IRRESPECTIVE OF THE care and conservatism applied to the design of an anchor system, thoughtless or careless constructional procedures can cause rock anchors to fail at very low loads. The majority of failures seem to be related to the grinding stage although some bond failures have clearly been due to poor tendon preparation. On a few occasions the drilling and flushing techniques may have been incorrect. Fortunately, failures have not occurred too often and these have usually been highlighted at the stressing and testing stage.

It is significant that although the technology of drilling and grouting can be highly complex, site techniques on the whole are left to skilled and experienced specialists, and close on-site inspection by supervising engineers has been relatively uncommon to date. Thus, rock anchoring after 40 years is still regarded as an art. Whilst it is appreciated that the highly variable ground conditions encountered in practice, giving rise to a large number of constructional techniques, add to the mystique of anchoring, nevertheless it seems that the time is overdue for certain guidelines on construction practice to be presented for consideration by civil engineers.

The second part of this review discusses anchor construction techniques related to drilling, flushing, water testing, tendon prestressing, and corrosion protection. Since anchor construction is sensitive to poor workmanship emphasis is placed on quality control and close on-site supervision.

Aspects of anchor stressing and testing will be reviewed in the third and concluding part of this series of articles.

DRILLING

Introduction

In practice drilling rates often dictate anchor production rates and therefore influence in a major way overall costs. As a result major decisions to be taken by anchor specialists before each contract include

(i) The selection of the most suitable and efficient drilling method, and

(ii) The prediction of penetration rates.

With respect to choice of drilling method, the rock type, rate and scale of drilling operations, availability of plant, hole geometry, and labour and drilling costs must all be assessed.

The prediction of drilling rates involves careful study of machine characteristics, bit and flushing medium properties as well as rock and borehole parameters. It is considered that a prior knowledge of drilling rates provides a sound basis for evaluating the feasibility of planned operations and for selecting alternative operational procedures if necessary.

The range and selection of drilling equipment and methods are described briefly, together with guide information on the prediction of drilling rates. The latter is performed qualitatively, simply because insufficient research has yet been conducted—or published—on the determination of "rock drillability indices". Drilling tolerances are mentioned in relation to current rock anchor practice.

Drilling methods

The major mechanical drilling systems in use are rotary, percussive and rotary percussive. Each system is characterised by the manner in which the bit attacks the rock, and a simple comparative analysis of the mechanics of various drilling systems can often reveal the inherent limitations of each and indicate the most promising systems for a specific type of rock. For example a rock of high compressive strength, regardless of its abrasive properties, is likely to respond well to the crushing/chipping action of a percussion bit. On the other hand, a rock classified as hard because it is highly abrasive, but which is weakly bonded, may respond to percussion action more like a ductile material than a brittle one. For such a rock a percussion bit would do inferior work compared with a wear-resistant rotary drag bit. A current rule of thumb for the applicability of drilling methods for different rock categories is based on the resistance of rock to penetration as shown in Table I.

Rotary drills

A rotary drill imparts two basic actions through the drill rod and bit into the rock

(i) Axial thrust (a static action), and

(ii) Rotational torque (a dynamic action).

The resultant force applied to the rock is increased until rock fracture is induced and each machine has a point where an optimum axial thrust, interacted with the available torque can achieve a maximum penetration rate for a particular rock. Operating below the optimum thrust decreases the penetration and imparts a noticeable polishing or grinding action to the bit. Operating above the optimum thrust requires high rotational torque, and stalling of the machine is likely.

In general, rotary drills have a higher torque output than either percussive or rotary-percussive drills and require higher thrust capabilities. Types of machines and operating practice are described in detail in a US Army Report [1964].

Where specified, the core drilling is carried out using diamond bits which are available in two main forms—"Surface set" bits with individual diamonds set in a metal matrix, and "Impregnated bits" with fine diamond dust incorporated in a matrix.

The diamonds used for the surface set bits vary in both quality and size. Choice is governed by the rock to be drilled, but it can be summarised that "the harder the rock the smaller the size and the higher the quality of the diamonds". Dixon and Clarke (1975) give specific recommendations on size of diamonds in bits related to type of rock. It is noteworthy that tungsten carbide bits are less costly than diamond bits but are not regarded as suitable for drilling in very hard rocks.

When drilling with surface set diamond bits, Paone et al [1968] have shown that the most significant parameters affecting penetration rates are thrust and rotation speed of the drill, and the rock compressive strength, hardness, and quartz content.

