Chapter 5

Subsurface exploration: boring, drilling, probing and trial pitting

INTRODUCTION

Chapter 4 considered the various indirect methods by which the ground can be investigated, using geophysical techniques. Whilst these methods can be extremely valuable for ground investigation purposes, they are not in everyday use. The bulk of ground investigation is carried out using the direct methods of investigation described in this chapter, coupled with *in situ* or laboratory tests.

The primary functions of any ground investigation process will be one of the following:

1. locating specific ‘targets’, such as dissolution features or abandoned mineworkings
2. determining the lateral variability of the ground;
3. profiling, including the determination of groundwater conditions;
4. index testing;
5. classification;
6. parameter determination.

Geophysical methods can be very good at giving information on the location of specific targets, and investigating the lateral variability of the ground, but their results are often more qualitative than is preferred by design engineers. Parameters for engineering design most commonly are derived from *in situ* tests carried out in boreholes or from self-penetrating probes although, as was noted at the end of Chapter 4, seismic geophysics methods can give valuable information on the stiffness of the ground. Most profiling is done on the basis of soil and rock descriptions, carried out either on samples obtained from boreholes, or on the faces of trial pits or shafts. And the majority of classification and index testing is carried out on samples taken from boreholes and trial pits.

Therefore the direct methods of testing described in this chapter are at the centre of routine ground investigation. They provide the opportunity to obtain samples for visual description and index testing, which are the primary ways in which the strata at a site are recognized, and for sampling and much of the *in situ* testing needed for parameter determination, as well as allowing the installation of instrumentation such as piezometers.

Boring is carried out in the relatively soft and uncemented ground (engineering ‘soil’) which is normally found close to ground surface. The techniques used vary widely across the world. The most common methods are augering, washboring and (in the UK) light percussion drilling. This latter technique is well adapted to stoney soils, and has its origin in water well drilling techniques.

Drilling has traditionally been used in the more competent and cemented, deeper deposits (engineering ‘rock’). It is now also widely used to obtain high-quality samples of heavily overconsolidated clays, for specialist laboratory testing. Both of the above methods can produce holes to great depths, which can be used for *in situ* tests as well as for sampling, and can allow the installation of instrumentation (for example, to measure groundwater pressures).

Probing is increasingly being used as a cheap alternative to boring and drilling. It is used as a qualitative guide to the variation of ground conditions, and is particularly valuable for profiling. The techniques used are often fast, and are generally cheaper than boring and drilling, but they cannot be used to obtain samples or to install instruments.

Finally, examination *in situ,* by trial pits and shafts, provides by far the best method of recording both the vertical and lateral ground conditions. Borehole methods generally only take restricted samples, perhaps at every metre or so of depth, for engineering description. Rotary coring normally attempts to recover continuous core, but cannot give a guide to lateral variability, and gives only restricted information on discontinuity patterns in the rock. But trial pitting allows continuous description of soil conditions over the entire face of the pit or shaft, allows measurements of discontinuities in rock, and in addition permits very high quality samples to be obtained.

An understanding of these techniques is important not only because they represent the major element of cost in a ground investigation, and must therefore be used with care, but also because the way in which they are selected and used can have a great effect on the quality of site investigation.

BORING

A large number of methods are available for advancing boreholes to obtain samples or details of soil strata. The particular methods used any country will tend to be restricted, based on their suitability for local ground conditions. The principal methods used worldwide are:

- light percussion drilling;
- power augering; and
- washboring.

Light percussion drilling

Often called ‘shell and auger’ drilling, this method is more properly termed light percussion drilling since the barrel auger is now rarely used with this type of equipment. The drilling rig (Fig. 5.1) consists of:

1. a collapsible ‘A’ frame, with a pulley at its top;
2. a diesel engine; connected via a hand-operated friction clutch (based on a brake drum system) to
3. a winch drum which provides pulling power to the rig rope and can be held still with a friction brake which is foot-operated.

The rope from the winch drum passes over the pulley at the top of the ‘A’ frame and is used to raise and lower a series of weighted tools on to the soil being drilled. The rig is very light, and can be readily towed with a four-wheel drive vehicle. It is also very easy to erect, and on a level site can be ready to drill in about 15 mm. Where access is very limited, it can be dismantled, and rebuilt on the other side of an obstruction such as a doorway.

In clays, progress is made by dropping a steel tube known as a ‘claycutter’ into the soil (see Fig. 5.2). This is slowly pulled out of the borehole and is then generally found to have soil wedged inside it. The claycutter normally has a solid or slotted weight, called a sinker bar, attached to its upper end, the top of which is connected to the winch rope. When the claycutter is withdrawn from the top of the hole, the soil is removed with a metal bar which is driven into it through the open slot in the claycutter side.

In granular materials, such as sands or gravels, a shell is used. At least 2 m of water is put in the bottom of the borehole, and the shell is then surged, moving about 300mm up and down every second or so. Surging the shell upwards causes water to be drawn into the bottom of the hole, and this water loosens the soil at the base of the hole and forces it to go into suspension. As the shell is dropped on the bottom of the hole the mixture of soil and water passes up the tube of the shell, past the simple non- return valve (sometimes called a ‘clack’). As the shell is raised, the clack closes and retains the soil, which precipitates above it.

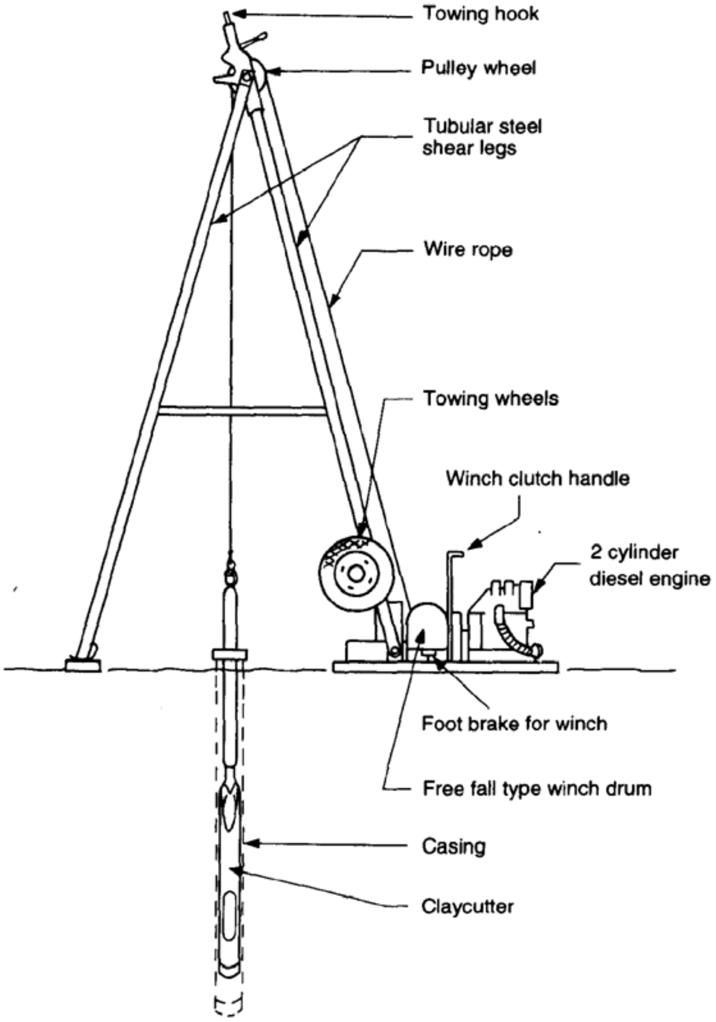


Fig. 5.1 Light percussion drilling rig (Pilcon Engineering Ltd).

By repeatedly surging the shell up and down at the base of the hole, soil can be collected and removed from the hole. The casing should either be allowed to follow the hole down (if it is loose) or should be driven so that it is just above the base of the hole, otherwise progress will be slow, and either large cavities will be formed on the outside of the casing or the soil will be loosened for a considerable distance around the hole. Of course, casing is nearly always used with the shell, because most granular soils will not stand vertically if unsupported in the presence of water.

Casing is not only used when drilling in granular soils, but is also necessary when drilling in very soft soils or when drilling in clays, to seal off groundwater after it is encountered. The presence of water in the base of the hole will allow samples to swell, but the reason that most drillers seal off water is more basic: stiff plastic clays become difficult to recover with the claycutter if large quantities of water are present and if this water cannot be controlled the driller will usually be forced to drill more slowly using the shell.

In the UK, where large parts of the South-east have stiff clays which provide ideal drilling conditions, the light percussion rig normally has 1000—1500kg capacity and most commonly uses 150—200mm dia. casing and tools. It will have little difficulty in boring to 45 m depth in a very stiff clay such as the London clay, but in sandy soils more casing sizes will often be needed to reduce friction.

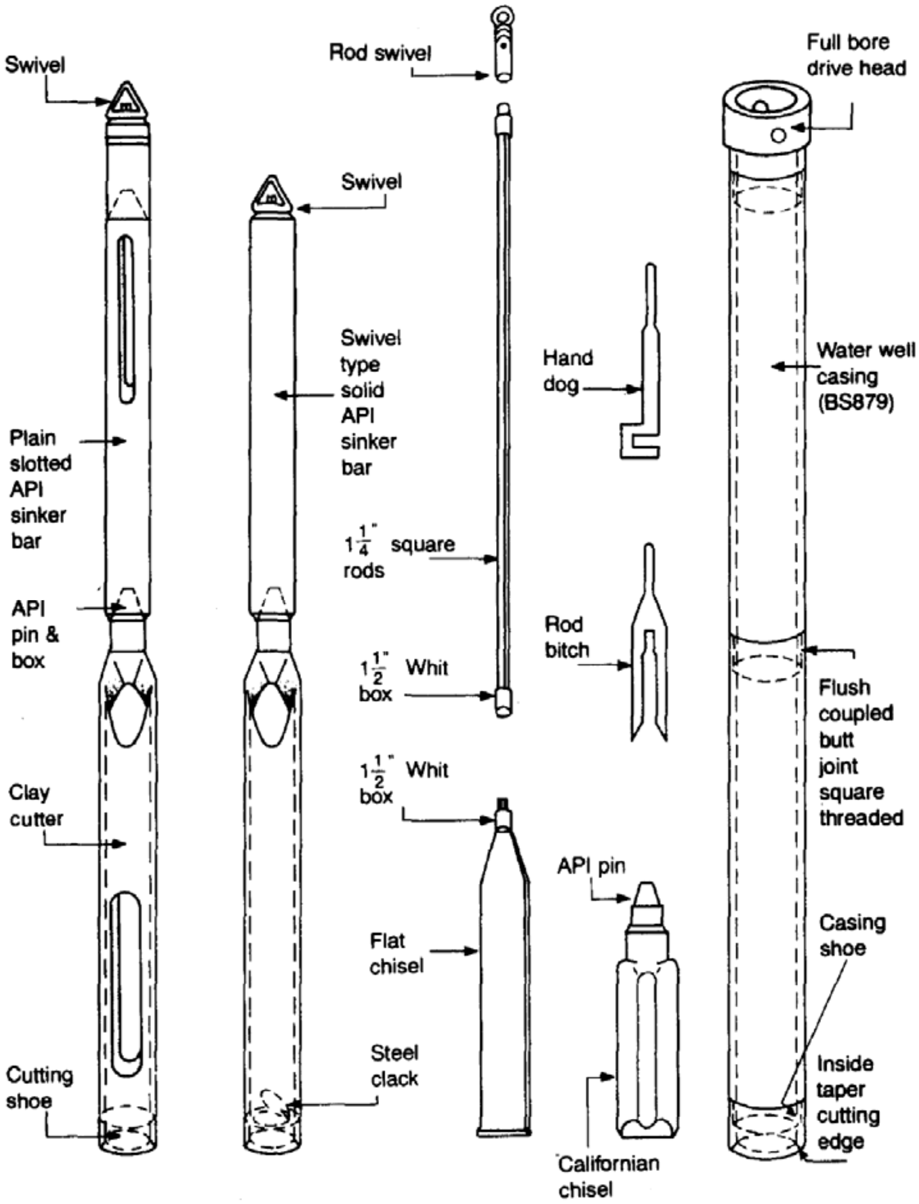


Fig. 5.2 Light percussion drilling tools.

