint and limestone blocks, both clay-free rocks.

The natural gamma logger has therefore performed well as an identifier of argillaceous rocks. The fact that it has also responded to the granite is no drawback because in nature argillaceous rocks and granites are found in different geological environments and there is little risk of confusion. It did not, however, detect the two 10mm thick clay-filled joints or the V-shaped fissures filled with clay in the central section of the array. This may have been because some of the clay in the joints and fissures has been washed out by the flushing water during drilling. When the drilling trials are completed and the assembly is dismantled this possibility will be checked.

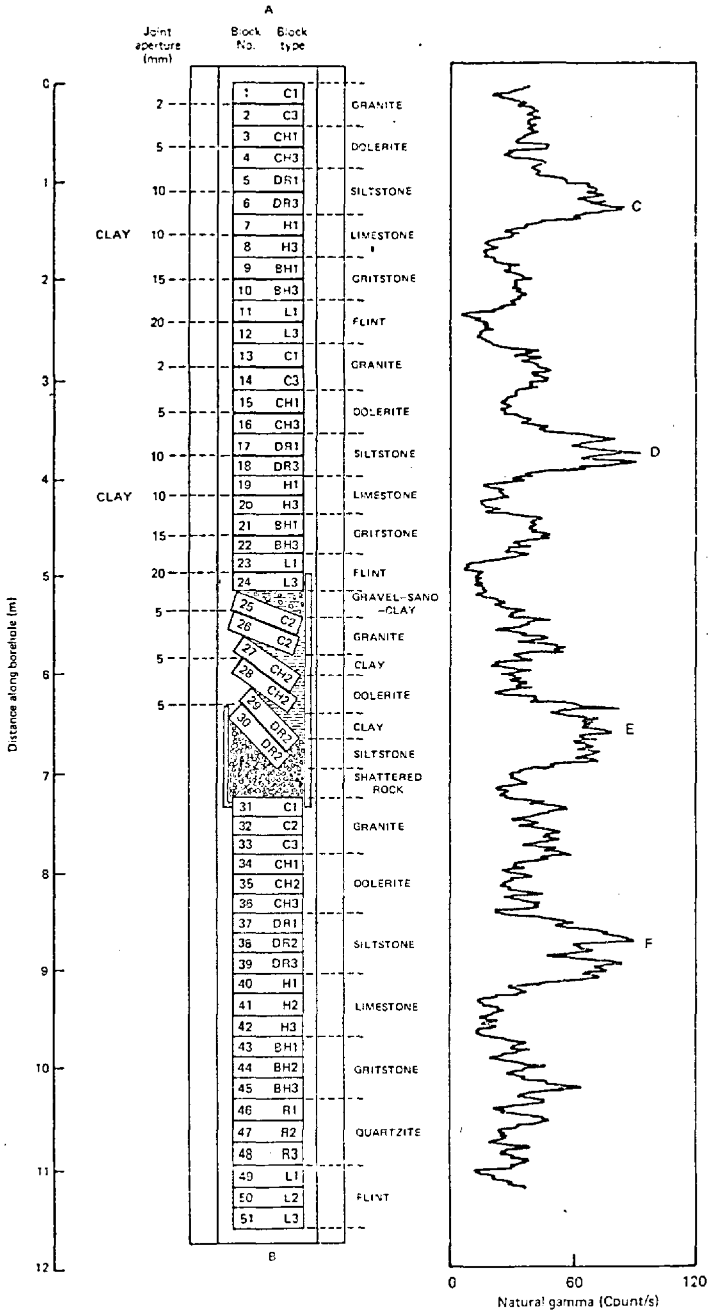

Fig. 7 NATURAL GAMMA LOG

4.4 Neutron-neutron log

The neutron-neutron log is shown in Figure 8. High neutron flux is shown by a high count rate at the detector. The highest peak on the log, at C, indicates the shattered rock zone, and the gravel-sand-clay is also indicated by the peak D. However the remainder of the log consists of a number of strong peaks and troughs which cannot be correlated with either block type or presence of joints.

4.5 Neutron-gamma log

The neutron-gamma log is shown in Figure 9. High neutron capture is shown by a high count rate at the detector. In contrast with the strong peaks and troughs shown in the neutron-neutron log (Figure 8), the neutron-gamma log shows a fairly uniform general level through the array of about 100 count/s. The peak at C corresponds to the shattered rock zone and is no doubt because of the high water content of this region (it will be recalled that this log was run in a water-filled hole). Other individual features of the log cannot be correlated with either block type or joints.

It is concluded that apart from picking up the shattered rock zone, neither the neutron-neutron log nor the neutron-gamma log have been able to indicate the nature or structure of the array, and therefore on the basis of these trials they would seem to have little application for probing ahead.

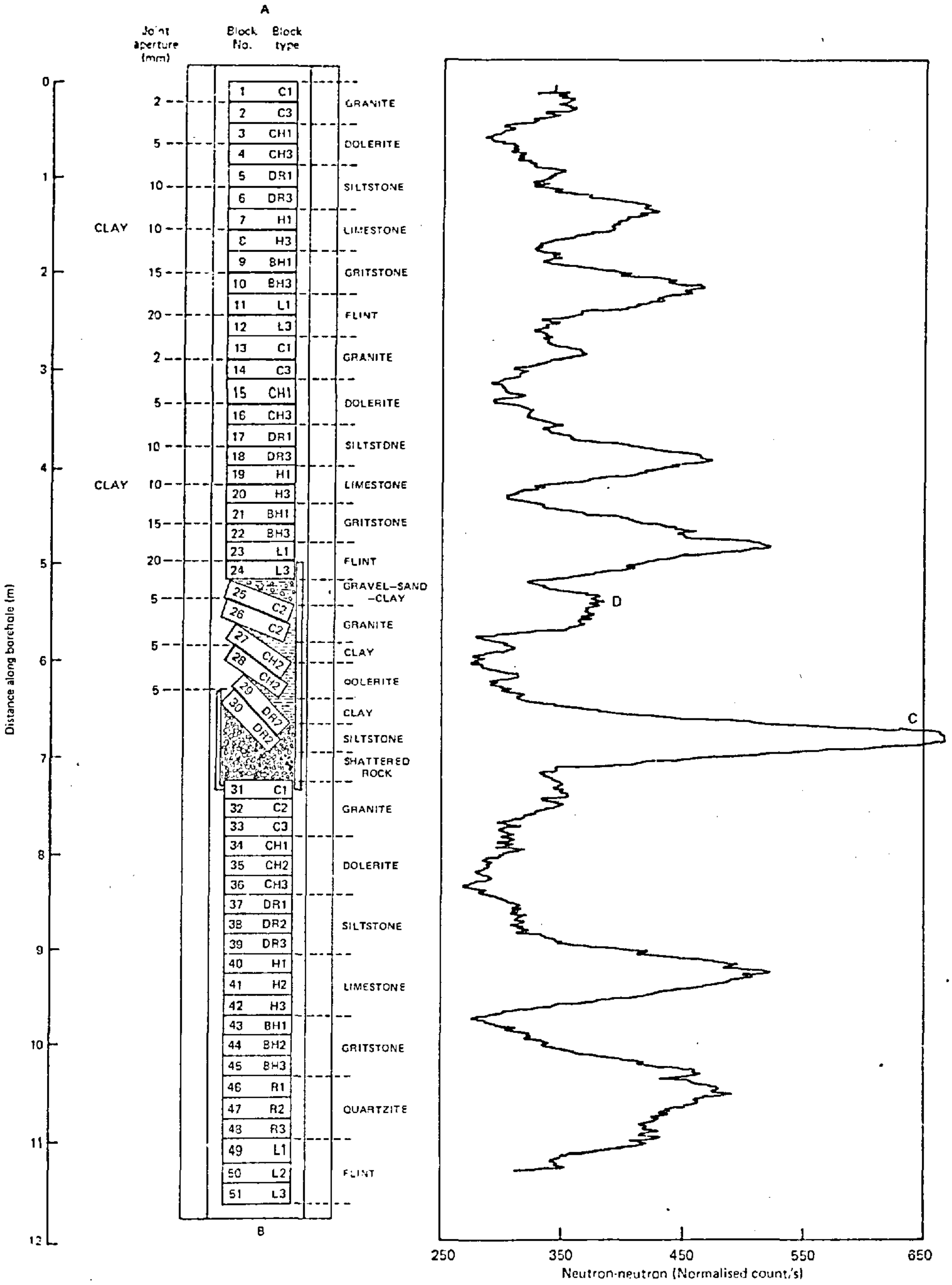

Fig. 8 NEUTRON–NEUTRON LOG

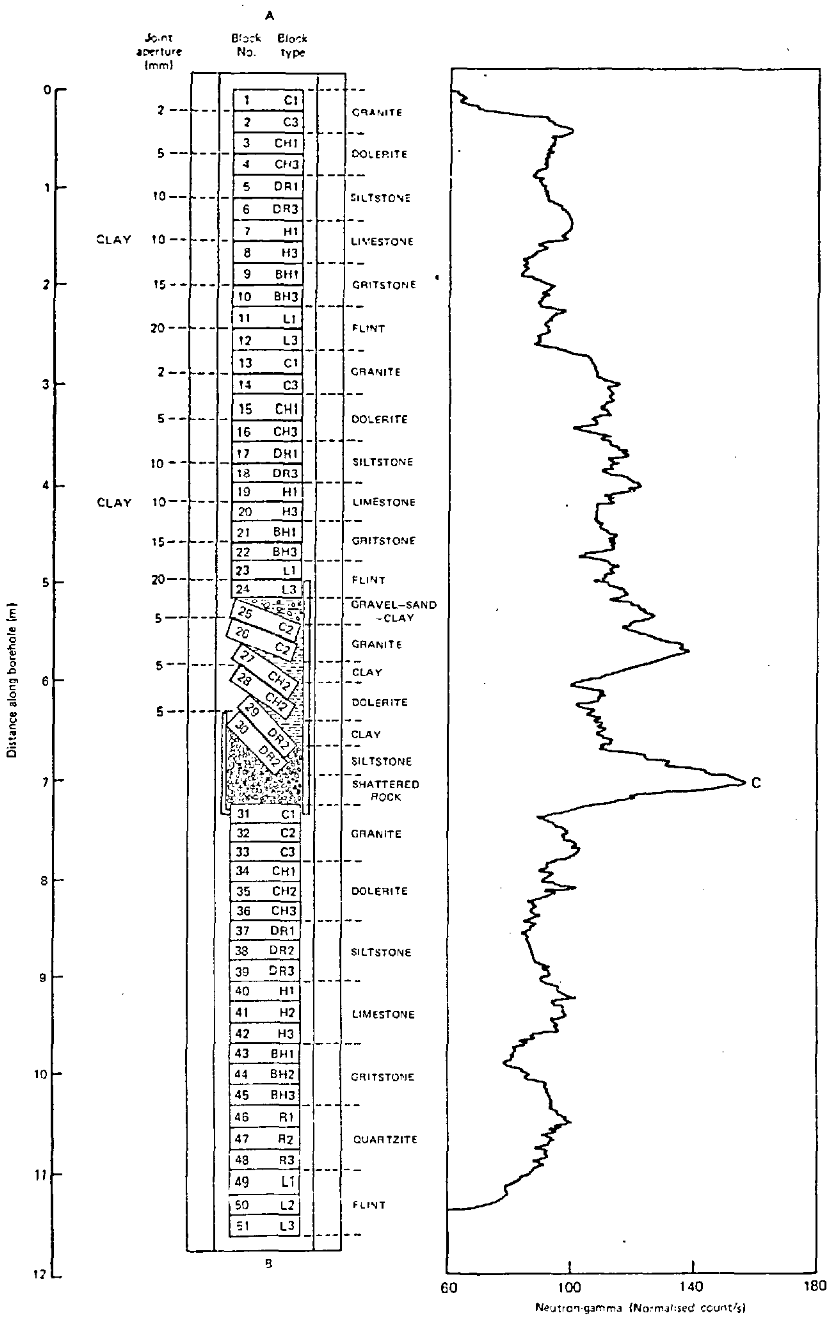

Fig. 9 NEUTRON–GAMMA LOG

4.6 Self-potential log

The self-potential log is shown in Figure 10. There is a general drift of the curve to the right showing decreasing self-potential as the electrode on the tool approached the electrode on the plinth at end A; this can be disregarded. The self-potential log is interpreted by drawing two lines, known as the shale line and the sand line, which define the positive and negative sides respectively of the envelope of the curve (Telford et al, 1976); these have been drawn on Figure 10. The proximity of the self-potential curve to either of these lines indicates the degree of shale or sand in the formation being logged. The blocks nearest in character to shale and sand are the siltstone and gritstone respectively. It can be seen that the self-potential curve has peaks lying towards the shale line at C, D, E and F which correspond to siltstone blocks, and peaks lying towards the sand line at G, H, and I which correspond to gritstone blocks. However other blocks also produce these effects, so the curve cannot be used diagnostically with confidence.