Diamond drilling is not commonly employed in anchoring, partly for economic reasons, and partly due to the smoothness of the hole it creates, thereby leading to poorer rock-grout bond characteristics. Borehole roughness is undoubtedly increased by using percussion methods, but to date this does not appear to have been quantified.

For anchor construction in soft rock formations, such as stiff-hard clays and

<table>
<thead>
<tr>
<th>Method</th>
<th>Soft</th>
<th>Medium</th>
<th>Hard</th>
<th>Very hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary-drag bit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Rotary-roller bit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Rotary-diamond bit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Percussive</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Rotary-percussive</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

(After Paone, Under and Tandamar, 1968)
marls, augers are often employed. They fall into three broad categories:

1. standard continuous flight augers for normal open/hole drilling.
2. continuous flight augers with hollow couplings to permit water, bentonite or cement grout to be pumped into the bottom of the hole, and
3. hollow stem augers with a removable centre bit to facilitate sampling through the centre of the auger during the drilling stage, and subsequently permit the removal of the tendon prior to withdrawal of the auger. Augers are available which can accept the standard U4 sampler tube, and on occasions this drilling method can be very attractive from a quality control point of view.

In general, a wide range of drill bits is available from auger tool manufacturers but experience is required in making the correct choice in practice. For example, a tungsten tipped finger bit is normally suitable for moderate to hard formations such as hard shale, siltstone, and soft decomposed sandstone whilst a fishtail bit is often ideal for boring clean holes through soft shale and stiff/hard clay.

**Percussive drills**

Percussive drills penetrate rock by the action of an impulsive blow, usually from a chisel or wedge-shaped bit: repeated application of a high intensity short duration force crushes or fractures rock when the blow is sufficiently large. Torque, rotational speed, and thrust requirements are significantly lower for percussive systems than they are for rotary or rotary percussive systems.

Hammer drills, in which the hammer remains at the surface, are used for drilling holes up to 125mm in diameter. Down-the-hole tools, (DTH) in which the hammer is always immediately above the bit, are used mainly for hole diameters ranging from 120 to 750mm.

Penetration rates of percussive drills are shown by Ryd & Holdo [1966] to be proportional to the rate at which energy is supplied by the reciprocating piston.

**Rotary-percussive drills**

These drills impart three actions through the drill bit:

(i) **axial thrust of lower magnitude than that of a rotary drill,**
(ii) **torque, lower than a rotary drill but much higher than a percussive drill,** and
(iii) **impact.**

The rotation mechanisms may be powered by the impact mechanism or by a separate motor, and the mechanism of rock failure is considered by White [1966] to combine the characteristics of both rotary and percussive mechanisms.

**Choice of drilling method**

The method of drilling is chosen primarily with respect to:

- the type and capacity of the anchor, and hence the diameter and depth of the hole,
- the nature of the rock material and mass,
- the borehole surface roughness requirements,
- the accessibility and topography of the site,
- the availability and suitability of the flushing medium, and
- the drilling rate.

**TABLE II. DRILLING METHODS AND EQUIPMENT RELATED TO GROUND CONDITIONS**

<table>
<thead>
<tr>
<th>Basic method</th>
<th>Percusive</th>
<th>Percusive</th>
<th>Percusive</th>
<th>Rotary</th>
<th>Rotary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill string</td>
<td>Standard coupled rods, separate anchor</td>
<td>Coupled rods also act as anchor</td>
<td>Coupled drill tubes and rods used simultaneously from same drive adapter, Atlas Copco Overburden Drills are recommended</td>
<td>Coupled flight augers</td>
<td>Standard rotary drilling tubes</td>
</tr>
</tbody>
</table>
| Drilling machine | Wagen drill with drifter or crawler drill with independent rotation drifter. Compressed air powered. | Wagon drill with drifter or crawler drill with independent rotation drifter. Compressed air powered. | Special independent rotation drifter mounted on heeled chassis or crawler. Compressed air powered. | Standard auger drill capacity of torque and thrust dependent on hole size and depth. Diesel hydraulic power. Chassis powered wheel or crawler designed for drilling of shallow angle holes. Wheeled or skid mount possible. | Rotary rod drill or diamond drill. 
Rotary auger: 2.7m/kN to 5.0kN thrust 0-500 r.p.m. Diesel/crawler or hydraulic power. Chassis powered wheel or crawler designed for drilling of shallow angle holes. Wheeled or skid mount possible. |
| Anchor | Multi-wire strand or single bar. | Special coupled rods | Multi-wire strand and single bar | Multi-wire strand most common. Single bar also possible. | Single bar most common as in Boreham. Multi-wire strand possible but ground is self-supporting. |
| Flushing medium | Normally air but water could be used. | Invariably water but occasionally useful. | Water. Air used very rarely. | None | Water. Air used very rarely. |
| SUITABLE STRATA | Self-supporting rock only. Few metres of overburden possible with aid of stand pipe. | All materials. | All materials provided drill tubes are uncoupled when rock is encountered and drilling continued alone with rods. | All self-supporting soft materials such as clay and chalk. Not rock. Not collapsible material such as sand and clay unless casing is used. | All soft materials such as clay, sand and gravel. Also soft and medium rocks. Not hard rock. |