The friction transmitted by sand or chalk to the outside of casing will often be too great to allow the rig to pull more than 10—20m of casing out of the ground without the use of short-stroke hydraulic jacks. Under these conditions strings of casing of different diameters are used to allow a greater depth of drilling. As an example, if a borehole were to be advanced to 50m in sand, the driller might start the boring using 300 mm dia. casing and tools and drill until the rig began to have problems pulling the casing, which might occur at 15 m depth. At this stage the driller would insert a string of 250 mm dia. casing and pull back the larger casing 1 m or so to make sure that it would still be loose at the end of boring the hole. The inner 250 mm dia. casing, of course, would receive no friction on the upper 14m of its length, and the hole could now be advanced until its second string became tight, when a 200mm string of casing would be inserted at, say 30 m below ground level (GL). At the end of boring the hole might be cased with four different sizes, as in Table 5.1.

The minimum casing size possible in Britain is 150mm dia., because this is the smallest size allowing the use of the British Standard General Purpose 100mm dia. sampler (BS 5930). The casing used in the UK is square threaded and flush coupled, in contrast to the drive pipe’ in use in the USA which is coupled via a threaded external collar. This type of coupling can be particularly troublesome in sands, where the coupling considerably increases the difficulty in extracting casing at the end of drilling.

Table 5.1 Example of casing for 50m borehole

Depth (m)	Casing (mm dia.)
GL—14	300
GL—29	250
GL—41	200
GL—50	150

Augering

Augers may be classified as either bucket augers (Fig. 5.3) or flight augers. Bucket augers are similar in construction to the flat-bottomed Sprague and Henwood barrel auger. They consist of an open-topped cylinder which has a base plate with one or two slots reinforced with cutting teeth, which break up the soil and allow it to enter the bucket as it is rotated. The top of the bucket is connected to a rod which transmits the torque and downward pressure from the rig at ground level to the base of the hole: this rod is termed a 'Kelly'. Bucket augers are used for subsurface exploration in the USA, but are rarely used for this purpose in the UK. This is probably because they require a rotary table rig, or crane-mounted auger piling rig for operation, and this is usually expensive to run. Casing also provides some problems, since a single rig cannot drill in cohesionless soil beneath the water table.

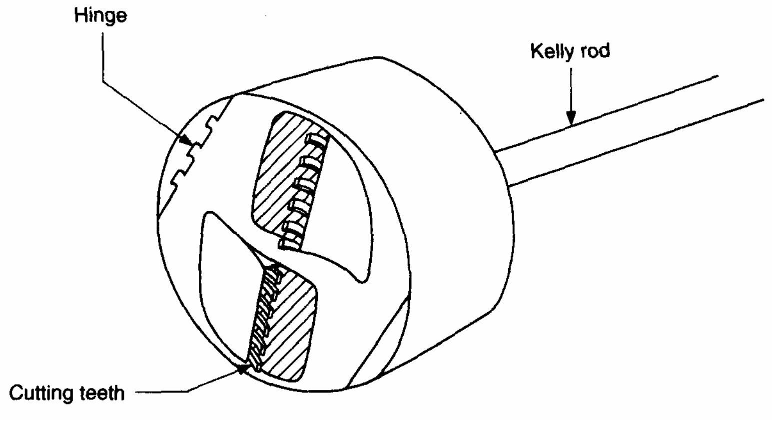


Fig. 5.3 Bucket auger.

Flight augers may be classified as short-flight augers (Fig. 5.4) or continuous- or conveyor-flight augers. Short augers consist of only a few turns of flight above cutting teeth or a hardened steel edge. A high-spiral auger may contain three or four turns of flight. The hole is made by forcing the auger downwards at the bottom of the hole, while rotating it. The cutting teeth break up the soil or rock, which is then transferred up the auger flights. When the flights become full, or when the auger has been advanced for the height of the flights, the auger is raised to the top of the hole and the soil flung clear by rapidly rotating it. Once again, the auger is supported by a Kelly rod which transmits the torque and downward thrust from the drill rig to the auger.

The principal limitation of short augering is that the hole depth is restricted to the length of Kelly rod which the rig can handle. For many of the rigs commonly in use this is only 3—6m. The use of a crane-mounted auger piling rig will allow holes to be drilled to 20—30m if a telescopic Kelly rod is fitted, but as already noted such rigs are very expensive.

The problems of deep drilling with short augers are largely overcome by the use of continuous or conveyor augers. Continuous augers can be classed as: (i) solid stem continuous-flight augers (Fig. 5.5); or (ii) hollow stem continuous-flight augers.

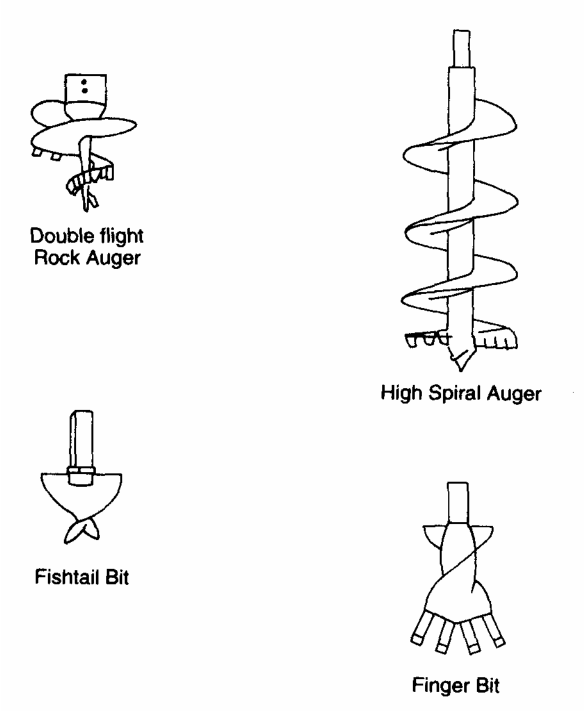


Fig. 5.4 Short-flight augers and auger bits.

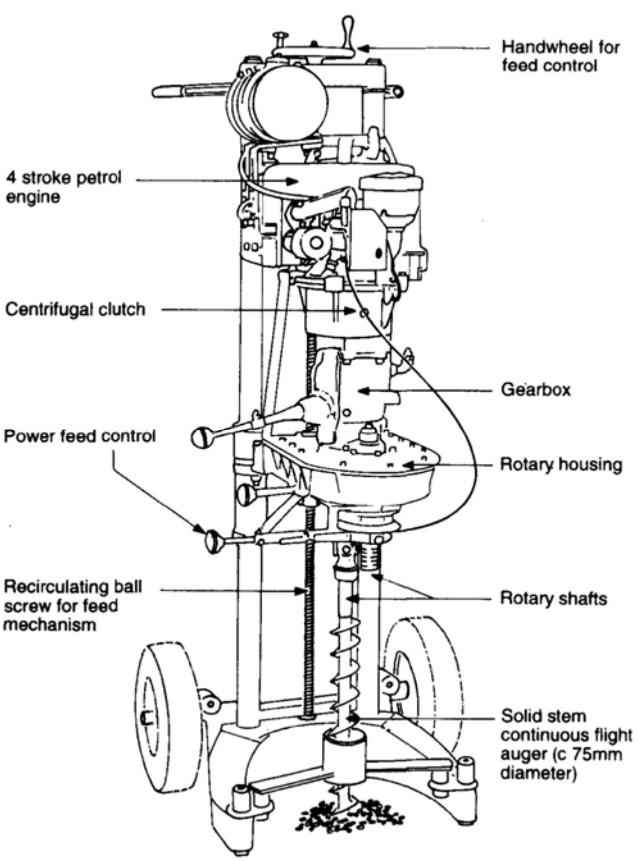


Fig. 5.5 Mobile Minuteman’ small diameter solid stem continuous-flight auger rig.

Solid-stem continuous-flight augers allow much deeper holes to be drilled with fewer problems. With this type of auger the Kelly never enters the borehole, as the auger flights extend to above ground level. As the auger is rotated and pushed downwards the soil removed from the base of the hole travels up the flights and emerges at the ground surface. Although this type of auger apparently overcomes the problems found in drilling deep holes with short-flight or bucket augers, it presents a serious problem in site investigation because soil moving up from the base of the hole is free to mix with the soil at higher levels on the edge of the borehole. Thus while auger tailings from short-flight augers or bucket augers may be fairly representative (even if highly remoulded), the soil emerging from the top of a continuous-flight auger will be of no use. In addition, in common with all the auger methods above, the need for casing in granular or other collapsing soils presents a problem. In fine-grained soils a casing can be inserted when collapsing soil is encountered, and can sometimes be advanced by jetting; but in coarse gravels the continuous-flight auger is unusable because it must be removed each time a sample or *in-situ* test is to be carried out. At this stage the hole will collapse.

Hollow-stem augers (Fig. 5.6) consist of an outer spiral continuous flight with a separate inner rod which blocks off the base of the hole when the auger is being advanced. Both the outer flights and the centre plug are furnished with a bit at the base. The auger is forced into the ground in the same way as a solid-stem auger, with the inner and outer sections rotating together. When samples are required, the inner rods and plug are removed and samples can be taken from the material below the base of the auger. Hollow-stem auger drilling would at first sight seem to be the ideal method of producing site investigation holes, because it is often fast and reliable. There are, however, several problems which should be considered.

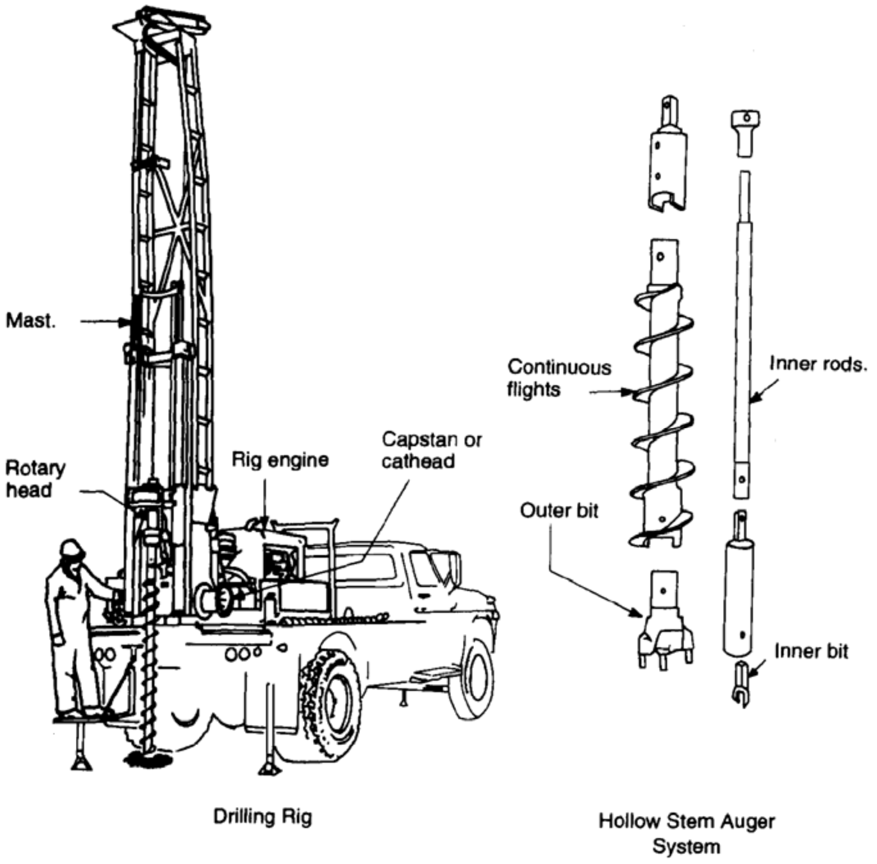


Fig. 5.6 Acker ADII drilling rig and hollow-stem auger system.