4.7 Resistivity log*

The resistivity log is shown in Figure 10. The section of blocks with closed joints at end B of the array shows fairly uniform resistivity, the section of blocks with open joints at end A shows some fluctuation of resistivity, while the central section of the array shows

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* Strictly speaking resistance, see page 40.

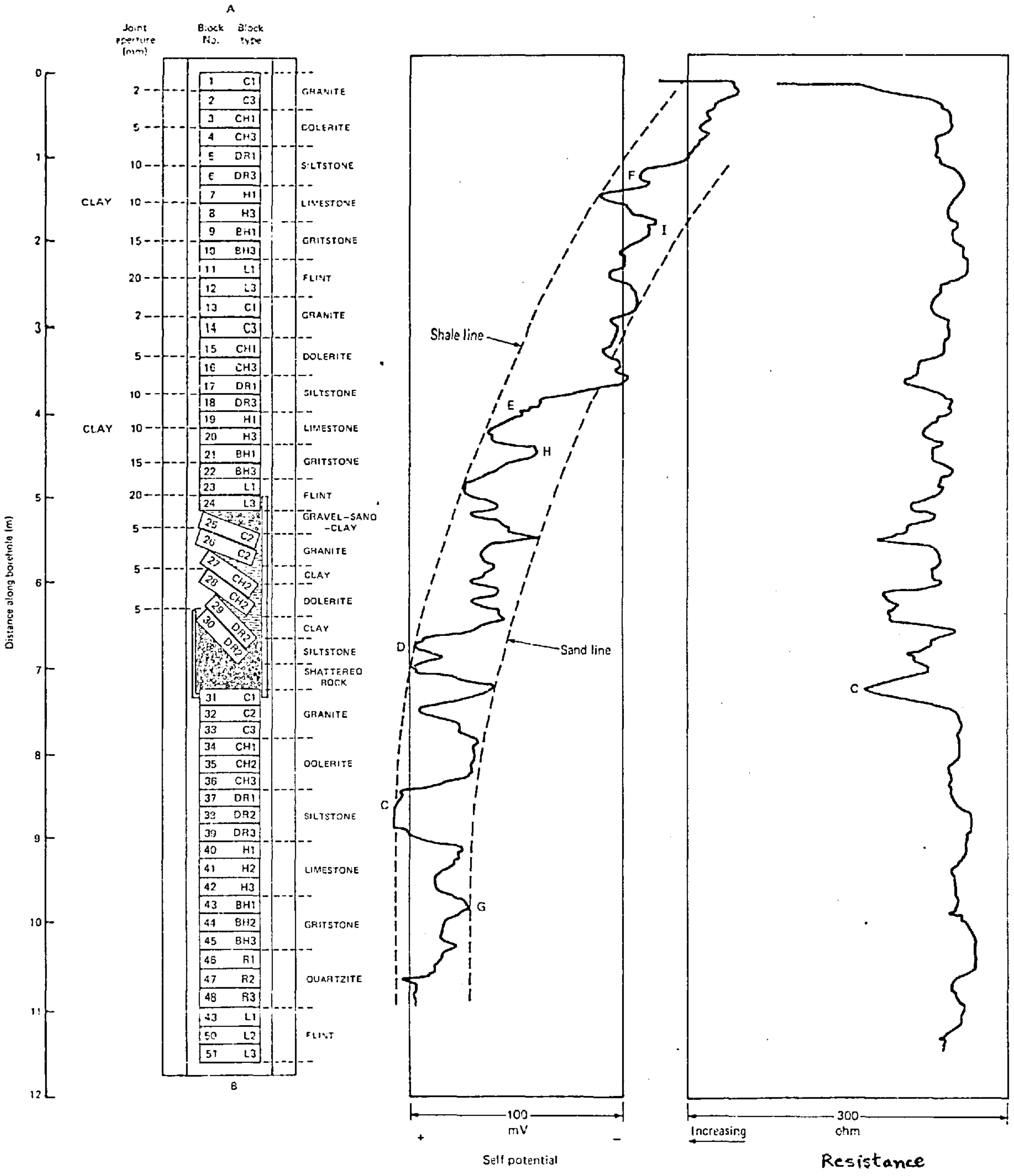

Fig. 10 SELF POTENTIAL AND RESISTIVITY LOGS

more marked fluctuation of resistivity including peak C which corresponds to the shattered rock zone. It can be noted that some of the features on the resistivity curve can be matched in reverse on the self-potential curve (for example, see the central section of the array). Apart from these rather general observations, the curve tells us little about the nature or structure of the test assembly.

On the basis of these trials it would seem that the self-potential tool and single-electrode resistivity tool would have little application for probing ahead.

4.8 Borehole television camera

The results of examining the borehole with the borehole television camera looking forward were most successful. The appearance of the borehole on the monitor screen was similar to the view of a circular tunnel seen when standing at the centre and looking along the axis. When the camera was pushed along with the drain rods the appearance was similar to that when travelling along a tunnel. Joints appeared as white circles around the borehole wall similar in appearance to the circumferential joints in a tunnel lining. The circles grew in size on the monitor screen as the camera approached the joints. Closed joints appeared as thin white circles while open joints appeared as thick white circles; in many cases the aperture of the joint could be clearly seen as the camera came close to the joint. The inclined joints also appeared as circles on the screen, but because of the perspective effect they had an asymmetrical appearance from which it could be deduced that they represented joints which were not at right angles to the borehole axis. The positions of the joints along the borehole were recorded as described in Section 3.7. Other features seen included longitudinal score marks made by the drill rods or logging tools, circumferential score marks made during drilling and, in some of the blocks, the aggregate in the concrete.

In the section of blocks at end A having numerous open joints, all the joints, both open and closed, were detected; the characteristic appearance of a joint is shown in Plate 7a. In the central section all the different features could be seen including the three inclined joints between blocks, which had an asymmetrical appearance as shown in Plate 7b, and the shattered rock zone. In the section of blocks at end B having all closed joints, all of the joints were detected.

Examination of selected parts of the borehole with the side-scanning head fitted to the camera was also successful. The appearance of the borehole on the monitor screen was similar to the view that would be had when standing in the centre of a circular tunnel and looking along the axis into a mirror held at 45 degrees to the tunnel axis. Because the borehole was not much greater in diameter than the camera, only a small portion of the borehole wall (about 22mm x 17mm) could be seen at any one time. At a

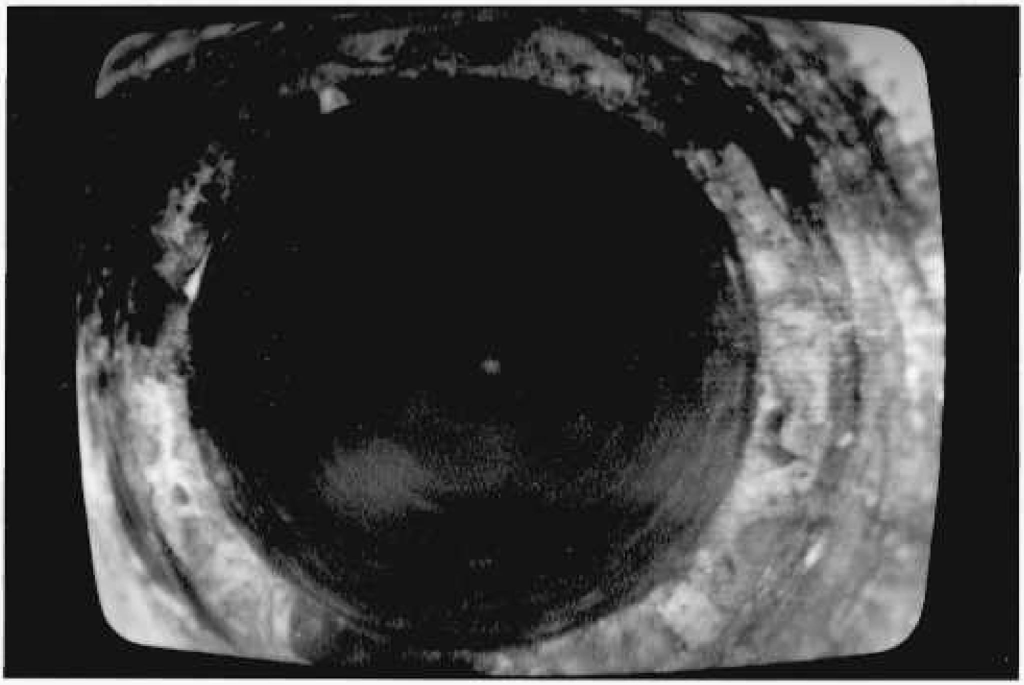

PLATE 7a Camera looking forward at 15mm wide open joint

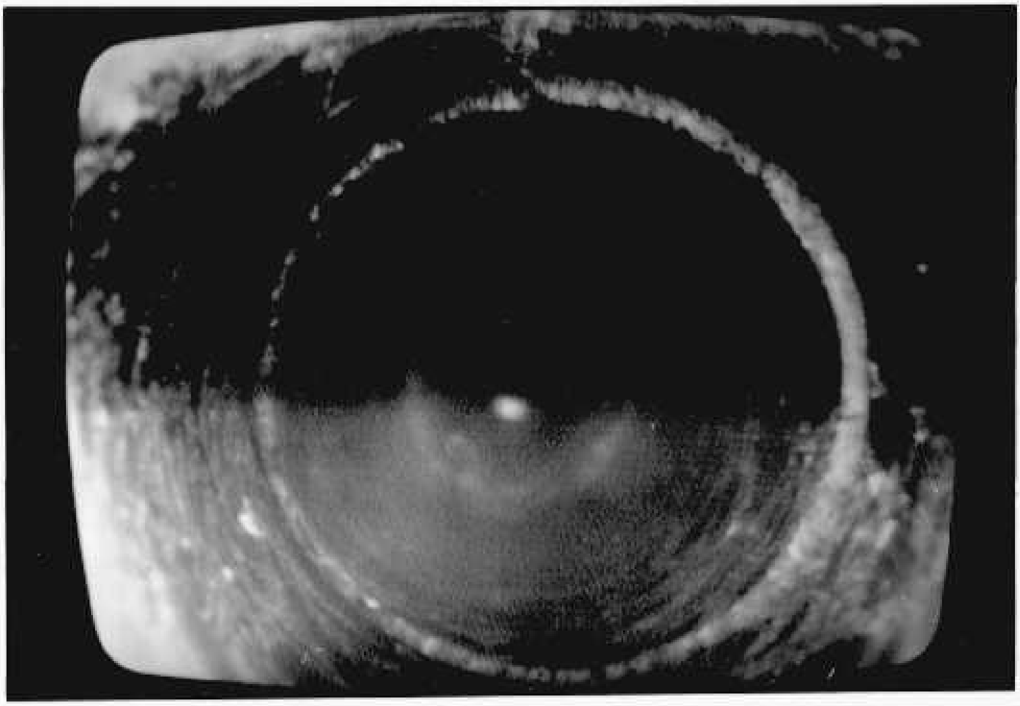

PLATE 7b Camera looking forward at 5mm wide joint inclined at 45 degrees

particular position, the borehole wall was scanned by rotating the mirror using a control on the camera control unit outside the borehole. It was found that the orientation of the image of a joint on the monitor screen depended on the position of the mirror; when the mirror was rotated the image of the joint rotated on the screen. Once the camera was in the borehole there was no way of knowing the position of the mirror, so that the orientation of the image could not be used to determine the orientation of the joint. Joint apertures could be clearly seen and it was found that their widths could be determined to within 1mm when the edges were undamaged and a sharp image could be seen (Plate 8a).

The borehole wall was also examined, and in some of the blocks the aggregate in the concrete could be clearly seen (Plate 8b) showing that the side scanner could be used to identify very coarse-grained rocks such as breccias and conglomerates. The shattered rock zone was also inspected and the individual pieces of rock could be seen. The circumferential score marks on the borehole wall were also seen. However, it was concluded that, except for the measurement of the width of joint apertures, the side-scanning head would be less useful in probing ahead than the forward-looking head.

The facility of making a videotape recording was also found to be most useful; in this way the borehole could be re-examined as required.