(1) Percussive drill, (ii) torque, lower than a rotary drill but much higher than a percussive drill, and (iii) impact.

The rotation mechanisms may be powered by the impact mechanism or by a separate motor, and the mechanism of rock failure is considered by White [1966] to combine the characteristics of both rotary and percussive mechanisms.

**Drilling equipment**

Irrespective of the method of drilling, there are certain desirable characteristics which are common to most rigs used in ground anchoring work. For instance, Mawdsley [1970] recommends the following items.

The rig should have powered traction so that it can be easily moved and positioned for each hole. When site floor conditions are very bad the rig should be mounted on crawler tracks. An exception to the above is when the rig is mounted on another piece of equipment which is itself movable, for example, a floating pontoon.

The centre of gravity of the rig should be as low as possible as many anchor holes are drilled at shallow angles. The necessary drilling thrusts cannot be applied safely unless the rig is stable.

The rig should be capable of drilling at any angle from horizontal to vertical and should be able to perform as many drilling methods as possible e.g. rotary and auger.

In the view of the authors, the following practical aspects may also merit consideration:

**Noise:** It is noticeable that there has been a recent swing away from the use of percussive or rotary percussive drills, to rotary drills in built-up areas. This is primarily due to noise restrictions and a noise level of 75dBa at 15m is now specified in urban areas. In 5-10 years it is anticipated that rotary percussive drifters will be banned in built-up areas. In future planning therefore it is recommended that consideration should be given to hydraulically powered rigs.

Nevertheless, whilst percussive drills continue to be employed it is important for engineers to appreciate the windup to high noise levels, usually above 90dBA, for extended time periods can produce physiological damage to the ear. On many construction sites, particularly in the UK, warnings of this potential hazard to drillers

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seem in the main to go unheeded. Versatility: All rigs should be designed to accommodate a rotary head, rotary percussive drifter, vibrodriver and down-the-hole hammer. Where high production is required, mechanical handling of drill rods and casing could be advantageous and use of drill racks, rod-changing units and hydraulic positioners merits consideration. Prime movers: All prime movers to operate rigs should be "built-in" to give a compact, independent unit. For the vast majority of anchor applications a power supply of 50-60 h.p. is considered sufficient. Mast movements: A sub-mast is required capable of rotating 90 deg, in elevation i.e. vertical to horizontal. The main mast, attached to the sub-mast through a turntable/sliding carriage, should be capable of rotating 180 deg. in plan.

The ability to (a) position the toe of the main mast at the hole location, (b) hold the main mast at any level from 0-2m above the ground is considered important. Hoist and feed rating: Bearing in mind possible use of vibrodrivers in the future to cope with unconsolidated ground overlying rock, a maximum feed rate of 10m/min may be desirable. A satisfactory hoist rate is 3m/min.; acceptable hoist capacity = 35kN; and acceptable feed capacity = 25kN.

Ideally, pressure gauges giving a measure of torque and feed capacity during drilling should be incorporated in the rig. These gauges could be monitored by an experienced driller or engineer to highlight changes in the strata, and thereby improve quality control. Exhaust pollution: In the future, attempts should be made to design and specify prime movers which emit "clean" exhaust.

In spite of the above recommendations, it is noteworthy that for anchors installed directly into rock the traditional wagon drill with a percussive hammer may still provide the most economical solution in some circumstances.

In general, the correct choice of a drilling method and machine for an anchoring project is a critical factor in the eventual successful completion of a project and therefore the greatest care should be exercised in making that choice.

Drilling rates
Since the rate of drilling holes in rock depends on the nature of the material drilled and the drilling machine, it is desirable to have as much knowledge as possible on both the rock and the machine.