First, fissured clays or soils with fabric require relatively large samples for the determination of undrained shear strength and consolidation properties. This means that the hollow stem of the auger must have a large internal diameter (typically 140— 150mm to allow the use of U100 sampling). This in turn means that a relatively powerful and therefore large drilling rig is required. Even if such a rig is available, access to the site of the borehole may be a problem.

Secondly, there are considerable dangers of disturbing soil ahead of the auger if the driller is overeager in soft or firm soils. Heavy downward thrust may cause the auger to be forced into the soil, displacing material ahead of it instead of boring through it. The hand auger provides a light, portable method of sampling soft to stiff soils near the ground surface.

At least six types of auger are readily available:

- posthole or Iwan auger;
- small helical auger (wood auger);
- dutch auger;
- gravel auger;
- barrel auger; and
- spiral auger.

Figure 5.7 shows a selection of these augers.

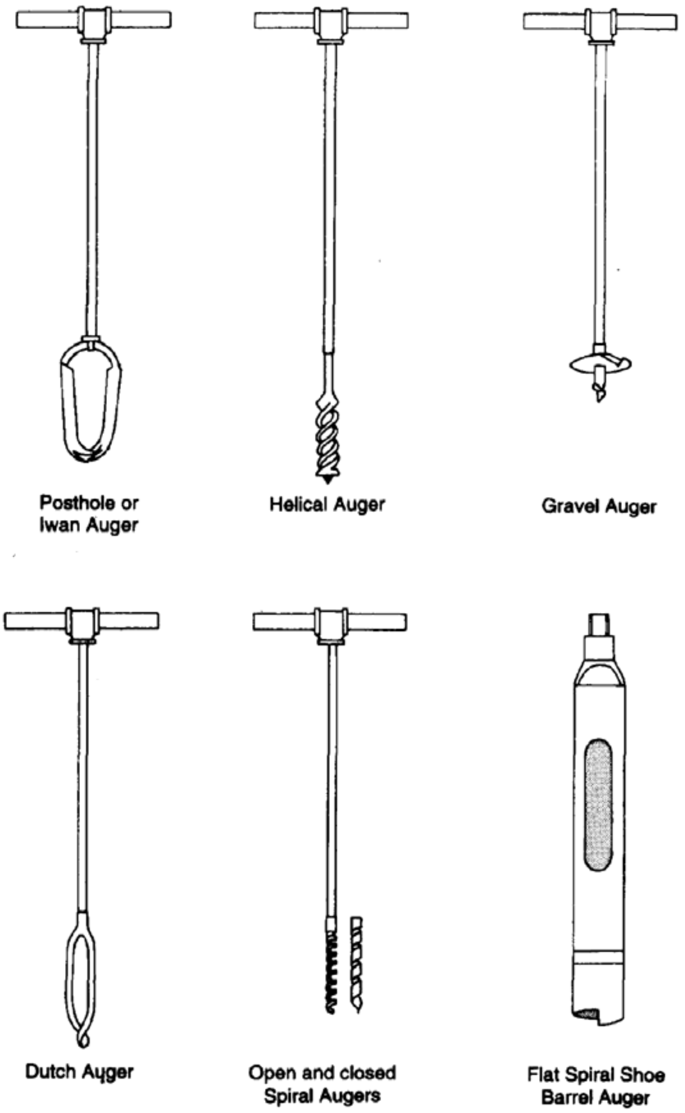


Fig. 5.7 Selection of hand-operated augers.

Hand augers are used by one or two men, who press down on the cross-bar as they rotate it thus advancing the hole. Once the auger is full, or has collected sufficient material, it is brought back to the surface and the soil removed. Although the method is cheap because of the simplicity of the equipment, it does suffer from several disadvantages.

The most commonly used auger for site investigation is the ‘Iwan’ auger. This is normally used at diameters of between 100 and 200 mm. Small helical augers are quite effective in stiff clays, but become difficult to use once the water table is reached.

Barrel augers are now rarely seen, but were formerly used with the light percussion rig when progress through clays was made using a shell. They allowed the base of the borehole to be very effectively cleaned before sampling took place. Because they are heavy they require a tripod for raising and lowering them in the borehole. When lowered to the bottom of the hole they were turned by hand (see Harding 1949).

In stiff or very stiff clays, hand-auger progress will be very slow, and the depth of boring may have to be limited to about 5 m. When such clays contain gravel, cobbles or boulders it will not normally be possible to advance the hole at all. In uncemented sands or gravels, it will not be possible to advance the hole below the water table, since casing cannot be used and the hole will collapse either on top of the auger (which makes it difficult to recover the auger from the hole) or when the auger is being removed. Only samples of very limited size can be obtained from the hole. In addition, it will not be possible to carry out standard penetration tests without a frame to lift the trip hammer and weight, so that no idea of the relative density of granular deposits can be obtained.

Despite these difficulties, where access for machinery is impossible the hand auger may give valuable information.

Washboring

Washboring is a relatively old method of boring small-diameter exploratory holes in fine-grained cohesive and non-cohesive soils. It was widely used in the USA in the first half of this century, but has been largely replaced by power auger methods. It is still used in areas of the world where labour is relatively cheap, for example southern Brazil.

A very light tripod is erected, and a sheave is hung from it (Fig. 5.8). In its simplest form there are no motorized winches and the drilling water is pumped either by hand, or by a small petrol-driven water pump. Hollow drilling rods are connected to the pump via a flexible hose, and the drilling crew lift the string of rods by hand, or using a ‘cathead’ (a continuously rotating steel drum, around which a manilla rope is wound).

Progress is made by jetting water out of a bit at the base of the rods. These are continuously turned using a tiller, whilst being surged up and down by the drilling crew. Cuttings of soil are carried up the hole by the drilling water (the ‘flush’) and emerge from a casing T-piece, being deposited in a sump. Routine identification of the ground conditions at the base of the hole is carried out by the driller placing his hand under the T-piece to collect a sample of cuttings.

Hvorslev (1949) commented that:

> Drillers with adequate experience in washboring can determine changes in and estimate the general character of the soil with satisfactory accuracy, especially when both the drill rod and the pump are operated entirely by hand. On the other hand very serious mistakes may be made by inexperienced or careless drillers, who often fail to recognize changes in the character of the soil, do not clean the borehole properly. and take samples of the coarse segregated material settled at the bottom, instead of the undisturbed material below the bottom. The results of such errors are very misleading soil profiles which often indicate strata of coarse materials at depths

where soft soils of low bearing capacity actually exist. The method should not be used above ground-water level when undisturbed samples are desired of the soil above this level, since the water will enter the soil below the bottom of the hole and change its water content.

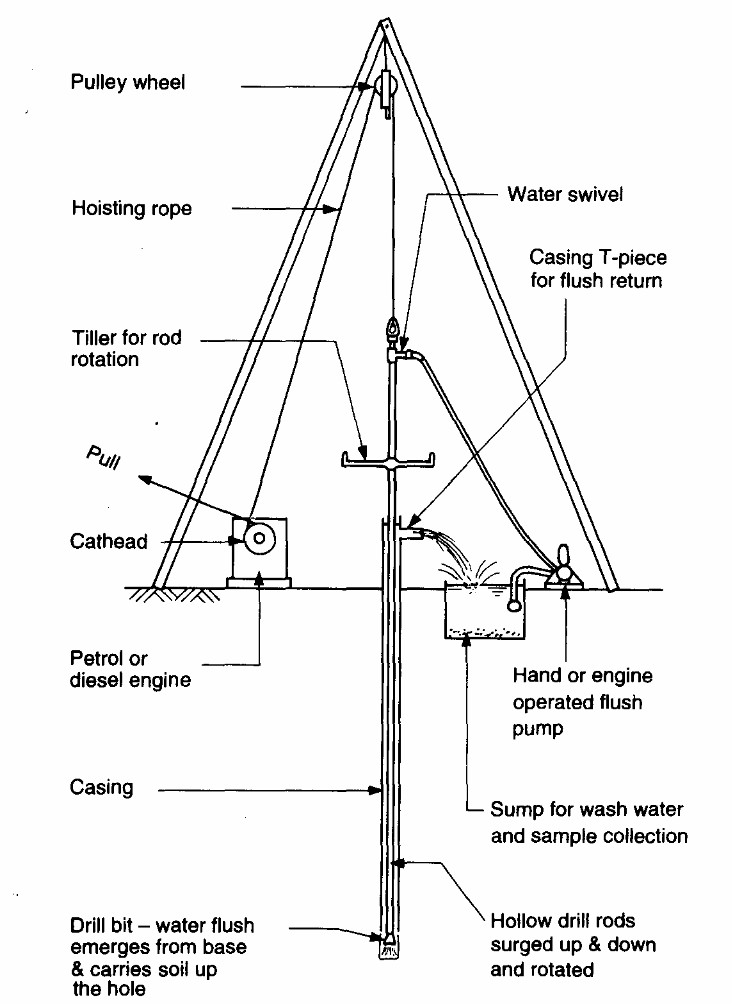


Fig. 5.8 Washboring rig (based on Hvorslev 1949).

DRILLING

Rotary drilling uses a rotary action combined with downward force to grind away the material in which a hole is being made. Rotary methods may be applied to soil or rock, but are generally easier to use in strong intact rock than in the weak weathered rocks and soils that are typically encountered during ground investigations. For a detailed description of equipment and methods the reader is referred to Heinz (1989).

Rotary drilling requires a combination of a number of elements (Fig. 5.9):

1. a drilling machine or ‘rotary rig’, at the ground surface, which delivers torque and thrust;
2. a flush pump, which pumps flush fluid down the hole, in order to cool the mechanical parts and lift the ‘cuttings’ of rock to the ground surface as drilling proceeds;
3. a ‘string’ of hollow drill rods, which transmit the torque and thrust from the rig, and the flush fluid from the flush pump to the bottom of the hole; and
4. a drilling tool, for example a corebarrel, which grinds away the rock, and in addition may be designed to take a sample.

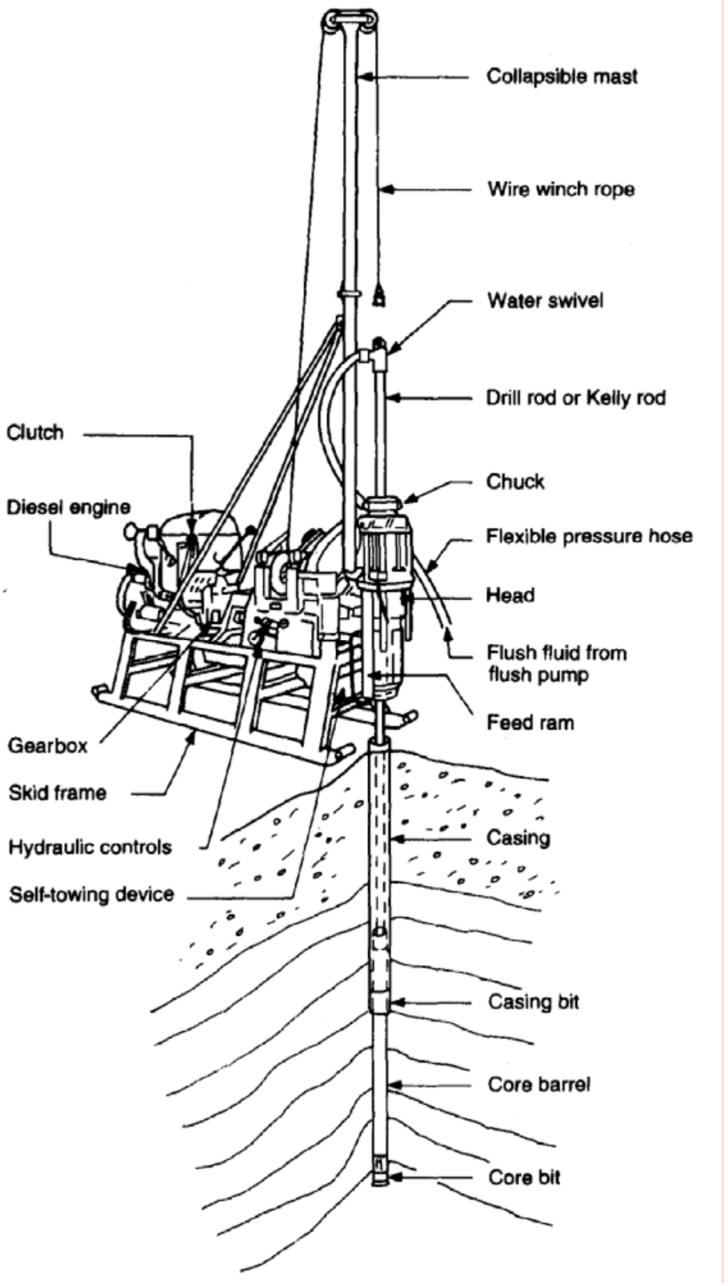


Fig. 5.9 Layout for small-scale rotary core drilling.