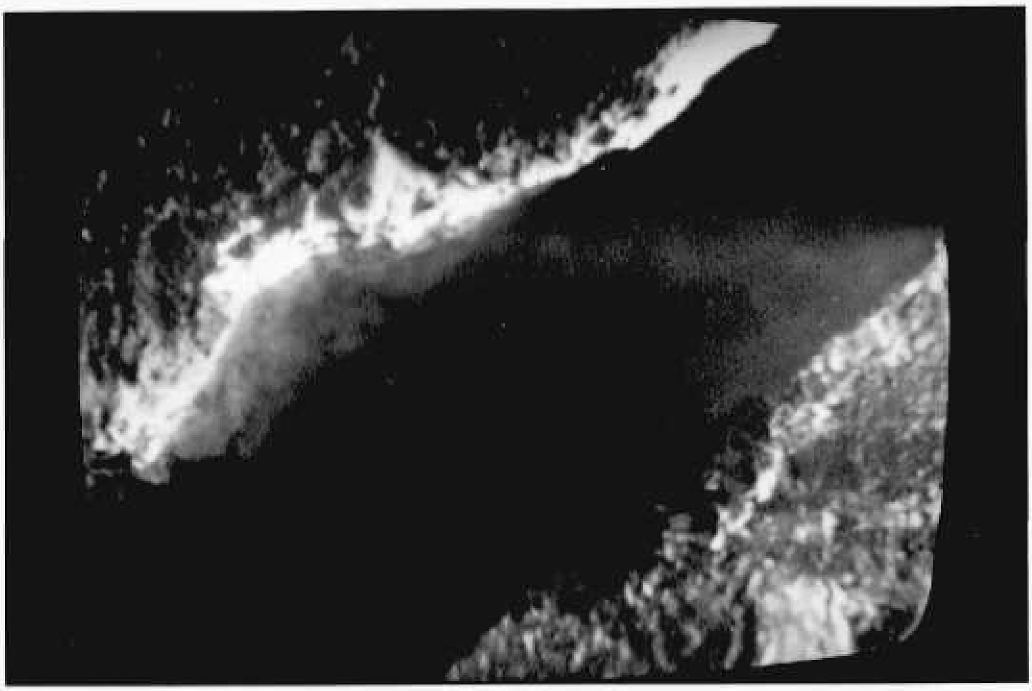

PLATE 8a Camera looking to side at 5mm wide joint inclined at 45 degrees

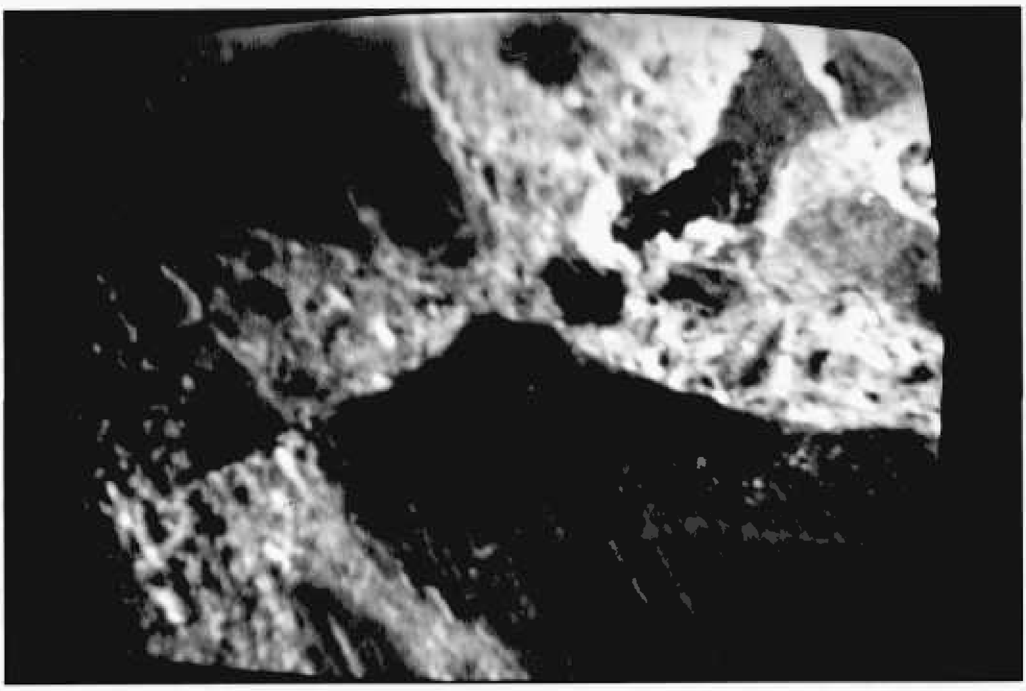

PLATE 8b Camera looking to side at borehole wall

It is concluded that the borehole television camera would prove most useful for probing ahead. Used in the forward-looking mode it is capable of locating closed and open joints and measuring their spacing, while the side scanner can be used to measure the width of joint apertures and to look at selected areas in more detail.

4.9 Ultrasonic velocity log

The ultrasonic velocity log is shown in Figure 11. The seismic wave velocity of the concrete ranges from 3000 m/s to 5000 m/s. It can be seen that the direct velocities determined on the intact cores (shown by solid circles on the log) agree reasonably closely with those determined by the velocity tool. However the purpose of velocity logging in this trial was not to determine the velocity itself, but to make an assessment of the strength of the material. This can be done for a given rock by using the velocity as a simple indication of the relative rock strength; the higher the velocity, the higher the strength of the rock. Alternatively, a quantitative relationship can be sought. This has been done previously in an empirical manner by Elvery (1973), who showed that the compressive strength C_o and the compressional wave velocity C_p of concrete could be related by the expression $C_o = Ae^{BC_p}$ where A and B are constants for the particular material being tested. Allard and Grenet (1972) also showed an experimental correlation of compressive strength and wave velocity for some rocks. But here a different approach will be followed.

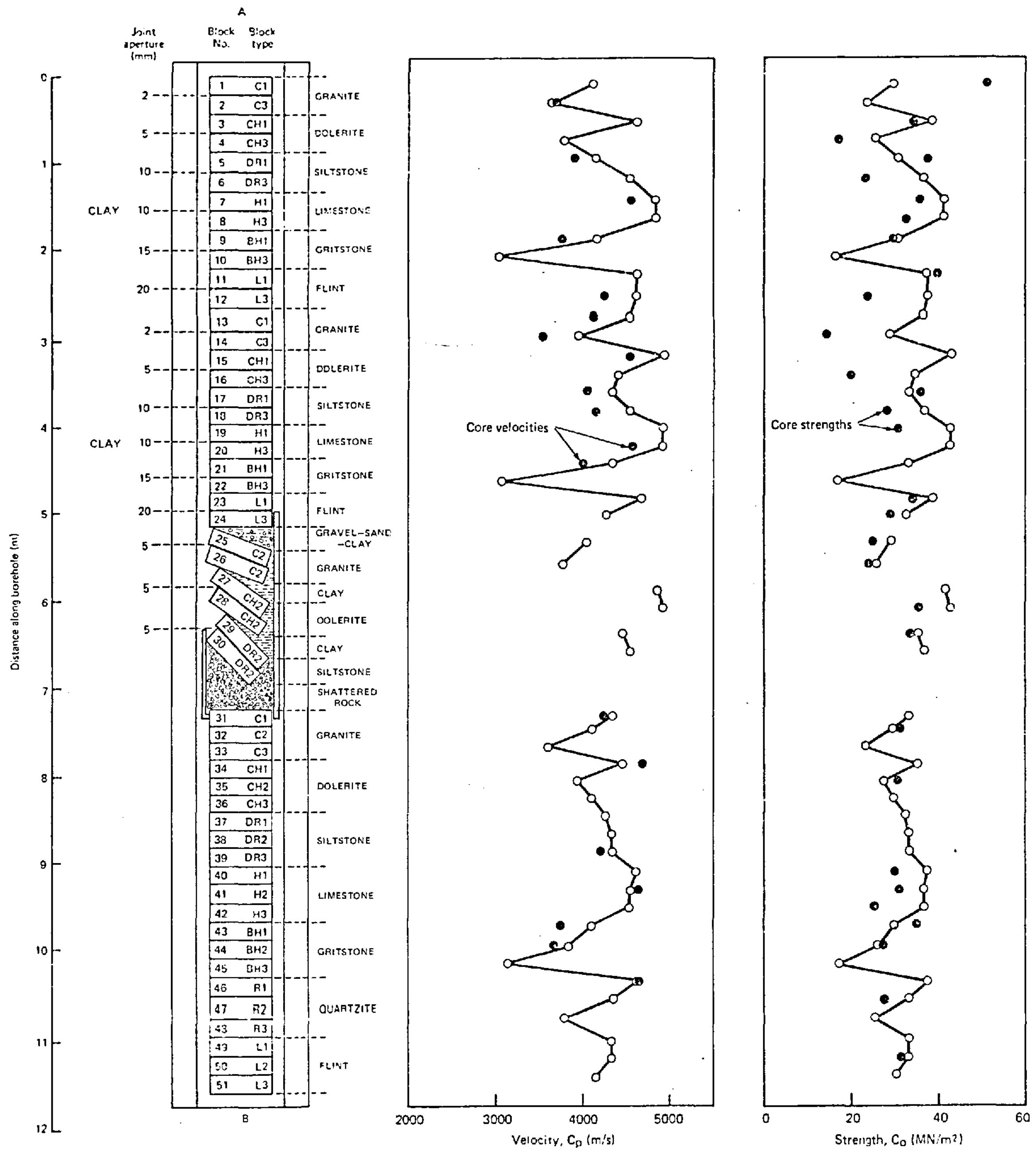

Fig. 11 ULTRASONIC VELOCITY LOG AND COMPRESSIVE STRENGTH LOG DERIVED FROM IT

4.9.1 Relationship between velocity and strength. For an unbounded elastic material, compressional waves (P-waves) propagate with a velocity C_p given by (Jaeger and Cook, 1976)

$$C_p = \sqrt{\frac{\lambda + 2G}{\rho}} \qquad \text{........ (1)}$$

where λ and G are Lamé's parameters and ρ is density.

$$\text{Now } \lambda = \frac{E\nu}{(1 + \nu)\ (1 - 2\nu)} \qquad \text{........ (2)}$$

$$\text{and } G = \frac{E}{2(1 + \nu)} \qquad \text{........ (3)}$$

where E is dynamic Young's modulus and ν is dynamic Poisson's ratio. Substituting (2) and (3) in (1) and simplifying we get

$$C_p = \sqrt{\frac{E(1 - \nu)}{\rho(1 + \nu)\ (1 - 2\nu)}}$$

$$\text{or } E = \frac{C_p^{\ 2}\ \rho(1 + \nu)\ (1 - 2\nu)}{(1 - \nu)} \qquad \text{........ (4)}$$

Using a value for the dynamic Young's modulus calculated from the mean properties of the concrete blocks given in Appendix 2, and a value of the compressive strength given by the mean of determinations made by Barr (1978) on core specimens, it was estimated that

$$E = 1000\ C_o \qquad \text{........ (5)}$$

where, as before, E is dynamic Young's modulus and C_o is compressive strength. Substituting (5) in (4) and re-arranging we get

$$C_o = \frac{C_p^2 \rho(1 + \nu)(1 - 2\nu)}{1000(1 - \nu)} \qquad \ldots\ldots\ldots (6)$$

In equation 6, C_o depends much more on C_p than on ρ or ν for values of ν less than 0.35. For the concrete blocks $\rho = 2.33$ Mg/m^3 (see Table 7 of Appendix 2) and $\nu = 0.292$ (see Table 8 of Appendix 2). Substituting these values in (6) we get

$$C_o = 1.77\, C_p^2 \qquad \ldots\ldots\ldots (7)$$

Equation 7 provided a means of estimating the compressive strength of the blocks from the velocity log.

It should be noted that the relationship between E and C_o (equation 5) is an empirical one and that the value of the coefficient, 1000, is applicable only to the concrete blocks of this test assembly. Each rock will have its own coefficient (for example, see equation 8 in Section 5.1.2). To give some idea of the likely range and variation of the coefficient, the values of E and C_o listed in their Appendix 2 by Lama and Vutukuri (1978) were abstracted and the coefficients calculated. The results were as follows:

Range	:	80 to 1660
Mean	:	392
Standard deviation	:	261
Number of samples	:	214

No correlation of the coefficient with the lithological type of the rock was apparent.

4.9.2 Strength log. The strength log, derived from the velocity log using equation 7, is shown in Figure 11. The compressive strengths of cylindrical specimens prepared from the more intact cores (Barr, 1978) are shown as solid circles on the same log. The agreement is reasonably close for some sections of the array. It can be seen that the actual compressive strengths are generally a little less than those derived from the velocity log, the difference of the means being about 2 MN/m^2. However, all the actual strengths fall within the range 14 to 51 MN/m^2, corresponding closely to the category of 'moderately strong' rocks (12.5 to 50 MN/m^2) of the classification system of the Geological Society Engineering Group Working Party (1970 and 1977), and all the derived strengths fall within the range 16 to 43 MN/m^2, showing that the strength log derived from the velocities was able to predict the general category of strength of the material if not always the actual strength of individual blocks.

It is, therefore, concluded that the ultrasonic velocity logger would be useful in probing ahead.

4.10 Conclusions of laboratory trials

From the analysis of the results of these trials an assessment of the potentiality of the various borehole logging methods has emerged. It can be seen that the gamma-gamma long spacing and short spacing density logs, which are obtained simultaneously, can provide useful information on the overall density of the material around the borehole and the presence of open joints respectively. The natural gamma logger, which is incorporated in the same tool, succeeded in indentifying the blocks made from naturally radioactive aggregates. Subject to the operational reservations outlined in Section 3.9, therefore, the combination tool has the potential to be a useful one for probing ahead of tunnels.

The neutron-neutron and neutron-gamma logs were not able to provide any information that the gamma-gamma long spacing density log had not already provided and were not able to indicate the nature or structure of the array. Because of this, and bearing in mind the possible hazard of the high strength source used, the neutron-neutron and neutron-gamma tools would seem to have little potential use for probing ahead.