Regardless of origin, all rocks may possess complex secondary structures, banding or foliation, and the degree of fracturing and weathering, and bedding of the rock mass can affect the physical properties and the drillability of the rock. Consequently, although average or typical properties can be established for sound, unweathered specimens of rocks, in practice each site tends to be evaluated individually, and purely geological classifications of rocks offer little help in grouping rocks according to drillability. On the other hand classifying rocks on the basis of their physical properties, such as compressive and tensile strength, Young's modulus, scratch and impact hardness, toughness and others, is a major factor in establishing a suitable drillability scale. Nevertheless, no definite conclusion has been reached as to which are the most useful physical parameters to determine, and no single property correlates perfectly with drilling rate, although rock compressive strength remains a popular and useful parameter in the hands of the specialist.

Most recently, van Ormer [1974] has attempted to relate penetration rate to rock mass and material properties, and considers texture (porous to dense fine), hardness (1-10 on the Moh scale), breaking characteristics (brittle to malleable) and geological structure (solid to laminated). In each case the first named in the range sustains a faster drilling rate than the other extremes. Table III summarises the data pertaining to hardness, and the drilling rate for various rocks relative to 1.0 (for solid, homogeneous Barre Granite) is shown in Table IV. The latter table does not take into account the secondary structure of the rock mass—the influence of which, it is claimed, is best determined from experience. Differences between measured and predicted drilling rates based on physical properties of the rock are probably due to the ever present variation of these properties throughout the length of hole. Although rock material and mass anisotropy is known to affect drillability, little work has been carried out to quantify its influence. In view of its importance however some effects are summarised by van Ormer in Table V.

While solid formations should provide good drilling, seamy, broken formations induce slow rates as tedious, careful supervision is necessary to avoid loss of flushing capacity, loss of drill string, and bit sticking.

From the standpoint of the anchor contractor, one of the simplest procedures at present for predicting penetration rates, particularly in percussive and rotary-percussive drilling, is to determine the coefficient of rock strength of the rock to be drilled. The test, which was first described by Protodiakonov [1962] and subsequently modified by the U.S. Bureau of Mines (Paone et al. 1968), consists basically of fracturing rock samples by impacting them with a falling weight. The resulting damage is measured by screening the broken sample. The test is relatively simple, does not require elaborate equipment and
one man can carry the apparatus into the field and make several determinations in one day. Good results have been obtained in correlating field penetration rates with the coefficient of rock strength for rotary-percussive drills (Unger & Fumanti, 1972) and for percussive drills (Schmidt, 1972).

One major disadvantage, however, in using only the coefficient of rock strength for prediction is that no account is taken of drill power and machine characteristics.

Penetration rates, particularly for percussive drills, are a function of the air pressure supplied to the drill, the condition of the drill and the type and condition of the bits. Other technical factors such as flushing medium and bit diameter are also important, but to date have received little investigation. Since these parameters are usually difficult to measure with any degree of precision, especially in the field, it is not surprising that some discrepancies between calculated and measured rates are evident.

As a result it is now widely appreciated that a step that considers energy output of the drill must be included to further refine the procedure for predicting drilling rates. Whilst much work remains to be tackled Paone et al. [1968] in a detailed account have already suggested a method of estimating penetration rate based on the quantity of energy required to cut a unit volume of rock and the energy output of the drilling system. It is also noteworthy that Paone et al. [1969] have suggested using the coefficient of rock strength to determine the energy required to remove a unit volume of rock.

**Flushing**

It is vital to remove particles from the bit quickly and efficiently. Energy expended on grinding such fragments obviously cannot be used for hole production; comminution of the fragments also increases wear of the bit.

Commonly used flushing media are air, water or "mud"—usually being a colloidal suspension of bentonite in water. A distinction is also drawn between normal and reverse flush circulation. In the former, the flush is introduced via the rods and bit, and returns to the surface between the rods and the hole wall. In the latter, the opposite situation occurs.

Of the media listed, air is probably the most efficient scavenger, water the best coolant and mud the best lubricant. Air is the commonest fluid used for surface drilling with percussive machines, and with drag-bit and roller-bit rotary drilling in quarries. Air is best used in dry ground, although it can be used in very wet conditions provided ample air is available but offers little advantage over wet drilling. Underground, and in confined spaces generally, air is unsatisfactory unless used in reverse circulation, because of the health hazard of dust particles. Rock-drilling in confined spaces such as tunnels is therefore normally restricted to wet or suction drilling, the latter being one example of reverse circulation.