Open-holing

Rotary methods may be used to produce a hole in rock, or they may be used to obtain samples of the rock while the hole is being advanced. The formation of a hole in the subsoil without taking intact samples is known as ‘open-holing’. It can be carried out in a number of ways, but in site investigation a commonly used tool is the ‘tricone rock roller bit’ (or roller core bit) (Fig. 5.10). In site investigation such methods are usually used to drill through soft deposits, which have been previously sampled by light percussion or auger rigs. Sampling during open-holing is usually limited to collecting the material abraded away at the bottom of the borehole, termed ‘cuttings’, as it emerges mixed with ‘flush fluid’ at the top of the hole.

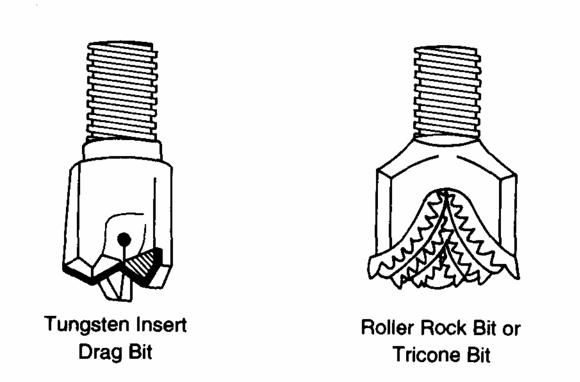


Fig. 5.10 Bits for rotary open holing.

Coring

The most common use of rotary coring in ground investigations is to obtain intact samples of the rock being drilled, at the same time as advancing the borehole. To do this a corebarrel, fitted with a ‘corebit’ at its lower end, is rotated and grinds away an annulus of rock. The stick of rock, the ‘core’, in the centre of the annulus passes up into the corebarrel, and is subsequently removed from the borehole when the corebarrel is full. The length of core drilled before it becomes necessary to remove and empty the corebarrel is termed a ‘run’.

Coring equipment
The manner in which the rock is abraded away, and by which the cuttings formed by this process are taken to ground level having been discussed, it becomes necessary to discuss the machinery used for the job. At the base of the borehole a bit is rotated against the rock, thus advancing the hole. This bit can be either solid or annular, depending on whether a sample is required. Annular corebits are screwthreaded to the bottom of a ‘corebarrel’, of which Fig. 5.11 is a typical example in use in site investigation. The corebarrel is screwthreaded to a ‘string’ (i.e. several lengths screwed together) of ‘drill rod’, which is generally of smaller diameter than the corebarrel. The function of the rods is to deliver torque and downward force to the bit (via the corebarrel) while at the same time providing the flush fluid to the bit. The drill rods are therefore hollow.

At ground level, the rods emerge from the hole and pass through the ‘chuck’ of the rig. The chuck grips the drill rods or ‘Kelly’ and transfers longitudinal and rotational movements to the rods. The Kelly continues upwards and is connected to a ‘water swivel’ or ‘gooseneck’, which connects the water or flush hose from the flush pump while allowing the rods to rotate and the hose to remain stationary (Fig. 5.9).

Drill rigs may vary considerably in size and design. Some of the smallest (for example the Acker 1200 PM) mount directly on top of $2\frac{1}{2}$—4 in. drill pipe (casing) installed by other means to rockhead. They consist of a small four-stroke petrol engine, typically of less than 10 h.p., which connects via a gearbox to the top of the rods. The water swivel is built into the machine, and feed is controlled by a mechanical system operated by a handturned wheel. Quite clearly, such a rig has a very limited capability. The load applied to the bit cannot be controlled, and the rig has no inbuilt hoist for lifting the drilling equipment out of the hole.

Most rotary drilling rigs used in site investigation tend to be rather small, when compared with the very large rigs used for oil exploration. They usually incorporate:

1. hydraulic feed control;
2. multispeed forward and reverse rotation;
3. cathead, wire drum hoist, or both;

4. a mast or tripod; and
5. variable mounting options, for both the rig and the drilling head.

Hydraulic feed control is used to vary the pressure between the corebit and the rock being drilled. In soft rocks, the use of excessive pressure will fracture the rock before it can enter the corebarrel, while in hard rocks the use of low feed pressures will result in very slow drilling progress. In very soft deposits the weight of the rods and barrel may be sufficient to fracture the rock and the hydraulic feed may need to be reversed to hold up the rods.

Multispeed forward and reverse rotation is important both from the point of view of good drilling and convenience. Slow speeds of the order of 50 r.p.m., are required for augering, and open-holing with the tricone. Faster speeds, of up to 1000 r.p.m. may be used for rotary coring, depending on the rock type and bit in use. Reverse is useful either for unsnagging or backing out auger tools or ‘breaking’ rods.

For shallow rotary work, or where augering is being carried out, a cathead is used to lift the drilling tools in or out of the hole. A rope attached to the tools or rods requiring lifting is taken up the rig to the top of the mast or tripod, passed over a pulley, and then brought down to the cathead. The cathead consists of a drum which rotates at constant speed. The rope is given two or three turns around the cathead, but because the drum is smooth it does not grip and pull on the rope. The cathead is made to lift the tools by the operator pulling on the free end of the rope. This tightens the rope on the drum, and the friction then acts to pull the rope and lift whatever drilling tools are attached. The cathead normally has limited lifting power, but perhaps more importantly, fine control requires considerable skill.

In situations where greater lifting capacity or finer control of lifting are required a wire drum hoist is normally used. This is particularly necessary when long strings of drill rods or augers are being lifted.

Smaller rigs, such as the Craelius D750 or Boyles BBS 10 provide the rotation of the rods via a bevel gear, which drives an octagonal spindle. Hydraulic feed is then developed by a piston on each side of the spindle, which pulls the spindle down by acting on a crosshead. Rigs with this configuration usually have a limited stroke:

Acker ADII	1.80m
Acker Hillbilly	600—900mm
Acker Teredo	600—900mm
Craelius D750	500mm
Mobile B31	1.73m
Mobile B53	1.98m

Since the corebarrels normally used for rotary work in site investigation are 1.5 m or 3.0 m long these rigs cannot drill the complete length of the corebarrel without having to rechuck; that is to undo the chuck, move it up the rods and reclamp it. To do this, rotation of the corebarrel must be stopped and restarted. This inevitably leads to the exposure of the rock being drilled by the bit to the flush fluid for a longer period than during drilling, and any bad effects of the flush fluid will be emphasized at points on the core where rechucking has taken place.

It can therefore be argued that a long-stroke rig will give much better results when coring soft rocks than the type of rig described above. One type of machine which provides a very long stroke for core drilling is the Acker MPIV hydraulic top drive rig. The rotary action is provided by an hydraulic motor, connected to the engine by flexible hose, which can travel long distances up the mast. The feed is provided by a mechanical system. The Pilcon Traveller 30 and Traveller 50 rotary drilling rigs are examples of lightweight machines capable of drilling a 3 m run without rechucking.

The most common mounting options for site investigation are skid mounting, trailer mounting and lorry mounting. In the UK access is normally poor and many contractors use either trailer or skid mounting. In the Middle East and the USA many more rigs are lorry mounted.

BARRELS

The corebarrel is the normal equipment for recovering samples of rock in site investigation. In its simplest form (as used, for example, to obtain cores of concrete), the corebarrel consists of a single tube with an abrasive lower edge which is loaded and rotated while a flush fluid is passed around the bit under pressure. In this process, first the core inside the barrel is subjected to rotative forces due to the friction of the inside of the barrel against the outside of the core, because the core (being attached to the parent material) does not rotate. Secondly, the flush fluid passes over the surface of the core continuously while it is inside the barrel during drilling.

The effect of the first mechanism is to tend to rotate the core at any points of weakness, such as bedding planes in rock. When rotation of the upper part of the core occurs at such a discontinuity a considerable length of core may be ground away, and a distinctive pattern of circular striations (often called a ‘rotation’) can be seen on the end of each stick of core.

When the flush fluid passes continuously over the core inside the barrel, erosion will occur. This will be particularly serious in soft rocks, where the flush fluid (particularly if water) will tend to soften the outside or along fissures in the stick of core and may well lead to total disintegration of a rock such as soft shale. To counteract these two effects the *double-tube, swivel type corebarrel* is now used as standard in the UK. Figure 5.11 shows a typical example. It consists of the following.

1. An outer barrel, connected to the drill rods and drilling rig above.
2. An inner barrel connected to the outer tube at the top via a swivel which allows the inner barrel to remain stationary while the outer barrel is rotated. Flush passes down the barrel between the inner and outer barrel.
3. A reaming shell (optional and not shown in Fig. 5.11) attached to the base of the outer barrel. This is intended to enlarge the hole produced by the corebit, so that wear on the upper part of the barrel is reduced.
4. A corebit attached to the lower end of the reaming shell. The corebit can be one of many different types, and the illustration shows a face discharge bit.
5. A core lifter or catcher. This device prevents the core from dropping out of the base of the barrel as it is lifted at the end of the run. It consists of:
    i. the catcher box, which is an open-ended cylinder which tapers downwards, and is of slightly greater diameter than the rock core; and
    ii. the catcher spring, which fits inside the catcher box and is fluted or grooved so as to grip the rock core. The catcher spring is cylindrical in shape and has an inside diameter slightly smaller than the diameter of the rock core. The wall of the cylinder is cut through at one point, to allow the spring to expand. When the core tries to drop out of the barrel the spring travels down, and is compressed against the core by the inside taper of the catcher box. Thus the greater the downward force, the more friction is developed between the core and the spring.

The details of the available rotary corebarrels are discussed in Chapter 7.

Triple-tube barrels are identical to double-tube barrels except that a tight-fitting liner tube is used inside the inner barrel. This may be made of stainless steel, or of brass, but in recent UK practice has been composed of clear plastic tube (‘Coreline’). A previously used alternative was Mylar sheet, a thin clear plastic sheet which was held at the lower end of the barrel by a special retainer clip. When using a triple tube, the internal diameter of the catcher and corebit must, of course, be reduced to suit. The advantages of using a third barrel are primarily that the core can easily be withdrawn from the corebarrel, at the end of a run, by pulling the inner liner while holding the barrel horizontally, and that the core can be stored in the liner without disturbing it from its position when drilled. Disadvantages are that the driller cannot immediately see how much recovery he has achieved, and that the engineer or geologist logging the core must cut the liner (usually with a disc cutter) before he can start work. On balance, the use of Coreline seems to have produced a significant improvement in the quality of core available for logging.