The self-potential log suffered from uncertainty of interpretation, while little can be said of the resistivity log. It should also be remembered that the resistivity and self-potential tool suffers from the inconvenience, in a horizontal borehole, of requiring a liquid-filled hole in which to operate. These methods would seem, therefore, to have little potential use for probing ahead.

The borehole television camera is clearly of considerable use in probing ahead. Its application is in the detection ahead of the face of joints, cavities, broken ground and similar features of vital interest to the tunnel engineer. The spacing of joints can be measured with sufficient accuracy to classify the rock mass and to indicate primary support requirements; however, the orientation of joints cannot be quantitatively determined at present. The existing equipment could be used for inspecting boreholes ahead of the tunnel face with little modification so long as a suitable electrical power supply was available in the tunnel.

The ultrasonic velocity log shows velocities which are close to the velocities measured directly on cores. The ultrasonic velocity tool would be useful in probing ahead if the results were used simply as a method of indicating relative rock strength within a given rock type; higher velocities indicating higher strengths. However, an alternative approach of deriving the rock strength from velocity is suggested in Section 4.9.1. From the experience of the trials with the concrete blocks, it would seem that the results, whilst not giving the exact strengths of the rock ahead of the face, would give the engineer an indication of the category of rock strength to be expected in the forthcoming drive. The ultrasonic velocity logger described in Section 3.8 is a prototype, but a tool for routine use could be readily produced.

It will be recalled that two of the prime needs of the tunnel engineer from methods of probing ahead of tunnels are advance information on rock strength and joint spacing. On the basis of these trials and the assessment of them that has emerged it would seem that these needs can best be met by the borehole television camera and the ultrasonic velocity tool. The first of these is commercially available for purchase or hire and the second, although existing as a prototype only, could be readily manufactured.

In investigations where it is essential that information on joint orientation is obtained, it is suggested that the borehole impression packer be used (Barr and Hocking, 1976 and Harper and Hinds, 1978). This instrument has a proven capability of recording all the information from which the orientation of joints can be determined (Brown, Harper and Hinds, 1979). The existing borehole impression packer is designed for use in a 76mm diameter borehole, but the design might be adapted for smaller holes. The impression packer records can also be used to measure the width of joint apertures.

It should be noted that the conclusions of the geophysical logging of the test array relate only to one set of equipment operated by one firm. Other methods or other equipment may have potentiality when used for specific purposes.

CHAPTER 5

UNDERGROUND TRIALS

In order to demonstrate the practicability of logging horizontal boreholes under realistic conditions somewhat similar to those that might be encountered in actual probing ahead of tunnels, some underground trials were carried out. The methods employed were television borehole logging and ultrasonic velocity logging because, as discussed in Section 3.9, these are the only tools of those tested in the laboratory trials that are at present capable of being used underground without extensive modification.

The site of the underground trials was a disused underground Bath Stone quarry at Corsham, Wiltshire. Here the Great Oolite Limestone has been worked in underground galleries some 30m below ground level (Kellaway and Welch, 1948). A very comprehensive description of the underground workings and the method of winning and dressing the stone, illustrated by numerous photographs, has been given by Hudson (1971), who has also provided a briefer account, also illustrated (Hudson, 1976). Lithologically the rock is a pale yellow oolitic limestone. The hole that was logged was drilled horizontally from A to B through a large section of rock comprising part of the wall of one of the galleries (Plate 9) using the same drilling rig that was used to drill the hole for the laboratory trials; as before, the borehole was 56mm in diameter. Cores obtained during drilling were placed in core boxes and brought back to the Laboratory

PLATE 9 Site of underground trials. Borehole was drilled through rock wall on right

where the seismic wave velocity, density and compressive strength of selected pieces were determined as described in Appendix 4.

5.1 Ultrasonic velocity logging

The ultrasonic velocity tool was the same one that was used for the laboratory trials with the exception that an amplifier was fitted between the receiver and the oscilloscope. This gave a stronger and improved display of the received signal on the oscilloscope screen, and in many cases it was possible to recognise and measure the shear wave arrival as well as the compressional wave arrival which was useful because it allowed an estimate of the dynamic Poisson's ratio of the rock to be made.

The pulse generator and oscilloscope were set up at end B of the borehole (Plate 10a) and logging was carried out by attaching drain rods to the tool and advancing it along the borehole. A surveyor's measuring tape, graduated to 0.01m, was also attached to the tool with its zero midway between the transducers and velocity measurements were made every 140mm (it will be recalled that 140mm is the spacing between the transducers) until a distance of 14m was reached which was governed by the length of cable that happened to be fitted to the tool. The drill was then swung out of the way, the apparatus was set up at end A (Plate 10b) and the remaining 5m of borehole was logged from this end in a similar manner.

PLATE 10a Ultrasonic velocity logging of underground borehole at end B

PLATE 10b Ultrasonic velocity logging of underground borehole at end A

No difficulties were encountered in logging the borehole. The mechanical coupling proved effective, a strong signal being received on the oscilloscope except at certain positions where no signal at all was received. These positions were noted to see if they corresponded with any joints found during the television logging which was to be done subsequently.

5.1.1 Ultrasonic velocity log. The ultrasonic velocity log for the underground borehole is shown in Figure 12. Apart from one low reading at position C and the positions indicated where no signal was received, the seismic wave velocity of the rock ranges from 2500 m/s to 4000 m/s. It can be seen that the direct velocities determined on cylindrical specimens cut from the borehole cores, shown by solid circles on the log, agree very closely with those determined by the borehole logging tool.

5.1.2 Strength log. To compile the strength log, an expression relating the strength to the compressional wave velocity similar to that developed in Section 4.9.1 was required. From the properties of the oolitic limestone at Corsham determined from the borehole cores and given in Appendix 4 it was estimated that

$$E = 1150\ C_o \qquad \ldots\ldots\ldots (8)$$

Substituting (8) in (4) we get

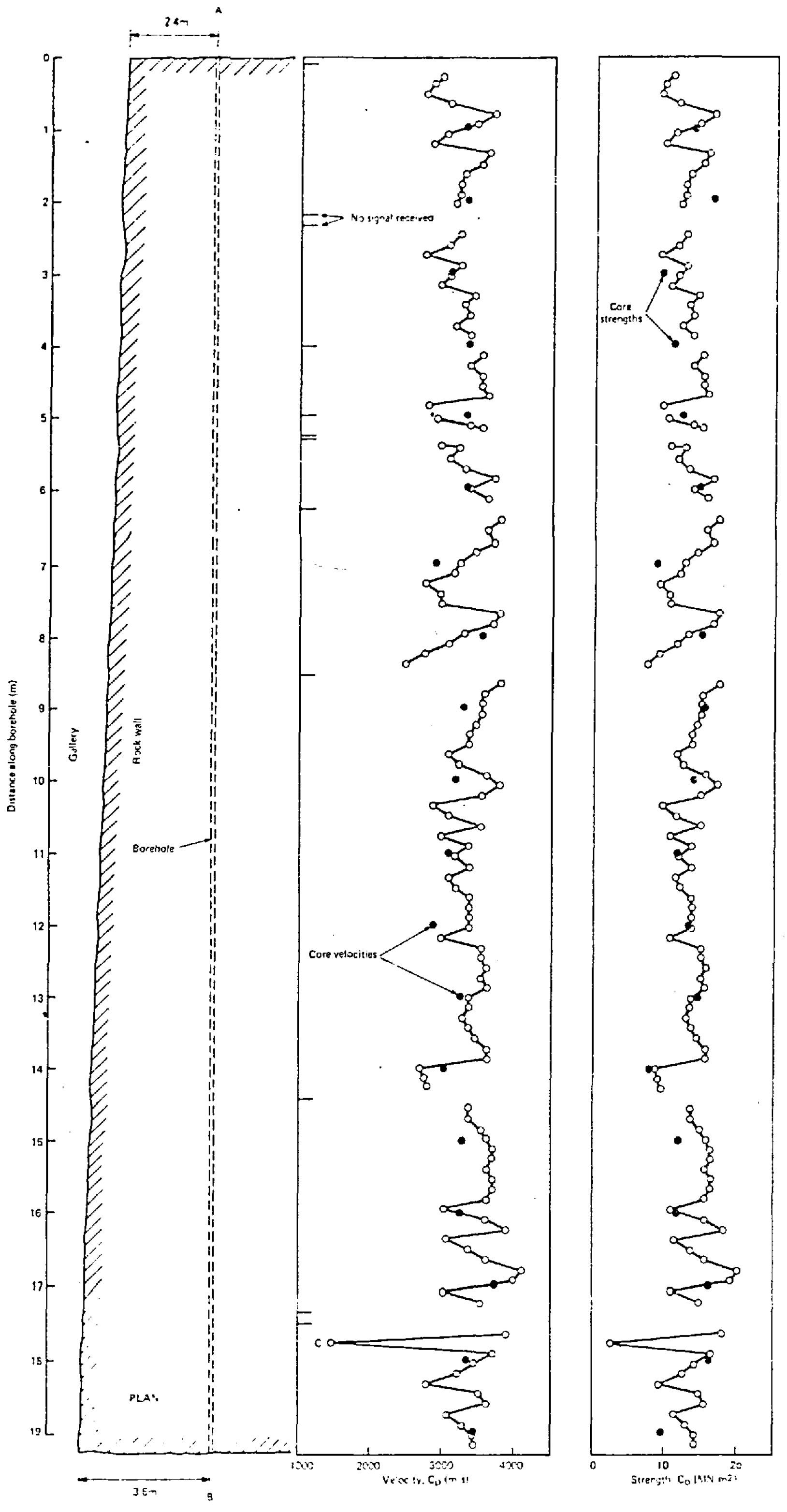

Fig. 12 ULTRASONIC VELOCITY LOG AND COMPRESSIVE STRENGTH LOG DERIVED FROM IT FOR BOREHOLE THROUGH OOLITIC LIMESTONE

$$C_o = \frac{C_p^{\,2}\ \rho(1 + \nu)\ (1 - 2\nu)}{1150\ (1 - \nu)} \qquad \ldots\ldots\ldots (9)$$

For the oolitic limestone $\rho = 2.07$ Mg/m^3 and $\nu = 0.333$; substituting these values in (9) we get

$$C_o = 1.20\ C_p^{\,2} \qquad \ldots\ldots\ldots (10)$$

The strength log, derived from the velocity log using equation 10, is shown in Figure 12. The compressive strengths of cylindrical specimens prepared from the cores are also shown by solid circles on the same log. It can be seen that the mean level of strength of the strength log derived from the velocity log agrees with the mean level of strength of the cores; this was expected because equations 8 and 10 were obtained using mean values of the properties of the oolitic limestone determined from the cores. However, Figure 12 also shows that many of the individual core strengths lie very close to or actually on the strength log; 15 out of 19 points being closer than 3 MN/m^2 and no point being further than 4.5 MN/m^2 away. This generally close correspondence does not necessarily follow from the assumptions made in deriving the relationship between strength and velocity, and therefore can be considered as indicating that equation 10 is valid for this particular rock.

The strength of the oolitic limestone ranges from 8 to 20 MN/m^2, omitting one low value derived from the low velocity reading at C. The rock, therefore, falls into the strength categories of 'moderately weak' (5 to 12.5

MN/m^2) and 'moderately strong' (12.5 to 50 MN/m^2) of the classification system of the Geological Society Engineering Group Working Party (1970 and 1977).

Comparing the results of the underground trials (Figure 12) with the results of the laboratory trials (Figure 11), it can be seen that the velocity log and the strength log are closer to the core velocities and core strengths in the underground trials than in the laboratory trials. The ultrasonic velocity logger has, therefore, performed rather better in logging the borehole through real rock than in logging the borehole through the laboratory test assembly of concrete blocks.

5.2 Television logging

The borehole television camera and control system was of the same model as had been used for the laboratory trials except that an additional television monitor and a waveform monitor were provided for the use of the television operator.