Water flushing is the standard method used for drilling in sticky ground (i.e. where there is a small inflow of water into the hole from the rock, only sufficient to combine with the cuttings to form a paste or where there are clayey layers), for drilling under the water table at depth, and for diamond drilling. The quantity of water used is not excessive—usually less than 4 litres per minute for conventional

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**TABLE III. HARDNESS OF SOME ROCKS AND MINERALS**

<table>
<thead>
<tr>
<th>Mineral or rock</th>
<th>Hardness</th>
<th>Scratch test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Carborundum</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>Sapphire</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>Chrysoberyl</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Topaz</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Zircon</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Quartzite</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Chert</td>
<td>6.5</td>
<td>Quartz</td>
</tr>
<tr>
<td>Trap rock</td>
<td>6.0</td>
<td>Glass</td>
</tr>
<tr>
<td>Magnetite</td>
<td>5.5</td>
<td>Knife</td>
</tr>
<tr>
<td>Schist</td>
<td>5.0</td>
<td>Knife</td>
</tr>
<tr>
<td>Apatite</td>
<td>4.5</td>
<td>Knife</td>
</tr>
<tr>
<td>Granite</td>
<td>4.0</td>
<td>Knife</td>
</tr>
<tr>
<td>Dolomite</td>
<td>3.5</td>
<td>Knife</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.0</td>
<td>Copper coin</td>
</tr>
<tr>
<td>Galena</td>
<td>2.5</td>
<td>Copper coin</td>
</tr>
<tr>
<td>Potash</td>
<td>2.0</td>
<td>Fingernail</td>
</tr>
<tr>
<td>Gypsum</td>
<td>1.5</td>
<td>Fingernail</td>
</tr>
<tr>
<td>Talc</td>
<td>1.0</td>
<td>Fingernail</td>
</tr>
</tbody>
</table>

(After van Ommer, 1974)

**TABLE IV. DRILLING CHARACTERISTICS OF COMMON ROCKS**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Comparative drilling speed</th>
<th>Rock material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness— 1-2</td>
<td>1.5 and up</td>
<td>Shales</td>
</tr>
<tr>
<td>Texture— Loose</td>
<td></td>
<td>Schist</td>
</tr>
<tr>
<td>Breakage— Shatters</td>
<td></td>
<td>Ohio Sandstone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Indiana Limestone</td>
</tr>
<tr>
<td>Hardness— 3-4</td>
<td>1.0 to 1.5</td>
<td>Limestone</td>
</tr>
<tr>
<td>Texture— Loose grained to granitoid</td>
<td></td>
<td>Dolomites</td>
</tr>
<tr>
<td>Breakage— Brittle to shaving</td>
<td></td>
<td>Marbles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Porphyries</td>
</tr>
<tr>
<td>Hardness— 4-5</td>
<td>0.6 to 1.0</td>
<td>Granite</td>
</tr>
<tr>
<td>Texture— Granitoid to fine grained</td>
<td></td>
<td>Trap Rock</td>
</tr>
<tr>
<td>Breakage— Strong</td>
<td></td>
<td>Most fine-grained igneous rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Most quartzite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gneiss</td>
</tr>
<tr>
<td>Hardness— 6-8</td>
<td>0.5 and less</td>
<td>Hematite</td>
</tr>
<tr>
<td>Texture— Fine grain to dense</td>
<td></td>
<td>(fine-grained, grey)</td>
</tr>
<tr>
<td>Breakage— Malleable</td>
<td></td>
<td>Kimberly chert</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Taconite</td>
</tr>
</tbody>
</table>

(After van Ommer, 1974)

Barre Granite is used as the standard for determining a comparative drilling speed of 1.0 because of its even texture, hardness, and consistent drilling.

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**TABLE V. EFFECT OF ROCK MASS STRUCTURES ON DRILLING RATES**

<table>
<thead>
<tr>
<th>Rock mass</th>
<th>Nature of fractures</th>
<th>Drill rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive</td>
<td></td>
<td>Fast</td>
</tr>
<tr>
<td>Stratified</td>
<td>Perpendicular to drill rod; &gt; 1.2m apart, clean</td>
<td>Fast Medium</td>
</tr>
<tr>
<td>Laminated</td>
<td>Perpendicular to drill rod; &lt; 1.2m apart, clean</td>
<td>Medium</td>
</tr>
<tr>
<td>Steeply dipped</td>
<td>Small angle to drill rod, 1.2m apart, clean</td>
<td>Slow Medium</td>
</tr>
<tr>
<td>Seamy</td>
<td>Various inclinations to drill rod; close, open fractures</td>
<td>Slow</td>
</tr>
</tbody>
</table>

(After van Ommer, 1974)
anchor hole drilling. In spite of this wet drilling is often regarded as a messy and inconvenient method, whilst mud flushing is considered expensive and thought to require a great deal of preparation. Mud flushing is not common in rock anchor construction although it has been successfully in France for open hole drilling through silts and sands overlying rock.