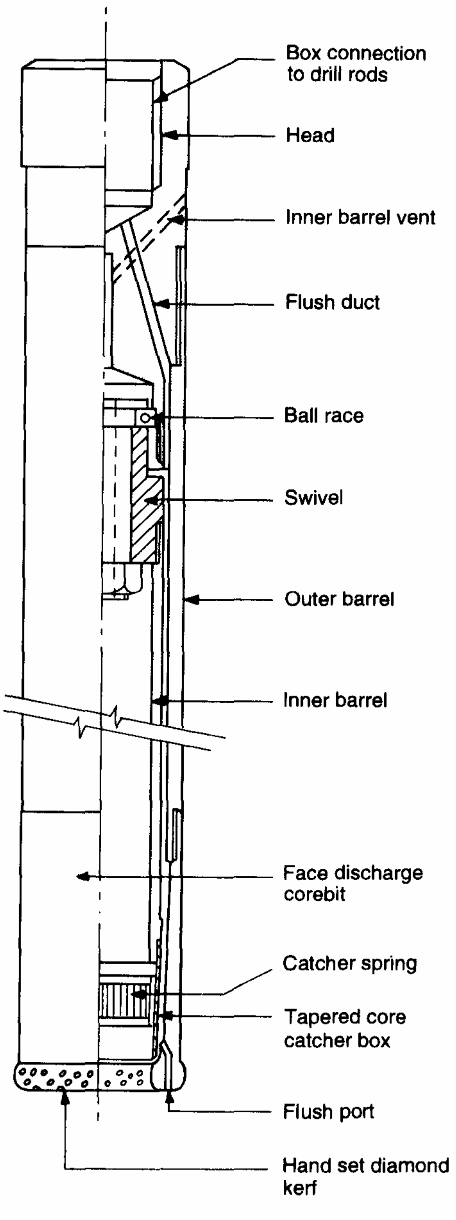


Fig. 5.11 Double-tube swivel type corebarrel with face discharge bit.

Retractor barrels have inner barrels which are spring-mounted, and protrude ahead of the kerf of the bit, in order to provide some protection for the core from the flush. Notable examples are the Mazier and Triefus barrels (see Chapter 7).

Wireline drilling is a technique which has been widely used for deep mineral drilling for many years, principally because it reduces the trip time (i.e. the time necessary to extract the corebarrel from the bottom of the hole, empty the core and replace the barrel). This technique has, in the past ten years, become well established on high quality ground investigations, and has proved particularly effective in the coring of relatively difficult deposits, such as overconsolidated clays, chalks, and interlayered sands, gravels, limestones and clays.

In conventional drilling the outer barrel is connected to a smaller-diameter string of rods, which in turn is passed through the chuck of the drilling rig. Each time the core barrel is withdrawn the entire string of rods must be withdrawn and 'broken' (i.e. unscrew one rod from the other), the core must be extracted from the inner barrel, and then the rod string must be reassembled. Because the corebarrel must be lowered on the rods, trip time increases approximately linearly with depth, and at large depths greatly exceeds drilling time. In unstable ground an outer casing must also be used, further increasing the time necessary to drill a given length.

Wireline drilling does not use any outer casing, but instead uses an outer barrel which extends at full diameter to ground level (Fig. 5.12). The inner barrel is lowered through the full length of the outer barrel, on a wire line. When it reaches the bottom of the hole it latches inside the outer barrel, in the correct vertical position. The outer barrel is then turned by the rig, as flush is pumped down it. The latching mechanism holds the inner barrel down, but does not fix it so that it must rotate with the outer barrel. When the outer and inner barrels have been drilled for the length of the run, the wire line is winched upwards, and the latching mechanism automatically disengages the inner barrel from the outer. The inner barrel and core are hoisted to ground surface, where the core is extracted and a new length of outer barrel is added to the string.

In principle, wireline coring is considerably simpler than conventional double-tube swivel type coring. No casing is used, and there is no swivel to become jammed. In practice, however, the rig used must be considerably heavier than for conventional drilling, because of the torque required to turn the outer barrel, which is in contact with the ground for the entire depth of the hole. Lorry-mounted rigs are the norm. In addition, the bit on the outer barrel can only be changed at the expense of considerable loss of production. It is preferable to use a single bit for the entire length of the hole. Therefore bit wear, and the choice of a type of bit appropriate to the ground conditions are important factors.

Scarrow and Gosling (1986) describe the extensive use of SK6L wireline drilling (producing a core diameter of 102 mm) in the alluvial valley at Baghdad, Iraq. As might be expected, the soils encountered were very variable, consisting mainly of clays, silts and sands, with some gravel being present. Wireline techniques were used in conjunction with polymer drilling mud (see below). Care was taken to restrict the pumping rates, to keep erosion of granular soils in the bit area to a minimum. A constant fluid level was maintained in the borehole at all times, and especially when the corebarrel was being returned to the surface, and the corebarrel was raised and lowered slowly, in order to minimize suction effects and pressure surges, and therefore the chance of piping and base heave (see Chapter 7).

BITS

The selection of the right corebit for the job is a rather difficult task. The variables in a corebit design are:

- face contour;
- cutting material;
- diamond types, grades and sizes;
- mounting matrix;
- waterway size, shape and position; and
- 'kerf' width.

The face of the bit may vary from a 'flat' surface to a 'full-round' surface, where the radius of the surface is equal to half the 'kerf' width (i.e. half the thickness of the diamond inset part of the bit). In practice most bits are semi-round or semi-flat in design.

The cutting material may be tungsten, diamond impregnate, or hand-set diamonds. Tungsten bits usually have large tungsten inserts mounted radially across the kerf. This type of bit can only be used for drilling very soft formations, such as soft shale or coral. However, the coarseness of the inserts increases the bearing pressure on the rock, and may well lead to a disturbance and fracture ahead of the bit. This type of bit is also used for casing.

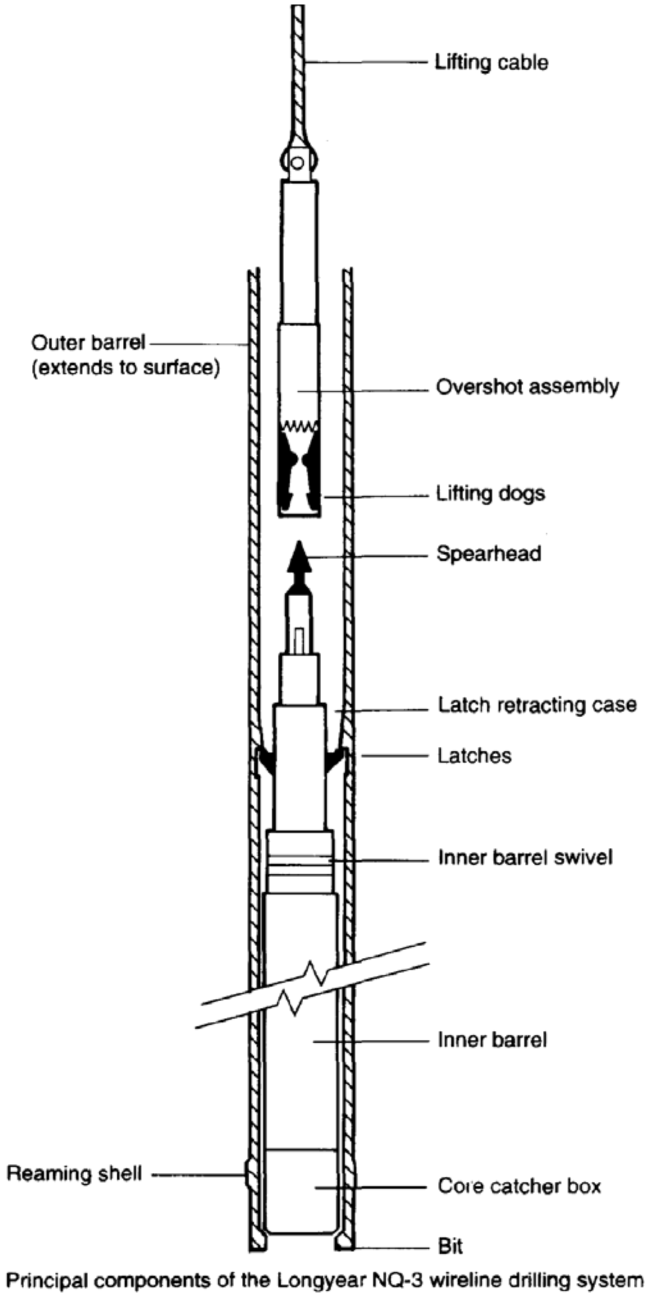


Fig. 5.12 Principal components of the Longyear NQ-3 wireline coring system.

Diamond impregnate bits consist of a sintered powder metal matrix with fragmented or fine ‘Bortz’ (i.e. low grade industrial diamonds) embedded uniformly throughout it. As the matrix wears down, new sharp diamonds are exposed. This type of bit is suitable for hard rocks, and may often be used for casing shoes where casing has to be advanced into the rock.

The best quality diamond bits contain hand-set selected Bortz. The diamonds are of selected size and grade and are placed in the matrix by hand, with the hardest vector of each diamond facing in the direction of the work. This type of bit differs from tungsten or impregnate bits because with the former the bit is used until the ‘crown’ (i.e. the part of the bit formed of the matrix, and set with diamond or tungsten) is consumed. A Bortz-set bit is only used until either the diamonds become polished, or the matrix is abraded around the Bortz to the point where they are over-exposed. At this stage the diamond bit is returned to the manufacturer, where the diamonds are removed and reset.

The quality of diamonds used in the bit varies. Diamonds are also sometimes classified on a geographical basis, such as ‘West Africans’, ‘Congos’, ‘Brazilians’, ‘Angolans’, etc. This means only that the diamonds resemble the typical products of these areas. Congos and West Africans are commonly used in drilling bits, with a preference for West Africans. According to Boyles Bros *Diamond Drilling Terms and Equipment Standards*, Congos were previously only considered for use in broken form, but more recent applications seem to use them as large stones.

The size of diamond in use in the bit should be tailored to the soil or rock being drilled. In soft material or fractured and weathered near-surface rock large Congos may be used, because the large size has good clearance and allows good washing without blocking the bit. Large diamonds are also apparently more capable of surviving the shocks administered during drilling fractured rock. As the rock becomes harder, smaller and more numerous diamonds are necessary to provide more cutting edge and therefore keep progress at a reasonable level. In addition, the use of more diamonds provides an even load distribution on the bit. The weight of a stone is measured in terms of its ‘carat’ where 1 international metric carat = 200 mg. The ‘carat weight’ is the total weight of diamond set in the bit, which may be between 5 and 50 carat depending on bit size.

The matrix must hold the diamonds in the required position, resist shock, and transfer heat away from the diamonds. The property often used to classify the abrasion resistance of the matrix is hardness, sometimes measured on the Vickers or Rockwell scale. This is not a perfect classification method because hardness is not directly related to either abrasion resistance or the other properties mentioned above.

The design of the waterways also depends on the type of rock to be drilled, and in addition on the flush fluid. Air or mud flush require larger size or more passageways. Soft formations require multi-waterway bits to allow the quick removal of cuttings before blocking occurs. Once the waterways have blocked then not only will the bit overheat, and therefore undergo excessive wear, but the core will also be seriously damaged. In hard rock the cuttings are of finer size and are more granular in nature. Fewer waterways need to be incorporated, and in some cases when drilling very easy materials no waterways are used.

Two types of bit are available: normal or face (bottom) discharge. In normal discharge bits all the flush passes down between the inner and outer barrels, outside of the catcher box, and out of the barrel between the core and the bit. The contact of the flush water with the core, even for this short distance, can have a serious effect and in soft deposits face or bottom discharge bits are commonly used. The drilling bit has ports in the lower end (the face) and the majority of the flush fluid is therefore discharged away from the core, flowing to the outside of the bit.

The face discharge bit represents an improvement on the conventional bit, but suffers from some disadvantages:

1. flush fluid is still allowed to make contact with the core; and
2. over-eager drilling may lead to the ports becoming blocked, especially when drilling in soft rocks or hard clays. Under these conditions it may be necessary to apply no downward pressure to the rods, or in extreme cases even to hold the rods up to reduce the pressure on the face.