The control unit and television monitors were set up at end B of the borehole. Drain rods and a surveyor's measuring tape, graduated to 0.01m, were attached to the camera which was then introduced into the borehole (Plate 11a). As before, the borehole was too small in diameter for the centering device to be used on the camera. The camera and its cable were then advanced along the borehole from B to A using the drain rods (Plate 11b). The borehole was logged by stopping the camera every time a feature was

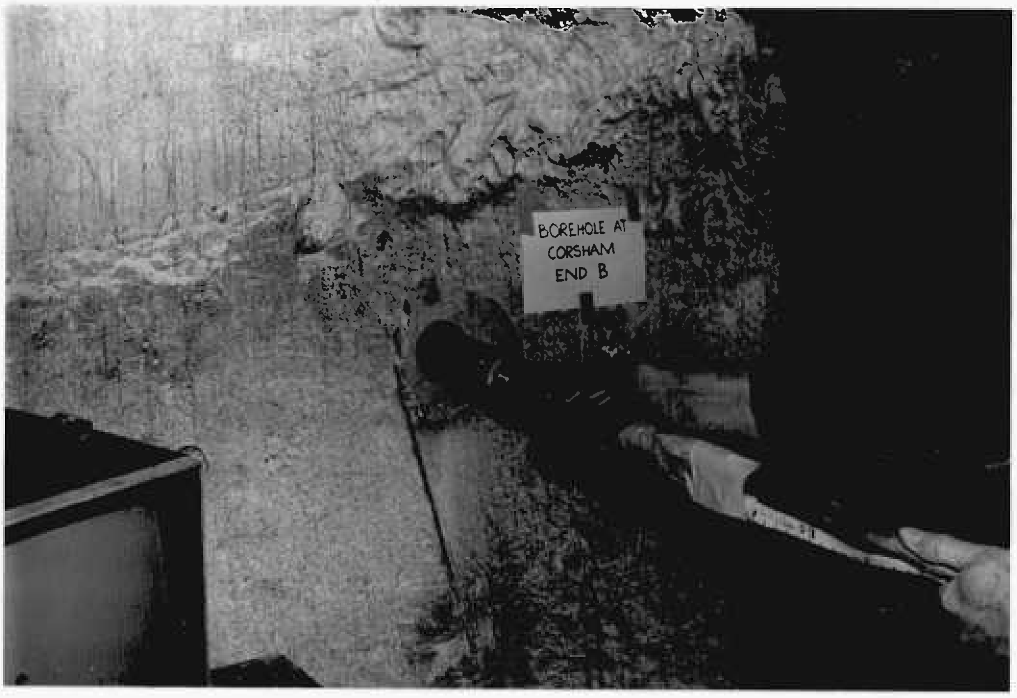

PLATE 11a Introducing camera into underground borehole at end B

PLATE 11b Television logging of underground borehole

encountered and noting the nature of the feature and its distance along the borehole as indicated on the measuring tape. The whole distance from B to A was also recorded on videotape. Still photographs of selected features were taken by photographing the monitor screen when viewing the videotapes back at the Laboratory.

5.2.1 Television log. The borehole television log, compiled as described above, is shown in Figure 13. Three kinds of feature could be seen: minor joints, major joints and cavities. These are distinguished on the log together with joints that could only be seen in part of the borehole wall. This classification was based on the experience of the appearance of different kinds of joints and cavities seen in the laboratory trials. Minor joints were recorded when the the television image was a thin white line around the borehole wall, major joints were recorded when the television image was a thick white line or when a definite joint aperture could be seen, and cavities were recorded when a large void could be seen. Minor and major joints are shown in their correct position on the television log, but cavities are shown not only in their correct position but with their length along the borehole shown to correct scale because the positions of both ends of each cavity were recorded. Where inclined joints were seen they are indicated as such on the log in a qualitative manner. The technique of recording joint position was the same as that used in the laboratory trials and described in Section 3.7.

From the television log a joint spacing log has been

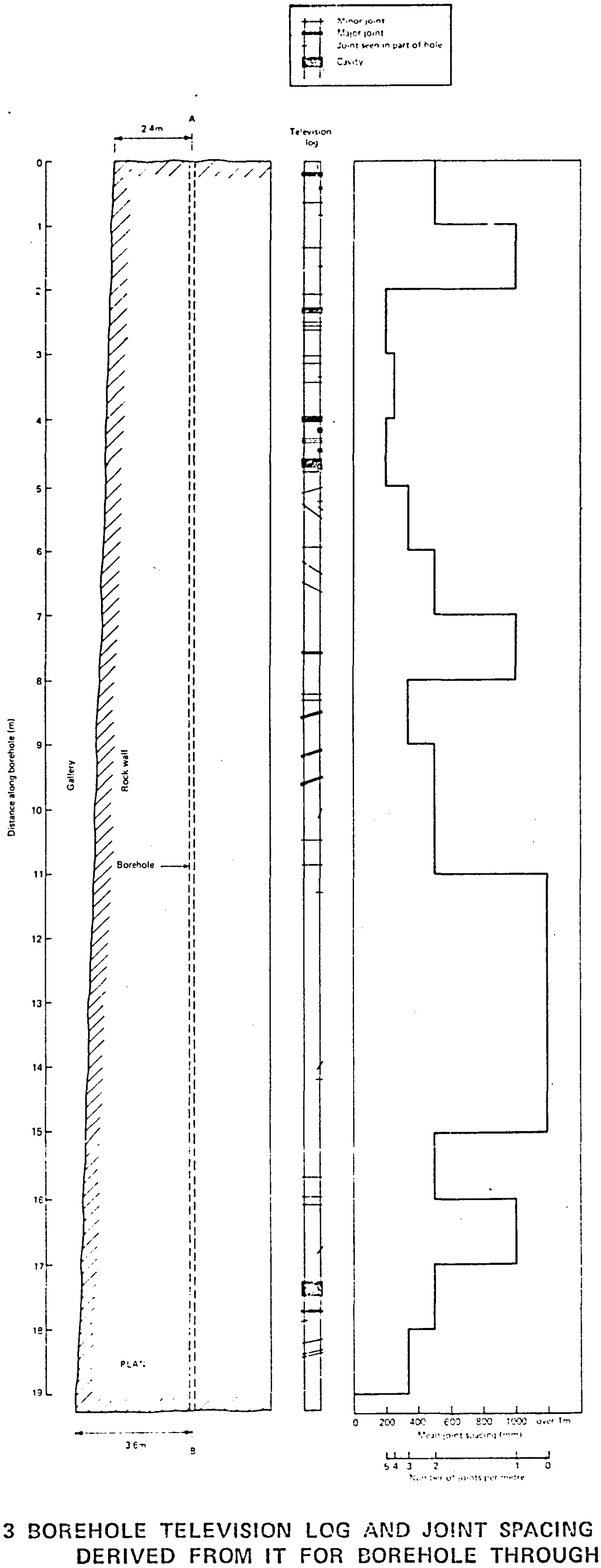

Fig. 13 BOREHOLE TELEVISION LOG AND JOINT SPACING LOG DERIVED FROM IT FOR BOREHOLE THROUGH OOLITIC LIMESTONE

derived which shows the mean joint spacing and the number of joints per metre for each metre of the borehole. In deriving the joint spacing log, cavities were counted as joints but the joints seen only in part of the hole were disregarded. The mean joint spacing is seen to vary from 200mm to over 1m, thus falling into the joint spacing categories of 'wide' (200 to 600mm) and 'very wide' (600mm - 2m) of the classification system of the Geological Society Engineering Group Working Party (1977). It can be noted that there is a large section of the borehole in which there are no joints for almost 5m. This is particularly interesting bearing in mind that the site was once an underground Bath Stone quarry.

If minor joints are disregarded, it can be seen that there are only 10 major joints and cavities along the whole 19m length of borehole, giving an overall mean joint spacing of almost 2m, and that the length of borehole without joints rises to almost 8m. These values are consistent with the fact that the galleries in the underground workings are mostly unsupported over wide spans (see Plate 9).

The positions of the joints and cavities were compared with the positions where no signal was received during the ultrasonic velocity logging and it was found that in every case except one the position of a joint or cavity corresponded to the positions where no signal was received. A joint also occurs at position C in Figure 12 where a low velocity was measured. However, signals were received at the positions of other joints and it may well be that in these cases the joints are acoustically closed by normal pressure or by filling material; previous work has shown that both these conditions can allow joints to transmit seismic waves (New and West, 1979).

Plate 12 shows the large cavity encountered at 17.3m along the borehole (see Figure 13). Because it is a photograph of the monitor screen taken from videotape, it lacks some of the quality of the original picture seen while logging.

5.3 Operational notes

For both the ultrasonic velocity logging and the television logging a four-man team was used. The author led the team and was responsible for planning and organising the work and for recording and logging all the results in a notebook as they were obtained. A technical assistant had the sole responsibility of seeing that the apparatus functioned properly. Two general assistants were responsible for rod, cable and tape handling and for providing the tension on the cord which actuated the mechanical coupling arrangement of the velocity logger. Having four men was also an advantage for manhandling while getting all the equipment, drain rods etc underground.

Each logging operation took about three hours, not including the time to transport the equipment underground, but including the time taken to set it up at the logging

PLATE 12 Large cavity encountered at 17.3 m along underground borehole

position and test that it was in working order and to assemble drain rods, attach cable etc. Processing of the results took place back at the Laboratory.

A 240 volt AC, 13 amp mains electricity supply was available underground at the logging position as was electric lighting - this proved to be of great benefit.

5.4 Conclusions of underground trials

The underground trials were most successful, demonstrating the practicability of logging a horizontal borehole in conditions to some extent similar to those that would be encountered in probing ahead of tunnels.

The ultrasonic velocity tool, although only a prototype, performed particularly well, it proving just as easy to use underground as it had been in the laboratory trials. On the few occasions when no signal was received, these proved to be in positions where joints or cavities were subsequently detected in the borehole during television logging. Also, it proved possible to derive the strength of the rock from the velocity log. Although the full procedure for doing this has been followed here, it is suggested that in practice it could be assumed that $C_o = DC_p^2$, and by obtaining some cores and directly measuring C_o and C_p, the value of D could be determined for the rock to be logged. The fact that the prototype ultrasonic velocity logger performed so well coupled with the possibility of using the results to indicate rock strength shows that this tool has considerable potentiality for use in probing ahead. The underground trials have confirmed the view that a version of the tool for routine probing ahead could be easily developed.

The borehole television camera provided considerable information on the nature and position of joints and cavities along the borehole. The underground trials have confirmed the view that borehole television logging would be worth doing with the existing equipment even if no further development of any other borehole logging methods is made. The trials have shown that it is a simple matter to advance the existing camera and its cable along a borehole by attaching them to drain rods. Since completing this work the development of an even more compact borehole television camera system than the one used in these trials has been announced (Anon, 1979).

CHAPTER 6

FINAL REVIEW AND RECOMMENDATIONS FOR FURTHER RESEARCH

The conclusions of the laboratory and underground trials have been given in Sections 4.10 and 5.4 respectively. These conclusions, together with the operational observations (Sections 3.9 and 5.3), show how the immediate objectives of the research have been attained. However it is also desirable to review the possible future prospects for probing ahead and for geophysical and television logging, and in the light of this review and the research results, to make recommendations for the future development of geophysical and television borehole logging methods. This will now be done.

The future of geophysical and television logging of horizontal boreholes for probing ahead of tunnels is, of course, critically dependent on the future prospects of probe drilling ahead of the tunnel face. In the Introduction two contrasting British attitudes towards probing ahead of the tunnel face by drilling were illustrated by the Channel Tunnel and the Kielder Aqueduct Tunnels. It was seen that at the present time the decision on whether to drill probe holes ahead of the face on a regular basis is only made if the risk to men or machinery is perceived to be high - as it is in the case of an underwater tunnel but generally not for other tunnels. Two recent examples from abroad reinforce this view and suggest that it may be widely held.

On the Seikan Undersea Tunnel, Japan, where the risk of flooding due to ingress of water along major faults and fault zones is high, probe drilling ahead of the face is being regularly practised (Anon, 1978). Horizontal boreholes are driven up to 700 to 1000m ahead of the face by drilling from special working chambers on each side of the tunnel near the face. As well as providing information on water conditions ahead of the drive and allowing grouting to be carried out, the boreholes were used for investigation of rock conditions (Mochida, 1979). It has also been said that some acoustic and resistivity borehole logging was carried out (Kitamura, 1979), but no published account has been seen to date except for a mention in a technical report in Japanese (Seikan Tunnel Technical Investigation Committee, 1972).

On the Beas-Sutlej Tunnels, India, which were not underwater drives, probing ahead was not routinely practised. Many fatal accidents occurred during construction of the tunnels, of which 29 were due to rock falls at tunnel headings and six were due to the unexpected bursting of tunnel headings. In an analysis of the causes of these accidents (Malhotra, 1977), the Superintending Engineer of the project considered that had the drilling of probe boreholes, say 100 to 150m ahead of the tunnel face, been carried out as a regular procedure, the unexpected situations which led to many of the fatalities could have been eliminated or minimised. It was considered that probing ahead would have warned the tunnel crew of dangerous conditions ahead of the face by disclosing the nature and condition of the rock and the presence of ground water under pressure.

However in Britain the situation may well change. The Health and Safety at Work etc Act (1974) states that it is the duty of every employer to ensure the safety at work of all his employees. One of the matters to which that duty extends includes in particular:

> "So far as is reasonably practicable as regards any place of work under the employer's control, the maintenance of it in a condition that is safe and without risks to health and the provision and maintenance of means of access to and egress from it that are safe and without such risks."

It may well be that routine probing ahead of tunnels will become more common as a result of the need for the employer to give some reasonable assurance that he is complying with the Act.

If for this, or other reasons, probing ahead was to become more widely practised than it is at present, then the case for developing those methods of geophysical and television logging that have been shown here to have potentiality becomes strong, because once drilled the holes could be quickly logged. The research work described in this thesis has identified the borehole logging methods that seem most promising, and the following recommendations for their development are made on the assumption that the prospects for probe drilling are good.