The type of flush employed may in cases improve the efficiency of hole formation. In weakly cemented sandstones for example, water flushing widens and cleans the hole and ensures a better bond at the grout/rock interface. However, in rock strata liable to deterioration from water action such as marls and chalks, water flushing where necessary should be kept to a minimum.

Regardless of the supposed efficiency of the flushing process, it is usual in anchor construction to leave a "sump" length for debris at the bottom of the borehole. In current practice, 0.3-0.7m is commonly added to the designed borehole length. After each hole has been drilled to its full depth and thorough flushed out in order to remove any loose material, the hole should then be sounded to ascertain whether "fall-in" or "blow-up" of material has occurred and whether it will prevent the anchor tendon reaching the required depth. If satisfactory the top of the hole should then be effectively plugged to prevent debris falling into it.

With regard to the logging of data relating primarily to ground water and flushing methods, it should be noted that variations in ground conditions, over a few metres, can have marked effects on subsequent anchor performance—especially in soft rocks. Much qualitative data can be obtained on ground conditions by logging drilling rates and the degree of bit blocking, but a more sensitive record is often provided by observing changes in the amount and composition of flush return.

Other data relating to ground water, pressure and permeability can also be readily obtained if close liaison is established and maintained with the driller. For example, the following should be noted:

(i) the depth at which ground water is first encountered in the hole,
(ii) any water added to the hole to assist drilling,
(iii) the level of water, and amount and diameter of casing in the boring at the end of the shift, and
(iv) the level of water when work recommences.

**Alignment and deviation**

In the drilling of rock anchor boreholes, it is important to maintain a true, straight hole, terminated in the expected, calculated position. Three causes of errors may be recognised:

(a) incorrect setting-up, with the drill pointing in the wrong direction at the start of drilling,
(b) misalignment, in which the drill is incorrectly lined up but the hole is out of line with the axis of the drill, and
(c) deviation in which the hole is started in the correct line but subsequently alters direction.

Correct setting-up of a drill is largely a matter of care and a good eye, but should always be aided by the use of a profile and spirit level. The use of a casing or drill rod guide plate at the base of the drill mast is advantageous.

Regardless of cause, misalignment is troublesome and can result in damage to the drill and string as well as causing jamming of the rods. Furthermore, McGregor [1967] notes that the rubbing of the rods on the wall of the hole may dislodge rock fragments whilst the resultant friction—especially in rotary drilling—can increase enormously the torque requirements.

Deviation of the rig when the drilling thrust is relaxed may also be a problem in soft ground and experience indicates that special care is required when drilling from free-floating platforms.

Deviation of the hole during drilling does not normally arise from a single circumstance. It may originate by using too thin rods, from excessive thrust, or by the bit following a fissure or other rock planar structure. Deviation is not usually a serious problem for DTH drills, but is aggravated by the hole length in diamond drilling.

The above remarks have been primarily related to vertical downward-holes. With angled holes, the rods are apt to lie on the lower side of the hole and this has the effect of upturning the bit slightly. Hence angle holes often—but not invariably—tend to follow a shallow curve away from the vertical.

Wherever possible, drill holes should be planned so that they intersect the major rock discontinuities at as high an angle as possible. If this rule is not observed, then it is probable that a proportion of the holes will tend to deviate along the planes of the rock. In mica-schist for example, the drill face follows the mica defined schistosity if originally drilled at, say, a 5 deg. angle to it.

It is therefore essential to set-up the drill with the greatest care and precision and to monitor the progress of the hole. It becomes progressively more difficult and costly to alter the direction of the hole after drilling has proceeded beyond a few metres.

The guidance on maximum permitted deviations has appeared, but tolerances of 0° 28’ (Parker, 1958), 1° 10’ (Eberhard and Veltrop, 1965) and 0° 43’ (Littlejohn and Truman-Davies, 1974) may be compared with the less rigorous maximum of 2° 30’ permitted by the South African Code. Contractors often quote average deviations of 1 in 50 i.e. 1° 09’ and tolerances are usually relaxed in the fixed anchor zone. (Tolerance is measured as a deviation of anchor hole from the specified centre line divided by the length of drill hole).