One method of overcoming the problems of over-stressing and port blocking may be to use a step-taper bit.

Flush fluid
Flush fluid is passed around the bit while drilling proceeds. The purpose of the fluid is:

1. to remove the cuttings from the borehole;
2. to cool the drilling bit, and drill rods;
3. to reduce mechanical and fluid friction; and
4. to help to retain an open hole wherever possible, without the use of casing.

At the same time, the flush fluid should not encourage the softening or disintegration of the cores, which are the purpose of drilling. A large number of different types of flush fluid are in use, but they are generally classed as:

- water-based (for example water, bentonite/water (drilling mud));
- oil-based;
- air (or mist); and
- stable foam.

The most common flush fluid in use in British site investigation is water, with air being used when water causes serious softening of the formation being drilled. Water is, however, by no means the ideal fluid.

Most drill rigs use normal circulation; that is the flush fluid is pumped down through the drill rods, passes outwards over the bit and travels upwards in the annular space between the drill rods and the outside of the hole carrying the cuttings with it (Fig. 5.9). The requirement of removing cuttings from the base of the hole requires either viscous flush fluid or high flush velocity to maintain the cuttings in suspension.

AIR

Air is readily available for use on site as a flush fluid. It has the attraction that, provided groundwater inflows to the borehole are not great, it does not lead to degradation and softening of the core. From all other points of view, however, it is a relatively undesirable form of flush fluid.

Air has a very low viscosity, which means that satisfactory air flush drilling normally requires uphole velocities of about 1000 m/mm., which can only be obtained in the relatively large-diameter drillholes used for ground investigation by using expensive, high-output air compressors. A 600 cfm (cubic feet/minute) compressor is typically required, and this is noisy and difficult to tow to the site of remote drillholes. The air leaving the borehole produces a dust plume, unless special equipment is used to suppress it.

If air penetrates the ground then it may not reach the ground surface at a sufficiently high velocity to carry the cuttings with it. There will be ‘loss of return’, the cuttings will be dropped, and the hole may become blocked. This will seriously affect bit wear.

In addition to these problems, air flush has negligible lubrication properties, is not particularly effective as a coolant, and frequently leads to excessive erosion of soft rocks around the corebarrel and drill rods, which can make subsequent *in-situ* testing very difficult.

WATER

Water, being cheap to provide in the UK, is most frequently used and overcomes several of these problems. Being more viscous it can lift cuttings at a much lower velocity (c. 24—50m/min) which often means less borehole erosion, and less loss of return. But even water return may be lost in zones of high permeability, and water has the significant disadvantage of causing softening and disintegration of soft rocks, such as shale or chalk, and hard clays (for example, Keuper marl). In arid zones the need for large volumes of water often makes this type of flush impractical.

BENTONITE AND POLYMER MUDS

The use of ‘drilling mud’ (a thin mixture of water and bentonite) has various advantages over water. First, it is more viscous and can therefore lift cuttings adequately at a lower velocity. Secondly it will cake the edges of the borehole, and the outside of the core, and will largely eliminate the seepage of water out of the borehole, thus reducing problems of loss of return. Because of this, smaller volumes of flush fluid will be required and the fluid may he recirculated via a settling tank (where the cuttings are allowed to drop out of suspension). The cake formed on the outside of the borehole has the effect of considerably improving the stability of the borehole, provided the flush fluid head is maintained higher than that of the groundwater.

Mud is now widely employed in petroleum exploration drilling. Although used as early as 1901 in Texas, even in this field it has only developed into its present state of sophistication in the last 30 years (Cumming and Wicklund 1980). In deep well drilling, mud must have a relatively high density to keep the hole open, and it requires continuous checking and modification with additives as drilling proceeds. Thus a series of standard tests are used (API RP13B 1969) to monitor changes in the mud caused by the drilled formation, and additives are used among others to increase density, remove calcium, control hydration (swelling) and sloughing, and promote wall caking (see API Bul D11 (1965)).

In site investigation, the drilled depths are normally shallow and the demands made on the mud are often quite small. Frequently mud is made up by adding between 10 and 25 lbs of sodium montmorillonite (bentonite) to each barrel (35 imperial gallons) of fresh water. In clays and shales a thin mix is used, and the mud should have the consistency of a thin cream. In coarse-grained soils a thick mix is required to bring the cuttings to the top of the hole. When better wall support is required, barium sulphate (barytes) can be used to increase the density of the mud without giving it an unusable high viscosity. The disintegration of some water sensitive soils (for example, shale) can be reduced by additives such as organic polymers, starch derivatives, gypsum, sodium silicate, chrome lignosulphonates and calcium chloride, but the authors have not seen these used in site investigation drilling.

Whilst bentonite muds have many advantages from the viewpoint of borehole stability and the prevention of softening of weak rock cores, they have two significant disadvantages. First, they are difficult to dispose of, at the end of drilling a borehole. The mud cannot simply be tipped on the site, and it cannot be discharged into nearby sewers. Secondly, bentonite mud must be properly mixed, using appropriate equipment, in order to ensure that it is of the correct consistency and does not contain unmixed dry bentonite lumps, capable of clogging flush ports in the corebarrel. Both of these disadvantages can be overcome by the use of synthetic polymer mud. Many polymer muds are biodegradable, so that disposal is no longer a problem. They are also much easier to mix than bentonite muds. Despite the fact that they tend not to have the caking properties of bentonite, recent practice in the UK has been to use polymer muds in preference to all other forms of flush fluid. The viscous nature of polymer mud means that lower up-hole velocities are required than for water, and that there is less loss of return, and that as a consequence less water needs to be brought to site.

Scarrow and Gosling (1986) describe the use of polymer mud as a flushing medium, for coring alluvial deposits in the Middle East. Water was readily available, but an important consideration was the need to minimize the quantity of material to be transported to the site. In addition, few rig operatives had experience of using mud flush. To meet these considerations GS 550 viscosifier was adopted for general use, with the addition of Lubtub anti-swelling agent and lubricant for use in clays.

GS 550 is a non-toxic biodegradable synthetic co-polymer, with a molecular weight of around 25 million, which rapidly produces a viscous fluid at very low concentrations in water (Table 5.2 and Fig. 5.13). This fluid can however be pumped at relatively low pressures, an especially useful consideration with wire-line drilling equipment with its restricted annular return space. Although biodegradable, the fluid is stable at high ambient temperatures and the use of a bacteriacide is not required.

Lubtub was used as an addition to drilling fluid in the early stages of the investigation to prevent swelling in the clay horizons which, from their mineralogy, were expected to be expansive and could have caused problems of swelling cores and squeezing boreholes. It was found, however, that although the boreholes did squeeze this was not sufficient to cause high torque build-up with either the wireline drill string or the conventional SX casing even without Lubtub. Consequently the use of the anti-swelling agent was discontinued.

Table 5.2 GS 550 Marsh funnel viscosities

GS 550/water (kg/m3) (%)		Initial viscosity (Marsh funnel seconds)
1.0	(0.1)	90
0.9	(0.09)	75
0.75	(0.075)	50
0.5	(0.05)	35

Marsh funnel viscosity of Water = 26s ± 0.5s.

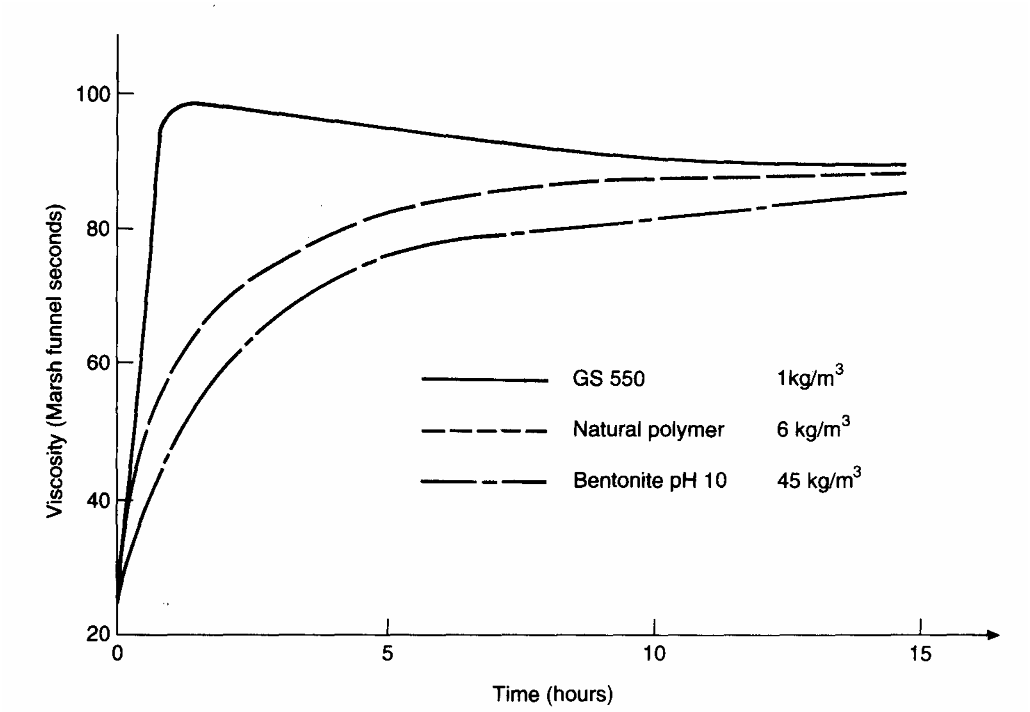


Fig. 5.13 Development of viscosity with time.

MSF

The use of mud has some disadvantages, in that fairly large volumes of water are still required, and some erosion will still occur as a result of the combination of upward flush velocity and viscosity. A seemingly almost ideal flush fluid which has not been greatly used in site investigation is Modified Stable Foam (MSF). MSF consists of a small quantity of water and foaming agent which is injected into the airstream of a low-volume high pressure compressor (Fig. 5.14). The foaming agent may incorporate high molecular weight polymers which increase the foam bubble strength and in this way reduce the required upward flush velocity to as little as 15 m/min. This low up- hole velocity limits hole erosion and reduces the size of air compressor necessary to provide the flush.

In addition to low erosion and good lifting properties, MSF cakes over shales and soft rocks, and rapidly expands into voids and fissures to block them and prevent loss of return. England (1976) gives some examples of the necessary plant outputs required to drill a 375 mm dia. hole with 127 mm dia. drill rods, which is much larger than would normally be required for site investigation purposes:

Outside hole diameter 375 mm ($14^{3/4}$in)
Outside drill rod diameter 127mm (5 in)

Air compressor output 3.5 m3/min (125 cfm)
Water/foaming agent
injector pump output 23 l/min (5 gal/min).

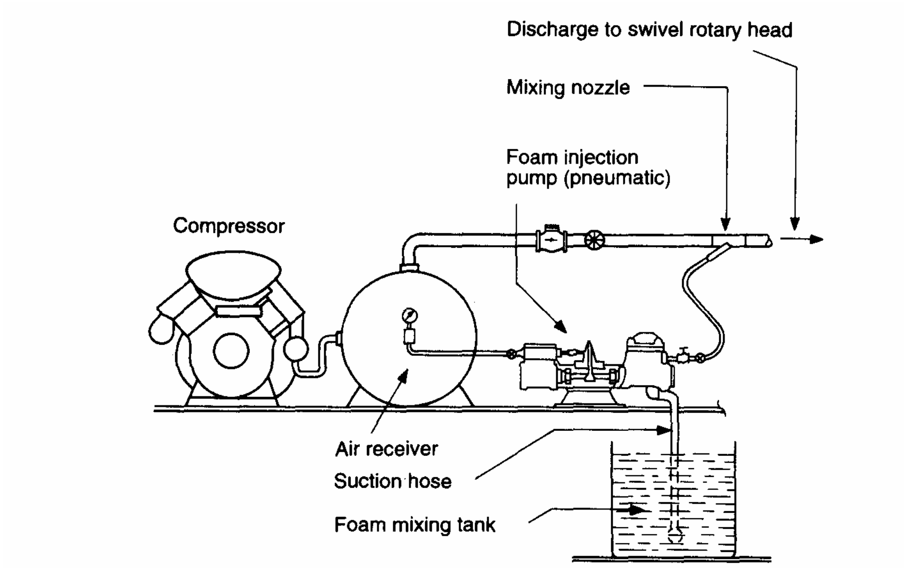


Fig. 5.14 Liagrammatic layout of the pump/compressor circuit for foam flush drilling (England 1976).