6.1 Borehole television camera

The research has shown that the borehole television camera was most successful in showing the presence of joints, cavities and other features and that existing equipment could be used in probing ahead with little modification. However there are two areas where development and further research would be useful.

The first need is to provide some means of indicating the orientation of the camera during logging and the full requirements for doing this are means of showing the way up, the bearing and the inclination of the camera. A method of showing the way up is the most necessary of these, and could be provided by the incorporation into the front of the camera of a spirit level or simple gravity-operated device such as a pendulum or ball which would be visible in the field of view. In addition, a means of showing the position of mirror in the side-scanning head is required.

The second need is for research into determination of joint orientation from the television pictures. It will be recalled from Section 4.8 that a joint at right angles to the borehole axis had a symmetrical circular appearance on the television screen (Plate 7a) while a joint which crosses the borehole obliquely had an asymmetrical circular appearance (Plate 7b). This difference in appearance provided a qualitative indication of joint orientation relative to the borehole, but what is needed is a quantitative method. The following analysis provides the theoretical basis for a possible approach.

The intersection of an inclined joint with a horizontal borehole is an elliptical line on the borehole wall. This is also true, of course, for a tunnel and the elliptical traces are well shown in the photographs of a wooden block model representing a horizontal tunnel in jointed rock that are given by Ward (1978). To define the orientation of a joint two properties must be determined: the angle of dip of the joint from the horizontal, α, and the angle between the strike of the joint and the borehole axis, θ. Angles α and θ can be determined as follows.

Figure 14 shows the side elevation and plan of a horizontal borehole with the elliptical trace of an intercepted inclined joint. Points P and Q are where the ellipse touches the crown and invert of the borehole and R and S are points where the ellipse touches the springlines of the borehole. Then, angles θ and α are given by:

$$\tan \theta = \frac{d}{n} \qquad \text{........ (11)}$$

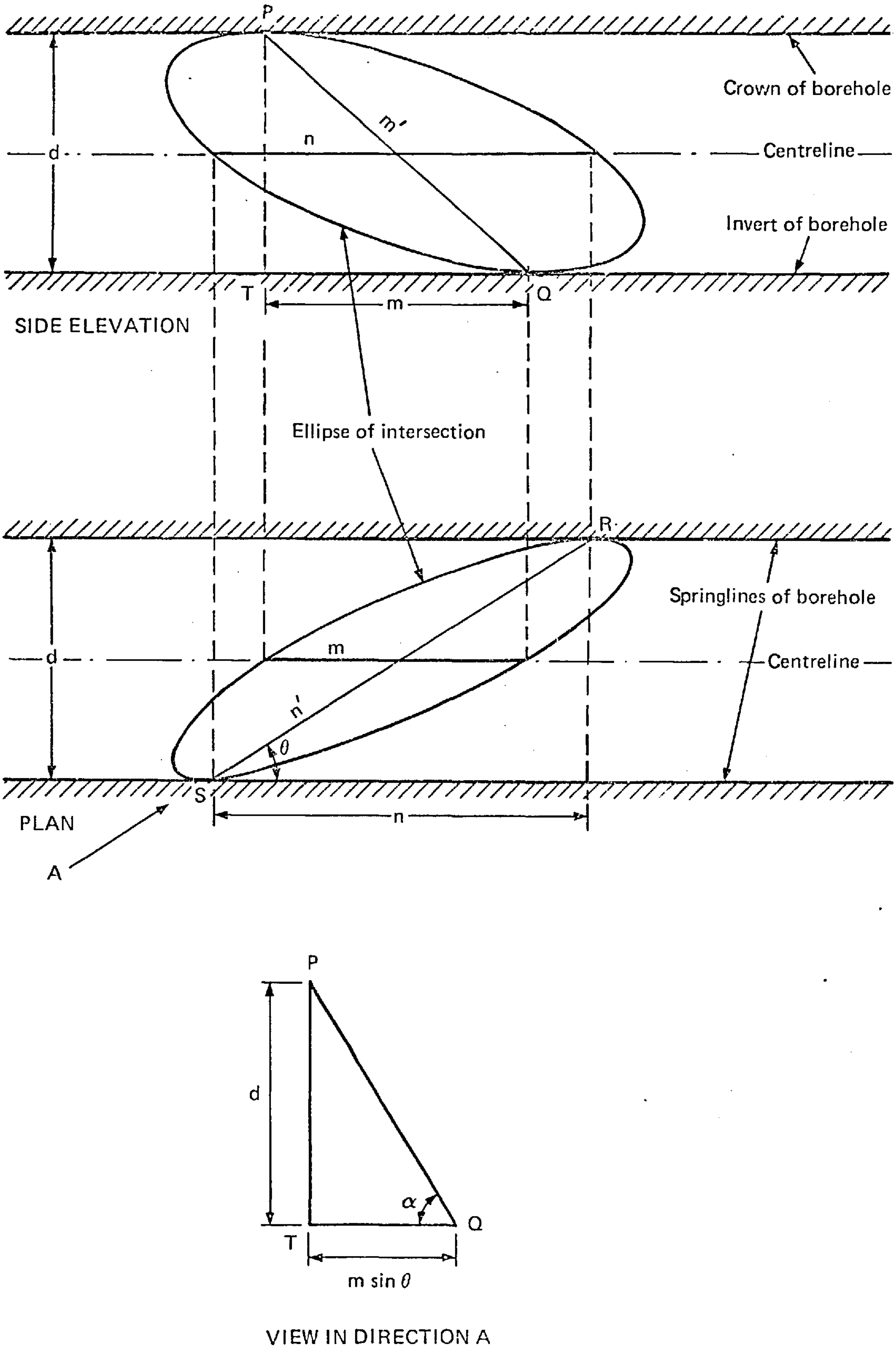

Fig. 14 INTERSECTION OF INCLINED JOINT AND HORIZONTAL BOREHOLE

$$\tan \alpha = \frac{d}{m \sin \theta} \qquad \ldots\ldots\ldots (12)$$

It can be seen that equations 11 and 12 can be evaluated by measuring n and m, d being the known borehole diameter.

What is needed, therefore, is a means of measuring n and m with the borehole television camera. It should be noted that the crown, invert and springlines of the borehole must be accurately identified and this emphasises the need for providing orientation indicators on the camera that has been discussed above. Any method devised could be checked in an artificial borehole made from a tube with joints of known orientation accurately sawn across it.

6.2 Ultrasonic velocity logger

The research has shown that the prototype ultrasonic velocity logger was easy to use in a horizontal borehole and that the results can provide a general indication of rock strength. The logger could readily be developed for use in routine probing ahead.

The method of activating the mechanical coupling lever on the tool by applying tension to a cord passing down the borehole proved entirely practicable during both the laboratory and underground trials but would probably not be suitable for a working instrument in routine use. Instead, the lever on the tool could be actuated by a hydraulic piston operated from outside the borehole via a hydraulic line. Alternatively, each transducer would be pressed against the borehole well directly by a hydraulic piston as in the borehole logger described by King et al (1978).

The prototype tool has a transducer spacing of 140mm. The advantages of a short transducer spacing are good resolution, a relatively strong signal and less likelihood of loss of signal due to the presence of a joint; the disadvantage is that a high frequency of reading is required. The choice of transducer spacing for a tool for routine probing ahead will be a compromise between these factors and research would be needed to find the optimium spacing. It can be noted that the tool described by King et al (1978) has a transducer spacing of 300mm.

6.3 Gamma-gamma logger

The research has shown that of the geophysical logging methods, only the gamma-gamma (long and short spacing) method would seem to be useful in probing ahead of tunnels, giving a good overall measure of the density of the material and an indication of the presence of open joints. However the tool requires considerable modification before it could be used in horizontal boreholes for probing ahead. These needs have been discussed in detail in Section 3.9 and are of such a nature that were they to be implemented it would have to be by the geophysical instrument manufacturer. It is reasonable to suppose that this will not be done unless there were a firm intention to use the tool on a regular basis.

Since completing this work the development of a more compact gamma-gamma logger than the one used in these trials has been announced in the United States*, and this instrument may provide a more suitable starting point for the development of a horizontal borehole logger for probing ahead of tunnels than the one described here.

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*The Portable Borehole Logger, Mount Sopris Instrument Company, Delta, Colorado, USA.

6.4 Discussion

In the main, the foregoing material in this thesis has been a factual presentation of the research except for some discussion in the Introduction and at the beginning of this chapter. In the discussion that now follows, an attempt is made to place the research in a wider context, discussing other geophysical methods, the practicability of probing ahead and its place in tunnelling site investigation.

The feasibility trials have shown that the gamma-gamma logger, the borehole television camera and the ultrasonic velocity logger can provide useful information on the density, the jointing and the compressive strength respectively of rock ahead of the tunnel face. It must be emphasised, however, that these conclusions are based on the methods tested and the two holes logged. In particular it should be noted that the conclusions regarding the geophysical methods relate to one set of tools operated by one firm (BPB Industries (Instruments) Ltd, 1978). Other equipment or methods may find application in particular geological or engineering circumstances.

For instance, in geological regions containing basic igneous rocks, which contain minerals exhibiting strong magnetic properties, some of the principles and methods described by Blundell (1961) as having been successful in solving geological problems by measurements at surface outcrop, may be applicable also to the solution of engineering problems by borehole logging. Deeply weathered fault zones in basic igneous rocks or dolerite dykes and sills in sedimentary rocks are examples of features of engineering importance that might be detected by magnetic methods of borehole logging - the former by their weaker magnetic properties and the latter by their stronger magnetic properties than the surrounding rock in each case.

An example of a particular engineering application of geophysical borehole logging, as yet unpublished, is the description of the use of resistivity and sonic logging of horizontal boreholes drilled ahead of tunnels driven in tuffs for siting underground nuclear tests (Carroll and Cunningham, 1980). Measurements were made by pumping the geophysical tool down the drill rods and out of the bit into a section of open hole at the end. Logging was then carried out by withdrawing the drill rods and the tool together. Holes have been logged from a distance of over 1,000m. The sonic logger used consisted of a single transmitter and three receivers; the tool diameter was 45mm for use in the 76mm diameter holes drilled. The resistivity logger consisted of a length of 31mm diameter PVC tubing carrying four electrodes equally spaced - the two outer being the current electrodes and the two inner the potential electrodes. The purpose of the sonic logging was to locate zones of partially saturated rock because of the undesirable attenuating effect such zones have on the shock wave generated by the nuclear explosion, and for this application zones of rock with velocities less than 2450m/s were considered of potential concern. The purpose of the resistivity logging was to define clay zones because of the unstable ground conditions such zones can present to tunnelling, and for this application rock with a resistivity of less than 20 ohm m was considered potentially unstable.

In regions of dipping sedimentary rocks that include sequences of inter-bedded shale and sandstone, the Dipmeter or the focused-current resistivity tool (described in Section 2.3) would find application as possibly being suitable tools for detecting this change in lithology.

In the analyses of the results of the ultrasonic velocity logger (Sections 4.9 and 5.1), concentration was made on deriving the compressive strength log from the velocity log because this is probably the most important property of the rock material to the engineer concerned with the rate of excavation of the tunnel. However, if it is possible to obtain some shear wave velocity measurements as well as the compressional wave velocity measurements, then the dynamic elastic moduli can be calculated as mentioned in Section 2.1. To illustrate what can be done, Figure 15 has been prepared which shows the dynamic Young's modulus log for the underground borehole at Corsham, derived from the velocity log (Figure 12) using equation 4. This kind of information would be useful to the engineer concerned with analysing the stress/strain conditions around the tunnel excavation and with designing the tunnel lining, particularly if the information could be obtained early on from pre-tunnelling horizontal boreholes; although in situ ground and lining studies would be required later to compare the design assumptions with the actual behaviour of the ground (Curtis, Lake, Lawton and Crook, 1976).