A common method of inexpensively checking the deviation in a vertical hole is to lower a thin string of lead into the borehole. The length of the string, measured and the deviation is noted (Littler and Jenman, 1965). It is therefore suggested that such devices could be considered as a reasonable threshold for water loss when ordinary Portland Cements are employed in the.

**WATER TESTING AND WATERPROOFING**

On completion of drilling, the anchor borehole must be tested for 'watertightness'. Since subsequent loss of grout from around the tendon in the fixed anchor zone is of prime importance in relation to efficient load transfer and corrosion protection. Reasonable threshold values for water loss or gain must be assessed, which, when exceeded, dictate the need for waterproofing. In practice, it has been generally accepted that cement is not suitable for the treatment of fissures which are less than 250 microns wide although recent experimental studies suggest that the lower limit is closer to 160 microns for Ordinary and Rapid Hardening Portland Cements.

The author believes that a logical approach is to establish the minimum width of fissure which will permit flow of cement at low pressure. The water flow per atmosphere which is caused by a single fissure is determined by the width of the fissure may then be specified as a threshold value which dictates the need for waterproofing.

It may be estimated that a single 160 micron fissure under an excess head of 1 atmosphere gives rise to a flow rate 3.2 litres/min (Littlejohn and Jenman, 1965). It is therefore suggested that this order of flow should be considered as a reasonable threshold for water loss when Ordinary Portland Cements are employed in the.
neat cement grout. A lower fissure width of 100 microns gives a flow rate of 0.6 litres/min/atm, and this may be a more realistic threshold for minimal penetration when fine-grained cements are employed.

With regard to rock anchor practice, the monitoring of water flow which have been permitted in various countries to date are listed in Table VI.

Clearly, great care must be taken in the interpretation of limiting flow rates, with particular regard to the length of section being tested. To avoid the serious misinterpretation, it is recommended that permissible flow rates should be quoted simply in terms of litres/min/atm, no reference being made to flow per unit length of hole or length of anchor.

In general, it is considered that water tests carried out over sections e.g. the fixed anchor, with the aid of packers are preferable to rate-of-fall tests carried out under atmospheric pressure from the surface, since more detailed information can be obtained over specific locations. Packer testing is not essential however and on many occasions rate-of-fall tests can be carried out more cheaply and quickly. In these tests testing points may only be warranted if the acceptable water flows are exceeded.

On the practical side the hole must be thoroughly flushed with clean water from the bottom before testing, and during the test it may be of value to reduce the level of water in any adjacent holes so that any interhole connections may be more easily detected.

From a review of current world practice, it is clear that water-testing is not a routine operation. When water-testing is carried out, generally acceptable water flows have not been established for rock anchor grouting. As a result, the following recommendations are presented for consideration:

(a) Waterproofing is required if leakage or water loss in an anchor borehole exceeds 3.0 litres/min/atm. The duration of the test should not be less than 10 minutes and in terms of the Lusignan value the above flow is equivalent to 100L.

(b) Where there is a measured outflow or water gain (under ation conditions) care should always be taken to avoid damage to the grouting by the creation of a "backpressure" during the grouting stage. If the flow cannot be stabilised in this way waterproofing is required, irrespective of the magnitude of the water flow.

(c) Permissible flow is related to "excess head". Therefore the position of the water table in relation to the section being investigated must be established so that the driving or excess head indicated for any given rate of flow can be calculated accurately. In fine fissures high applied pressures may induce turbulent flow, create high pressure gradients and open up the natural fissures, and therefore the local environment should be minimised and therefore the applied pressure inducing flow should be as small as possible.

(d) The flow rates in (a) are minimum values since they all pertain to single fissures. Clearly, larger limiting flow rates are acceptable if a number of fissures (thickness < 160 microns) exist. This situation however must be confirmed by close examination of the borehole interface using a camera or close circuit television and/or multipacker injection technique.

In order to waterproof the hole against water loss, grout should be trenched into the hole from the base upwards. After a period of time (usually from 6 to 24 hours) the hole is redrilled and the water test repeated. The anchor construction procedure may only continue when the waterproofing criteria are satisfied. If the pregrouting is not successful on the first attempt a greater pressure may be used, but pregrouting may be required to force the grout into the fissured rock mass and thereby stabilise the borehole wall against subsequent redrilling.

Tendon Storage and handling

Longbottom and Mallett [1973] make a number of sound recommendations regarding this topic, on the basic assumption that anchor tendons must be protected against mechanical damage and severe corrosion on site.

Tendons must not be dragged across abrasive surfaces or be accessible to weld splash. Bars should be stored in straight lengths in racks, and the coils of diameter at least 200 times that of the tendon diameter. Kinked or twisted wire should be rejected, since experience has shown that bond and load/displacement characteristics can be adversely affected.