Thus the ratio of foam fluid to air is about 1:150, and foaming fluid usually consists of about 1% by volume of foaming agent mixed with water. At the start of drilling the air and foam injection pumps must be adjusted so that the foam emerges from the top of the hole with the appearance of an aerosol shaving cream'. A steady rush of air indicates too much air input, or too little foaming agent/water injection. The foam is channelled to waste after use. The foam and polymer additives are non-toxic and biodegradable and can therefore be used without danger to the environment. One of the disadvantages of both foam and mud flush is that they may make a drillhole unsuitable for permeability testing.

Diamond drill sizes

The use of combinations of letters to identify the size of drilling equipment is at first confusing, but it results from the development of the equipment in the USA, Canada, South Africa and the UK and therefore is widely used.

The earliest sizes E, A, B and N (or about $1^{1/2}$in., 2in., $2^{1/2}$in. and 3m, hole size) resulted from the use of standard steel pipe sizes during the development of equipment by various manufacturers. With the expansion of drilling work before 1930, many problems were found, principally because these sizes were not exact and therefore equipment from different manufacturers could not be interchanged. At a conference held in Chicago in 1929 the sizes of casing and the front end (i.e. bits, catchers and reaming shells) of corebarrels were standardized, and in order to distinguish equipment made to these sizes an X was added after the size letter, for example, EX, AX, BX and NX.

At this stage drill rods were more or less standard, and were not considered. However, the effect of changing the sizes of the drilling equipment caused the Canadian Diamond Drilling Association (CDDA) to introduce larger rod sizes, for which the letter C was added (i.e. AC, NC, etc.). These sizes were experimental, and after some further work in the late 1940s, the US Diamond Core Drill Manufacturers Association (DCDMA) also introduced a larger series of rods to cope with the bigger drilling equipment, which was distinguished by the letter U (for Universal). Finally with the co-operation of both organizations, a common standard was established, which used the suffix, W, for Worldwide (e.g. NW, AW).

In the early stages each size of corebarrel was used with either the E, A, B or N rods (i.e. a BX corebarrel used a B rod). At this stage it therefore became necessary to distinguish barrels which were threaded to match the new W series rods. The corebarrels matching these rods were therefore termed NWX, EWX, etc.

In the immediate post-war period, it became desirable to develop a size which would bridge the gap between rotary drilling and oil well drilling. The size developed and introduced by the CDDA in 1963, HW, is designed for use with both diamond core equipment and with rock roller bits. Later, the British Standards Institution (BS 4019:1966) developed four larger sizes, P, S, U and Z, and based the standards for the smaller sizes on the existing DCDMA and CDDA equipment.

Four standard interchangeable corebarrel designs are available.

1. *WF Series (BS 4019:1974)*. British design, using medium kerf bits, and available in HWF, PWF, SWF, UWF and ZWF sizes. The barrels feature:
    i. face discharge bits;
    ii. double-tube swivel type barrel; and
    iii. knock on catcher box (i.e. friction fit); and are suitable for mud flush.
    This series of barrels is useful for soft formations.
2. *WT Series (CDDA)*. Canadian design, using narrow kerf bits. Sizes are limited to the smaller end of the range, that is: double-tube rigid — EWT, AWT, BWT, NWT, HWT; and double-tube swivel — BWT, NWT, HWT. Because of the narrow kerf design this series of barrels is of particular use in drilling hard dense rock.
3. *WM Series (DCDMA)*. American design, using medium-width kerf bits, with WG core sizes (see below). Screw on catcher box, available with either conventional or face discharge bits. All barrels are double-tube swivel type, available in the following sizes; EWM, AWM, BWM, NWM.
4. *WG Series*. A fully standard version of the WX design, where only the bit, catcher, reaming shell and rod thread were standard. The barrel uses a medium- width kerf bit and is of rigid design, convertible to swivel type in all sizes: double-tube rigid — EWG, AWG, BWG, NWG, HWG.

In addition to the above sizes, metric sizes are available from certain manufacturers such as Craelius (Atlas Copco). This equipment is designated by the hole size it produces (in mm).

In both metric and imperial designs, the size of core obtained varies with corebarrel design.

Figure 5.15 shows corebit sizes, with their respective casings, in diagrammatic form. For further information the reader is referred to BS 4019:1974, Cumming and Wicklund (1980) and information obtainable from diamond core drill manufacturers.

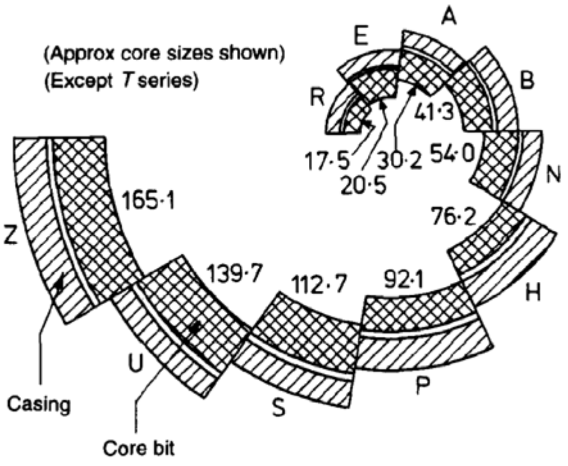
In the UK the conventional view is that soft rocks which may often be susceptible to softening by the flush fluid are better cored by large diameter double-tube swivel type corebarrels with face discharge bits. NWX, HWF, PWF and SWF barrels are most frequently used, in conjunction with NW rods. Thin-walled barrels are most easily damaged by careless handling, and are therefore more appropriate in hard rock conditions or long holes when faster drilling will give significant financial gain.

Drillhole testing

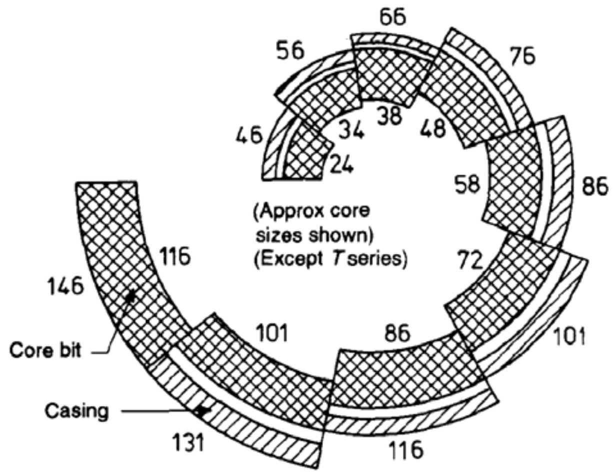
In the UK, the majority of site investigation for civil engineering purposes can be carried out without significant use of rotary drilling techniques. Where rotary drilling is used (for example for reservoirs, tunnels and dams) instrumentation is often very basic.

Where rotary core of any length is required four major types of information will be necessary in order to supplement that available from the core itself. These are:

1. the inclination of the drillhole at various points along its depth;
2. the plan direction of the drillhole at various points along its depth;
3. the orientation of the various runs of core and the discontinuities (fractures, bedding planes, etc.) within each run; and
4. the position of any cavities or highly fractured zones where core recovery has been missed.



General relation of casing to core bit
(From BS4019: Part 1: 1974)



General relation of metric casing to core bits.
(Craelius K_3 face discharge bits with CMS casing)

Fig. 5.15 Casing and core bit sizes (mm).

In general (1), (2) and (3) above are important only in major investigations in rock for projects where both the *in-situ* fracture pattern and orientation are of importance, such as tunnels, deep mines, and major underground excavations. The positions of cavities and missing core are of the utmost importance in all site investigation drillholes, particularly since it is not normally possible to detect whether low percentages of core recovery are caused by poor drilling techniques, low quality rock, or voids.

There are many different types of down-hole instrumentation, a considerable number of which have been discussed by Barr (1977) and Cumming and Wicklund (1980). This section discusses core and hole orientation, and the impression packer.

Orientation

When drillholes are relatively shallow and vertical, deviations from their intended line will not normally be significant unless worn or damaged equipment is used, or the drill string is deflected by harder ground or cavities. Long holes, and particularly angle holes, will suffer from deviations due to layering of hard and soft rock materials and due to the natural tendency of an angled drill string to flatten out as it progresses, particularly when smaller diameter drill rods are used above the corebarrel. In most site investigations it is not worth attempting to control the line of the hole, but it is often important that the hole is surveyed.

The inclination of a drillhole can be determined very simply using the etching tube. A glass culture tube is part filled with a 4% solution of hydrofluoric acid, sealed, placed in a watertight cylinder screwed to the base of the drill rods, and lowered to the desired position in the drillhole. The etching tube should be left in a stationary position for a time equal to that required to lower it down the hole, or a minimum of 30mm. When brought to the top of the hole, the tube is washed and the inclination of the line etched by the surface contact of the hydrofluoric acid to the long axis of the tube can be measured to obtain the angle of drillhole. More conveniently, a *Thompson— Cumming True-dip Etch Chart* (available from J. K. Smit of Toronto, Canada) can be inserted in the tube to overcome capillarity problems (see, for example, Cumming and Wicklund (1980)) (Fig. 5.16).

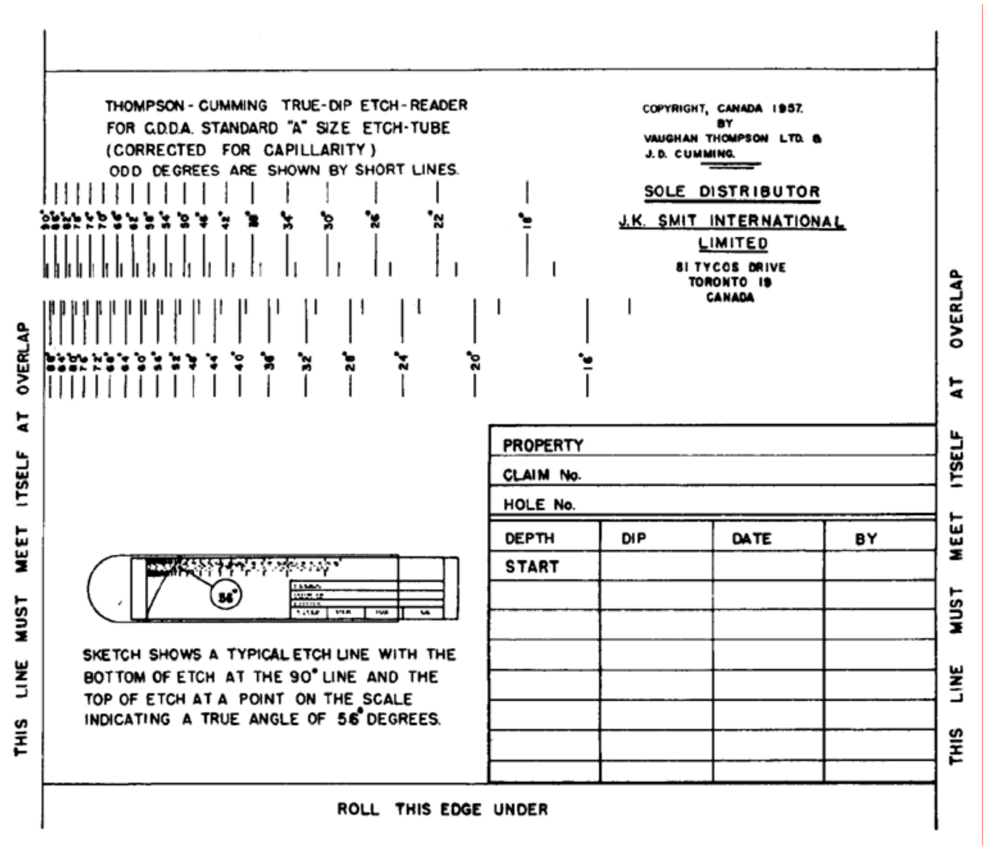


Fig. 5.16 Thompson-Cumming true dip etch reader.