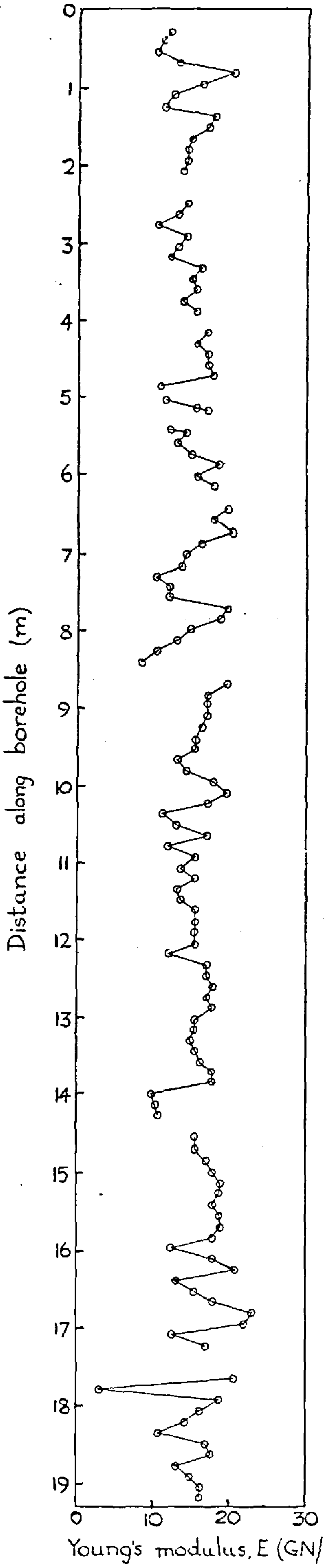

Fig 15 DYNAMIC YOUNG'S MODULUS LOG
FOR BOREHOLE THROUGH OOLITIC LIMESTONE

The trials reported here have, of course, been carried out under favourable circumstances, the first in a pilot-scale laboratory and the second in an underground stone quarry. In a tunnel under construction, conditions may be very different and may indeed be so confined that probe drilling itself may be impracticable, let alone geophysical or television logging of the probe borehole. The time available for probing ahead will also, by necessity of the construction operations, be limited. The cost has also to be considered and it has been estimated that if probing ahead from the face increased the construction time by 10 per cent, then the cost of the scheme would be increased by some 2 to 7 per cent (O'Reilly and Munton, 1973). Because of these considerations some practical tunnel engineers consider probe drilling on a routine basis from a tunnel under construction to be justified only in the most pressing circumstances such as to locate a likely hazard to life. These considerations apply also, although to a lesser degree, to in-hole logging of a probe borehole drilled from the tunnel face. The difficulties, however, should neither be exaggerated nor dismissed, but properly assessed each time a case for probing ahead is considered. Plate 13 shows the probe drilling arrangements at a forward position in the tunnelling machine used on the drive for the Phase 2 works of the Channel Tunnel, the probe drilling for which was described in the Introduction. One of the drill rigs can be seen in the top right of the view, the drill controls and pressure gauge console are almost at the centre and the aluminium drill rods can be seen on the left. The reader can decide for himself whether it would be practicable to carry out geophysical or television logging in this type of situation, perhaps also under wet conditions.

PLATE 13 Working space for probing ahead on the Channel Tunnel machine

For these reasons, the role of horizontal drilling may be more appropriate at the pre-tunnelling site investigation stage, as discussed on pages 17 and 18, rather than during tunnel driving. This would enable proper facilities for the drilling and logging to be provided, and the constraints of shortage of space and time would not apply. However, in pre-tunnelling horizontal drilling there would be enough time to use core drilling and consequently no need for geophysical logging of the borehole afterwards, because any desired measurements of rock properties could be made directly on the recovered core. Television logging would still be useful to indicate rock jointing, core drilling being likely to overestimate the number of joints because of the fact that core is often more broken than the rock in place unless well-maintained drilling equipment, triple-tube core barrel and experienced drillers are used. However, even in pre-tunnelling horizontal drilling there may be parts of the borehole, along sections of the tunnel route where uniform ground is expected, where non-coring drilling will be carried out and here geophysical logging may play a part by providing information through the non-cored lengths of borehole.

Mention was made in the Introduction (page 18) of the instrumented horizontal drilling trials that are being carried out in conjunction with the work described here. The results are not available at the time of writing, but preliminary results of instrumented vertical drilling trials carried out by the Construction Industry Research and Information Association have been reported by Brown (1979). The results show that considerable information on rock material properties can be obtained from relatively straightforward instrumentation fitted to commercial drill rigs and it is likely that the same will be true for instrumented horizontal drilling. If this is so, then the case for geophysical logging of the borehole diminishes, although television logging remains applicable because instrumented drilling is not likely to yield much information on rock jointing.

The geophysical and television logging of horizontal boreholes, either driven from the tunnel face during construction, or driven before tunnelling at the pre-contract stage, needs to be integrated into the overall scheme of the site investigation (Dumbleton and West, 1976). Information gained during the initial stages of the site investigation, particularly from the preliminary appreciation of the geology of the site, may indicate whether it would be appropriate to carry out horizontal drilling, and if so, whether over the whole length of the proposed tunnel, or only over particular sections. If a decision to carry out horizontal drilling is made, the early appreciation of likely geological and engineering problems will indicate which methods of borehole logging may be applicable. The preliminary appreciation will also indicate likely ground water conditions. Geophysical and television borehole logging equipment is designed to be waterproof, and although the borehole televison camera will operate satisfactorily under clear water, it will not, of course, give a picture if the borehole is full of turbid water. Finally, it should not be lost sight of that in certain circumstances surface geophysics, borehole-to-borehole geophysics and, in the case of sub-aqueous tunnels, marine geophysics may all have a part to play in tunnelling site investigation.

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APPENDIX 1

CONCRETE BLOCKS FOR TEST ASSEMBLY

This Appendix describes the design and manufacture of the concrete blocks and gives test results for the aggregate and concrete used.

1. DESIGN AND MANUFACTURE OF BLOCKS

1.1 Design of blocks

The size of the blocks was governed by the following considerations which were based on the needs of the instrumented horizontal drilling trials. An area 600mm square was required to allow the drilling of a sufficient number of boreholes through one assembly of blocks and to avoid drilling too close to the edge of a block. This size also provides some allowance for inaccuracy of drilling alignment over the complete length of the assembly. An overall width of 710mm was finally chosen so that edge reinforcement could be included to facilitate handling and to resist the drilling thrust. Because the blocks were to be supported on the plinth by embedding them in concrete to a depth of 150mm the height of the blocks was increased to 770mm. The thickness of the blocks, 205mm, was chosen to give a minimum yet adequate thickness of continuous material to drill through.

1.2 Design of concrete mixes

Three strengths of mix were required and these were obtained by a simple modification of the method of design of normal concrete mixes (Teychenné *et al*, 1975). Three cement contents were chosen and the coarse and fine aggregate contents followed from these choices, using a constant coarse to fine aggregate ratio of 1.78:1, the grading of the fine aggregate being Zone 2 in each case. The amount of water used was judged by experience to give a workable mix, using a water/cement ratio of 0.6 as a guide. Details of the mix compositions are given in Table 1.

TABLE 1

Composition of concrete mixes

Designation of mix	Cement per cent	Coarse aggregate per cent	Fine aggregate per cent
1	21	51	28
2	14	55	31
3	8	59	33

Seven aggregates were used to manufacture the concrete blocks; the origin of these is given in Table 2. Six were available from stocks held at the Laboratory but the siltstone was obtained directly from the quarry. All the aggregates were hard roadstones and consisted of angular shaped particles. A report on the properties of the ordinary Portland cement used to manufacture the concrete blocks showed that the cement complied with all the requirements of the British Standard specification (British Standards Institution, 1971) except for a very slight excess of sulphur trioxide.

TABLE 2

Origin of aggregates

Rock type	Designation of aggregate	Location of quarry or pit
Flint	L	Laleham, Middlesex
Quartzite	R	Rugeley, Staffordshire
Gritstone	BH	Bayston Hill, Shropshire
Limestone	H	Holcombe, Somerset
Siltstone	DR	Dry Rigg Quarry, Horton-in-Ribblesdale, Yorkshire
Dolerite	CH	Clee Hill, Shropshire
Granite	C	Croft, Leicestershire

1.3 Manufacture of blocks

The aggregates, cement and water were mixed in a mechanical mixer and the concrete was poured into wooden moulds containing the reinforcement and compacted with a vibrating poker. The exposed surface was trowelled flat. The blocks were cured under wet hessian for 5 to 7 days and then demoulded and stored under cover. Two threaded steel sockets were cast into the top of each block to take eye-bolts for ease of handling. The concrete was prepared and the blocks were cast by the Civil Engineering Services of the Laboratory. The aggregates were designated by letters and the mixes by numbers, allowing the concrete to be designated by combining these.

2. TESTS ON AGGREGATES

In order to provide information on the physical characteristics of the aggregates that are likely to be important in determining the properties of the concrete and the response to drilling, tests were carried out to measure the grading, specific gravity, point load strength and slake durability of each of the aggregates used in the manufacture of the blocks.

2.1 Grading

A particle size distribution test was carried out on samples of the coarse and fine aggregate of each of the aggregate types using the British Standard method (Section 7.1 of BS 812: Part 1: 1975, British Standards Institution, 1975a). Using the appropriate mix proportions the results were then combined to form a single grading curve representing the grading of the aggregate that was used to make the blocks. The grading curves showed that all the aggregates were well graded gravel-sand mixtures.

2.2 Specific gravity

The specific gravity of a sample of each aggregate, made up to the grading as used for the concrete, was determined by the British Standard method (Test 6(A) of BS 1377: 1975, British Standards Institution, 1975b). The means of three determinations for each aggregate are given in Table 3.

2.3 Point load strength

The point load strength index (Franklin et al, 1971), I_s, of each aggregate was determined on air-dry pieces of stone. The values were then corrected for specimen size and expressed as I_s (50mm) values. The means of twenty determinations for each aggregate are given in Table 3.

2.4 Slake durability

The slake durability index (Franklin et al, 1971), I_d, of each aggregate was determined on initially air-dry pieces of stone. The means of four determinations for each aggregate after two cycles of wetting and drying, I_d (2 cycles), are given in Table 3.

TABLE 3

Properties of aggregates

Rock type	Designation of aggregate	Specific gravity	Point load strength index I_s(50mm) MN/m^2	Slake durability index I_d(2 cycles) per cent
Flint	L	2.62	11.3	99.9
Quartzite	R	2.65	9.3	100.0
Gritstone	BH	2.78	7.2	99.2
Limestone	H	2.70	6.4	99.6
Siltstone	DR	2.77	6.4	99.5
Dolerite	CH	2.87	7.4	99.4
Granite	C	2.66	9.8	99.5

3. TESTS ON CONCRETE

In order to provide information on the properties of the concrete that was used to make the blocks, six-inch test cubes were made from the mixes by the British Standard method (British Standards Institution, 1970a) at the same time as the blocks were cast. The test cubes were demoulded after twenty-four hours, cured in water and tested after seven and twenty-eight days.

3.1 Density

After curing, the test cubes were surface dried and weighed; the density was then calculated and the means of six determinations for each concrete mix are given in Table 4.

3.2 Strength at 7 and 28 days

After the required period of curing, the test cubes were surface dried and their compressive strength was determined using the British Standard method (Section 2 of BS 1881: Part 4: 1970, British Standards Institution, 1970b). The means of three determinations for each concrete mix are given in Table 4.

TABLE 4

Properties of concrete

Rock type used for aggregate	Designation of concrete	Density Mg/m^3	Compressive strength MN/m^2	
			7 days	28 days
Flint	L1	2.48	34.2	48.6
	L2	2.50	38.0	51.3
	L3	2.50	18.7	25.6
Quartzite	R1	2.53	50.5	56.8
	R2	2.53	34.2	43.7
	R3	2.43	7.8	10.4
Gritstone	BH1	2.51	31.1	41.1
	BH2	2.54	20.8	27.9
	BH3	2.41	4.2	6.1
Limestone	H1	2.54	51.0	61.1
	H2	2.56	47.9	55.1
	H3	2.60	25.8	32.0
Siltstone	DR1	2.45	28.3	38.1
	DR2	2.59	30.2	37.1
	DR3	2.60	20.6	21.9
Dolerite	CH1	2.66	45.2	67.0
	CH2	2.69	44.2	47.7
	CH3	2.54	13.6	18.6
Granite	C1	2.46	43.4	56.8
	C2	2.45	24.4	32.4
	C3	2.40	7.5	10.1

4. DISCUSSION

The principal purpose of this Appendix is to describe the manufacture of the concrete blocks and to give test results for the aggregates and concrete used, but some brief comments will be made on the test results.

4.1 Aggregates

The specific gravity of the aggregates ranges from 2.62 for flint, through 2.65 for quartzite (the value for quartz is 2.65) and 2.70 for limestone (the value for calcite, the main constituent of limestone, is 2.71) to 2.87 for dolerite, a rock rich in ferromagnesian minerals of high specific gravity.

The point load strength index varied from 6.4 MN/m^2 for the limestone and siltstone to 11.3 MN/m^2 for the flint. Using the approximate relationship compressive strength = I_s (50mm) x 24, the rocks ranged in compressive strength from about 150 to 270 MN/m^2, the flint, granite and quartzite falling into the category of 'extremely strong' rocks (over 200 MN/m^2) and the rest falling into the category of 'very strong' rocks (100 to 200 MN/m^2) using the classification system of the Geological Society Engineering Group Working Party (1970).

The values of slake durability index are all very close to 100 per cent showing that these rocks suffer negligible breakdown by slaking, a result that was expected bearing in mind their use as roadstones. The results indicated that these aggregates would not break down by slaking during the drilling trials.

4.2 Concrete

The density of the concrete test cubes varied from 2.40 Mg/m^3 for the weak granite mix to 2.69 Mg/m^3 for the intermediate strength dolerite mix. The densest concrete was made from the densest aggregate. The 28-day strength varied from 6.1 MN/m^2 for the weak gritstone mix to 67.0 MN/m^2 for the strong dolerite mix. The 28-day strengths, therefore, correspond to rock strength types ranging from 'moderately weak' rock (5 to 12.5 MN/m^2) through 'moderately strong' rock (12.5 to 50 MN/m^2) to 'strong' rock (50 to 100 MN/m^2) using the classification system of the Geological Society Engineering Group Working Party (1970).