To avoid damage to protective sheathing, the ends of the tendon should be treated, after cutting to size, to remove very sharp edges. With respect to bars, care should be taken to protect the threads. Superficial damage to the threads can often be repaired by means of a file, but it is usually impracticable to recut or extend a bar thread on site because of the hardness of the steel.

Ideally, steel for anchor tendons should be stored indoors in clean, dry conditions. If this is impossible, the steel may be left outdoors for several months without serious corrosion, provided it is stacked off the ground and completely covered by a waterproof material, and the tar- paulin should completely cover the steel it should be fastened so as to permit circulation of air through the stack.

The humidity of the air, allied to possible atmospheric pollution (industrial and marine) is the major cause of corrosion during storage. There would appear to be little problem if the relative humidity is always less than 70 per cent, but severe corrosion occurs at levels in excess of 85 per cent. The worst conditions are experienced in marine tropical areas, where the average rate of corrosion is about three times that in a heavy industrial area in the UK. In such areas, wrappings should be上官 of a vapour phase inhibitor powder, and in this way the flow must be prevented.

Although it is known now that normal rusting actually improves the bond to grout, flakey, loose rust must be completely removed from the tendon prior to grouting of a bar, and therefore the tendons should always be prepared for use. This may be done by sandblasting or abrading the surface, and in fact this is the only acceptable method of removing the thin, but reactive, rust layer.

When the surface is smooth, the tendon can be wiped clean with a damp cloth and dried with a clean air compression before being passed through the grout port to be inspected microns, or until the surface layer is removed. Finally, the tendon should be wiped with a dry cloth and allowed to air dry before use.

Fabrication

With respect to bar anchors, all threads must be thoroughly cleaned and lightly oiled, and it is important to ensure that bars are properly screwed into couplers, and that full thread engagement is obtained in nuts and tapped plates. To minimise corrosion, the tendons should not be left ungrouted for long after grouting, especially if paraffin has been used.

Anchors with multi-strand or multi-wire tendons usually require more time for fabrication than the single wires, and the strand should be supplied already coated in PVC, then great care should be taken to decrease the intended fixed anchor length effectively, using solvents such as acetone, trichloroethylene or paraffin.

Some contractors specify unravelling of the strand to facilitate effective cleaning; the wires are afterwards returned to their correct lay. This basic method is recommended and an efficient, if somewhat time-consuming refinement to the strand system has been developed by U.A.C., Ltd., who introduce small ferrules on to the central wire prior to relaying the strand. This produces nodes in each strand and undoubtedly increases the resistance to the strand-grout failure. Alternatively, the laborious and inherently risky job of attempting to completely remove a graphited bituminous grease which has been designed to resist easy removal, a machine has recently been developed (Littlejohn and Truman-Davies, 1974) to remove the graphited individual strand and apply a protective plastic sheath only over the free length where it is required.

The fixing and location of spacers and centralisers must be done with care and precision, especially in the fixed anchor length where the tendon is usually formed into a roughly circular configuration with steel or polythene spacers and wire bindings. Attention should also be given to the integration of the tendons at anchor heads, a sleeve or nose cone which will minimise the risk of tendon or borehole damage during homing is recommended.

Homing

Any method can be used provided that it will ensure that the tendon is lowered at a steady controlled rate. It is recommended that for heavy flexible tendons of total weight in excess of 200kg, mechanical or hydrostatically pregrouted anchor (U.A.C., 1974) be used to gradually unreel the tendon into the hole. It has been found that 200t capacity anchor, weighing about 168g/m, are the largest that can be used in ungrouted areas, e.g. dam crests, without elaborate handling equipment.

If the borehole grout is preplaced under water, grout dilution can occur if the tendon is lowered too quickly. The use of cranes, the tendons into the hole is preferable to the use of cranes, or (for vertical anchors) handling, as both these methods often create sudden bending of the tendon which may damage the tendon during homing. As homing is immediately prior to homing, the tendon should be carefully inspected, and in certain situations the efficiency of the centraliser/spacer units may be judged by careful withdrawal of the tendon—prior to grouting—to observe evidence of damage or distortion, or the amount of smear.

In general the choice of the best methods of storage, handling, fabrication, and installation of anchor tendons is wholly an issue in crystalline rocks. In some places, steel and fittings are valuable stores, and tendons should be treated as such on site.

(Part 2 of this three part series will be concluded in our next issue)