The mix designs succeeded in producing concretes of three different strengths for each aggregate except with the flint and siltstone aggregates where mixes 1 and 2 have almost the same strength. The flint mixes were in fact the first two produced and it is thought that an error in batching for one of the mixes may have occurred. In the case of the siltstone, it was observed at the time that mix 1 was very wet.

5. REFERENCES FOR APPENDIX 1

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APPENDIX 2

PROPERTIES OF CONCRETE BLOCKS USED IN TEST ASSEMBLY

This Appendix gives the results of seismic wave velocity measurements and Schmidt hammer tests made on the 51 concrete blocks of the test assembly, and of density determinations made on cores obtained from the blocks during the drilling of the borehole. These tests were carried out to provide data against which the results of instrumented drilling and geophysical logging can be compared. Both the velocity and hammer tests are established methods of testing concrete non-destructively (Elvery, 1973). Measurements of the dynamic Poisson's ratio for the blocks were also made for use in processing the data from the velocity tool (see Section 4.9.1 in main text).

1. SEISMIC WAVE VELOCITY

The seismic wave velocity of the concrete blocks was determined using the equipment supplied by CNS Instruments (London) Ltd called the Pundit (portable ultrasonic non-destructive digital indicating tester). The instrument generates ultrasonic pulses and measures the time taken for them to travel between transmitting and receiving transducers, located with a known separation, on the material under test. The ultrasonic frequency used is 54 kHz and the pulse repetition rate is ten per second.

The seismic wave velocity is obtained by dividing the known pathlength between the transducers by the pulse transit time measured by the instrument. It is the compressional wave (P-wave) velocity that is measured.

After the blocks had been assembled in the required array they were tested in a direction perpendicular to the longitudinal axis of the array by placing the Pundit transucers on the sides of the blocks. For most of the blocks the direct configuration was used (as defined by the British Standards Institution, 1974) but for some of the blocks in the central section of the array where one side only was accessible the indirect configuration was used. Direct velocities measured on one block in directions perpendicular to and along the axis of the array were the same. Direct velocity tests were also made on the intact cores. The results are given in Table 5.

TABLE 5

Seismic wave velocity of concrete blocks

Block No.	Designation of concrete	Seismic wave velocity m/s		Block No.	Designation of concrete	Seismic wave velocity m/s	
		Blocks	Cores			Blocks	Cores
1	C1	4295	-	27	CH2	4444 i	-
2	C3	3656	3682	28	CH2	4566 i	-
3	CH1	4747	-	29	DR2	4124 i	-
4	CH3	4361	-	30	DR2	4396 i	-
5	DR1	4319	3902	31	C1	4255 i	4241
6	DR3	4573	-	32	C2	4053	-
7	H1	4688	4553	33	C3	3530	-
8	H3	4615	-	34	CH1	4747	4692
9	BH1	4189	3751	35	CH2	4456	-
10	BH3	3041	-	36	CH3	4382	-
11	L1	4490	-	37	DR1	4272	-
12	L3	4462	4265	38	DR2	4518	-
13	C1	4239	4108	39	DR3	4606	4197
14	C3	3590	3526	40	H1	4734	-
15	CH1	4697	4535	41	H2	4757	4620
16	CH3	4513	-	42	H3	4559	-
17	DR1	4249	4043	43	BH1	4098	3765
18	DR3	4562	4159	44	BH2	3950	3685
19	H1	4877	-	45	BH3	2992	-
20	H3	4612	4566	46	R1	4672	4636
21	BH1	4157	4004	47	R2	4479	-
22	BH3	3026	-	48	R3	3813	-
23	L1	4565	-	49	L1	4556	-
24	L3	4425 i	-	50	L2	4621	-
25	C2	3697 i	-	51	L3	4353	-
26	C2	3692 i	-				

The blocks were numbered consecutively, starting at end A of the array where drilling commenced.
The designation of the concrete is given in Appendix 1.
Indirect measurements: i.
Mean core velocity: 4154 m/s

2. SCHMIDT HAMMER TESTS

Schmidt hammer hardness tests were carried out on each of the concrete blocks using a Schmidt L-type instrument. This consists essentially of a metal plunger, one end of which is held against the surface of the material to be tested, while the other end is struck by a spring-loaded mass. The amount of rebound of the mass is known as the rebound number and can be empirically related to the strength of the test material.

Rebound values of 16 points within an area 100mm x 150mm were determined on each of the two vertical and opposite sides of a block, and the mean rebound number calculated. For some of the blocks in the central section of the array, where one side only was accessible, one side only was tested. The hammer was calibrated using the Schmidt standard steel block and the mean rebound number obtained for each of the concrete blocks was corrected. The results are given in Table 6.

3. DENSITY

The density of the cores from the borehole drilled through the array of concrete blocks was determined from measurements of the mass and dimensions of the cores. Density determinations could only be made on the more intact cores, and because some of them were broken or consisted of rubble, not all the blocks are represented.

TABLE 6

Schmidt hammer rebound number of concrete blocks

Block No.	Designation of concrete	Rebound number	Block No.	Designation of concrete	Rebound number
1	C1	35	27	CH2	35
2	C3	19	28	CH2	38
3	CH1	36	29	DR2	30
4	CH3	28	30	DR2	31
5	DR1	34	31	C1	38
6	DR3	32	32	C2	24
7	H1	38	33	C3	17
8	H3	33	34	CH1	34
9	BH1	35	35	CH2	34
10	BH3	14	36	CH3	25
11	L1	31	37	DR1	27
12	L3	21	38	DR2	27
13	C1	29	39	DR3	24
14	C3	13	40	H1	29
15	CH1	33	41	H2	32
16	CH3	22	42	H3	24
17	DR1	24	43	BH1	28
18	DR3	23	44	BH2	24
19	H1	32	45	BH3	11
20	H3	25	46	R1	30
21	BH1	30	47	R2	31
22	BH3	12	48	R3	18
23	L1	23	49	L1	27
24	L3	27	50	L2	30
25	C2	25	51	L3	25
26	C2	27			

The results are given in Table 7 which also shows the core density expressed as a percentage of the cube density reported in Appendix 1.

4. DYNAMIC POISSON'S RATIO

Measurements of dynamic Poisson's ratio were made for each of blocks 31 to 51, ie one of each type, except for two of the blocks for which values could not be obtained. The method used was to determine the transit time for the compressional wave (P-wave) and the shear wave (S-wave) to pass between the transducers of the Pundit when these were positioned at a fixed spacing. An oscilloscope was used to identify the arrival of each wave train. From these observations, dynamic Poisson's ratio was calculated from the expression (Jaeger and Cook, 1976)

$$\nu = \frac{\frac{1}{2}\left(\frac{C_p}{C_s}\right)^2 - 1}{\left(\frac{C_p}{C_s}\right)^2 - 1}$$

where ν is dynamic Poisson's ratio and C_p and C_s are the velocities of compressional and shear waves respectively.

TABLE 7

Density of cores from concrete blocks

Block No.	Designation of concrete	Core density Mg/m^3	Percentage of cube density	Block No.	Designation of concrete	Core density Mg/m^3	Percentage of cube density
1	C1	2.27	92	27	CH2	-	-
2	C3	2.19	91	28	CH2	-	-
3	CH1	2.46	92	29	DR2	-	-
4	CH3	2.46	97	30	DR2	-	-
5	DR1	2.26	92	31	C1	2.24	91
6	DR3	2.39	92	32	C2	2.24	91
7	H1	2.34	92	33	C3	-	-
8	H3	2.36	91	34	CH1	2.46	92
9	BH1	2.31	92	35	CH2	-	-
10	BH3	-	-	36	CH3	-	-
11	L1	2.17	88	37	DR1	-	-
12	L3	2.28	91	38	DR2	-	-
13	C1	2.29	93	39	DR3	2.42	90
14	C3	2.16	90	40	H1	2.34	92
15	CH1	2.47	93	41	H2	2.38	93
16	CH3	2.47	97	42	H3	2.35	90
17	DR1	2.29	93	43	BH1	2.27	90
18	DR3	2.40	92	44	BH2	2.27	89
19	H1	2.33	92	45	BH3	-	-
20	H3	2.41	93	46	R1	2.35	93
21	BH1	2.29	91	47	R2	-	-
22	BH3	-	-	48	R3	-	-
23	L1	2.24	90	49	L1	-	-
24	L3	2.28	91	50	L2	-	-
25	C2	-	-	51	L3	-	-
26	C2	-	-				

Mean core density: 2.33 Mg/m^3

The results are given in Table 8; for two of the blocks values could not be determined because the shear wave arrival could not be identified.

5. DISCUSSION

The principal purpose of this Appendix is to give the results of the seismic wave velocity, Schmidt hammer, density and dynamic Poisson's ratio tests, but some brief comments will be made on the test results.

5.1 Seismic wave velocity

The seismic wave velocity of the concrete blocks ranges from 2992 m/s for one of the weak gritstone blocks to 4877 m/s for one of the strong limestone blocks. When compared with the total range of about 2000 to 6500 m/s for all rocks it can be seen that the blocks represent a wide zone in the middle.

5.2 Schmidt hammer tests

The Schmidt hammer rebound number of the concrete blocks ranges from 11 for one of the weak gritstone blocks to 38 for strong granite and limestone blocks.

This range corresponds to the categories of 'moderately weak' rock (rebound number 10 to 20) and

TABLE 8

Dynamic Poisson's ratio values for concrete blocks

Block No.	Designation of concrete	Dynamic Poisson's ratio
31	C1	0.297
32	C2	0.305
33	C3	-
34	CH1	0.291
35	CH2	0.305
36	CH3	0.301
37	DR1	0.302
38	DR2	0.309
39	DR3	0.277
40	H1	0.326
41	H2	0.322
42	H3	0.310
43	BH1	0.312
44	BH2	0.295
45	BH3	-
46	R1	0.260
47	R2	0.267
48	R3	0.282
49	L1	0.262
50	L2	0.248
51	L3	0.284

Mean dynamic Poisson's ratio: 0.292

'moderately strong' rock (rebound number 20 to 40) using the correlation given by Carter and Sneddon (1977).

5.3 Density

The density of the cores varies from 2.16 Mg/m^3 for one of the granite blocks to 2.47 Mg/m^3 for two of the dolerite blocks. The core densities were about 92 per cent of the cube densities because the core densities were determined on mature air-dry concrete and the cube densities on fresh water-saturated concrete.

6. REFERENCES FOR APPENDIX 2

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APPENDIX 3

PROPERTIES OF MATERIALS USED IN CENTRAL SECTION OF ARRAY

This Appendix gives the properties of the gravel-sand-clay, the clay and the single-sized limestone aggregate used in the central section of the array. The clay was also used to fill 10mm wide joints between blocks 7 and 8 and blocks 19 and 20. Soil testing was done in accordance with the British Standards Institution (1975).

Gravel-sand-clay

Gravel 55%, sand 30%, silt and clay 15%
Moisture content 7.4%
Bulk density 1.87 $\mathrm{Mg/m^3}$

Clay

Liquid limit 76%, plastic limit 30%, plasticity index 46%, classification CH
Moisture content 28.7%

Shattered rock

Holcombe limestone aggregate, size 40 to 20mm
Bulk density 1.39 $\mathrm{Mg/m^3}$

Reference

BRITISH STANDARDS INSTITUTION (1975). Methods of test for soils for civil engineering purposes. British Standard BS 1377: 1975. London (British Standards Institution).

APPENDIX 4

PROPERTIES OF OOLITIC LIMESTONE

Cylindrical specimens were prepared from the cores obtained from the underground borehole. The density, seismic wave velocity and compressive strength of each of the specimens were determined using similar methods to those described for the concrete cores. The specimens were cut from sections of core obtained as near as possible to positions spaced at one metre intervals along the borehole. The results are given in Table 9. The dynamic Poisson's ratio of the rock, estimated from the compressional and shear wave observations made with the ultrasonic velocity logger and using the expression given in Appendix 2, was 0.333.

TABLE 9

Density, seismic wave velocity and compressive strength of oolitic limestone

Distance along borehole m	Density Mg/m^3	Seismic wave velocity m/s	Compressive strength MN/m^2
1	2.03	3292	13.4
2	2.11	3310	16.3
3	1.98	3086	9.1
4	2.09	3317	10.8
5	2.04	3296	12.0
6	2.11	3296	14.3
7	1.94	2881	8.5
8	2.08	3522	14.9
9	2.07	3269	15.0
10	2.02	3160	13.8
11	2.02	3073	11.6
12	1.94	2854	13.1
13	2.13	3235	14.4
14	2.03	3010	7.8
15	2.12	3271	11.8
16	2.07	3249	11.7
17	2.26	3717	16.0
18	2.14	3336	15.2
19	2.07	3406	9.7
Mean	2.07	3241	12.6