More accurate mechanical inclination measuring systems are available, for example the Eastman International Company (Hannover, Germany) borehole drift indicator, but where more precision is needed, it is normal to require measurements of both dip and direction of borehole discontinuities. Photographic survey instruments such as the Eastman International types A and DT instruments are reliable, but relatively expensive (Barr 1977). The Tro-Pari Surveying instrument (Trotter—Pajari Instruments, Ontario, Canada) is a mechanical device which incorporates a compass mounted on gimbals in a clockwork timing and clamping mechanism. When lowered down the hole the compass needle is free and the compass itself hangs plumb in the gimbals. When the preset time elapses, the mechanical system locks in position and fixes the compass and dip scales for examination when brought to the surface. Direct readings of inclination and orientation to about 1° can be made.

The use of the survey instruments described above gives an idea of the position of a drillhole, but not of the orientation of the core within it. In good rock the Atlas Copco Craelius core orientator, made in Daventry, England (for example, see Hoek and Bray (1974)) can be lowered to the bottom of a drillhole in a corebarrel to measure the fracture plane on the end of the core stub. The core orientator is a mechanical device which incorporates six self-locking prongs which take up the profile of the rock stub at the base of the hole, and a steel ball bearing in a cylinder which is impressed on an aluminium plate to mark the bottom of the device. The core orientator moves up the corebarrel as drilling proceeds, and allows adequate alignment of the top of the run, provided discontinuities are not approximately normal or parallel to the direction of drilling, and the hole is not within 10° of vertical (Barr 1977).

Borehole impression packer

A more satisfactory device, in that it combines mechanical simplicity and ruggedness with a complete record of the inclination and direction of the discontinuities traced on the walls of the drillhole, is the borehole impression packer (Hinds 1974; Barr and Hocking 1976). The device consists of an inflatable rubber packer overlain by two stainless steel shells, suitably curved to conform to the perimeter of hole, covered with a PVC foam over which is laid sheets of thermoplastic film (Parafilm ‘M’). The packer can best be orientated by incorporating a device such as the Tro-Pari compass at its base. When lowered to the desired section of the drillhole the packer is inflated and the thermoplastic film forced against the sides of the hole. The resilient foam forces the thermoplastic film into any voids or fissures, and, in soft rocks material on the sides of the drillhole, may adhere to the film. After about 1 mm at the required pressure the packer can be deflated and returned to the surface, providing a permanent record of the hole. This device appears ideally suited for site investigation purposes and is currently in regular use providing discontinuity data for slope stability analysis in Hong Kong (Fig. 5.17).

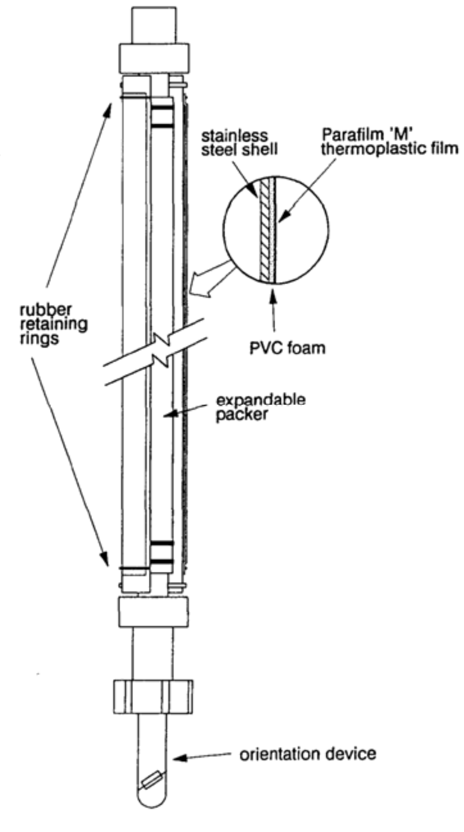


Fig. 5.17 Borehole impression packer.

PROBING

A wide range of dynamic and static penetrometers are available, with different types being used in different countries. However, the objective of all probing is the same, namely to provide a profile of penetration resistance with depth, in order to give an assessment of the variability of a site. Probing is carried out rapidly, with simple equipment. It produces simple results, in terms of blows per unit depth of penetration, which are generally plotted as blowcount/depth graphs.

The Mackintosh probe

The Mackintosh prospecting tool consists of rods which can be threaded together with barrel connectors and which are normally fitted with a driving point at their base, and a light hand-operated driving hammer at their top (Fig. 5.18). The tool provides a very economical method of determining the thickness of soft deposits such as peat.

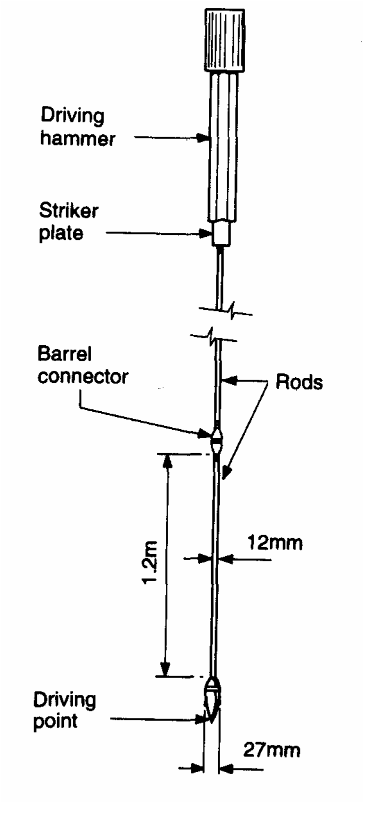


Fig. 5.18 Mackintosh probe.

The driving point is streamlined in longitudinal section with a maximum diameter of 27mm. The drive hammer has a total weight of about 4kg. The rods are 1.2 m long and 12mm dia. In the UK the device is often used to provide a depth profile by driving the point and rods into the ground with equal blows of the full drop height available from the hammer: the number of blows for each 150 mm of penetration is recorded. When small pockets of stiff clay are to be penetrated, an auger or a core tube can be substituted for the driving point. The rods can be rotated clockwise at ground level by using a box spanner and tommy bar. Tools can be pushed into or pulled out of the soil using a lifting/driving tool.

Because of the light hammer weight the Mackintosh probe is limited in the depths and materials it can penetrate.

Dynamic probing

Many dynamic probing tests appear in the literature, but in principal all are used for the same purpose, and in a similar way. Only the details of the apparatus differ. Dynamic probing tests were the subject of standardization in the Report of the SubCommittee on the Penetration Test for use in Europe (ISSMFE 1977), and are currently standardized in the UK (BS 1377: part 9, clause 3.2), and Germany (DIN 4094, parts 1 and 2).

Dynamic probing involves driving a solid cone into the ground, using repeated blows of a hammer with a fixed mass falling through a fixed distance. The hammer strikes an anvil which is rigidly fixed to rods which are of a smaller diameter than the cone, and transmit the hammer energy to it. Typically the rate of driving is between 15 and 30 blows per minute. This is achieved using a small, purpose built rig (Fig. 5.19). As the cone is driven into the ground the number of blows required to drive it each increment (typically 100 mm) is recorded. The blow count is plotted against depth to provide a more-or-less continuous profile of penetration resistance with depth. Rods are generally quite short, and as each new rod is added there is typically a requirement that it should be turned through one or more revolutions, in order to reduce friction. For some tests the torque necessary to turn the rod string is recorded, and these records can be used to judge the build-up of rod friction.

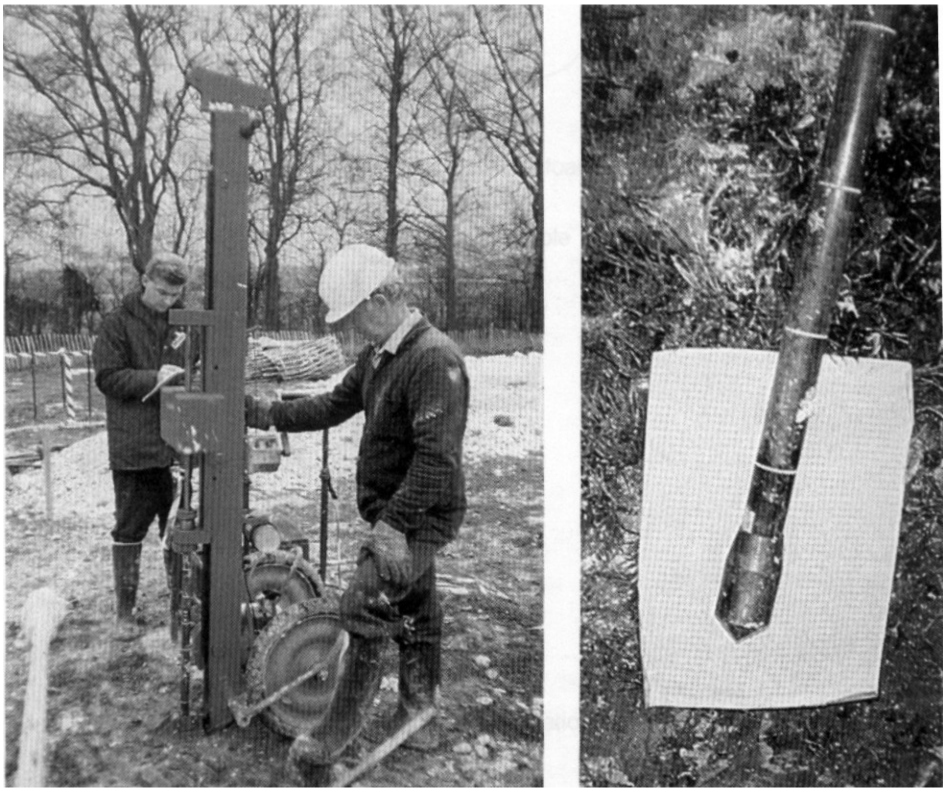


Fig. 5.19 Dynamic probing to DIN 4094.

Any build-up of friction between the rods and the surrounding soil will clearly influence the measured penetration resistance, and so several tests make provision for this to be reduced, either by pouring mud or water down the outside of the rods, or by pumping mud down the rods to a flush port just above the tip, or by the use of casing. In the authors' experience these measures are seldom used, since they complicate an otherwise attractively simple and rapid method of exploration.

For fine-grained soils (i.e. sands and finer) the results of probing to different standards can be compared by considering the work done per unit swept volume:

$$H_e = \frac{Mgh}{la} \tag{5.1}$$

where H_e = hammer energy/blow/unit volume (J/mm^3), M = mass of hammer (kg), g = gravitational acceleration, h = drop height (m), l = distance of standard cone drive (e.g. 100 mm), and a = cross-sectional area of cone (mm^2).

The hammer energy/blow/unit volume (see Table 5.3) can be multiplied by the blow count to give an average hammer energy/unit volume (referred to as ‘hammer energy’ in DIN 4094), for example:

$$A = H_e n_{100} \tag{5.2}$$

The International Society for Soil Mechanics and Foundation Engineering’s *Report of the Sub-Committee on the Penetration Test for use in Europe* suggests that the results from different types of dynamic probing may be presented as resistance values q or *rd* in units of stress (e.g. kPa) such as:

$$r_d = \frac{Mgh}{ae} \tag{5.3}$$

or

$$q_d = \left(\frac{M}{M + M'}\right)\left(\frac{Mgh}{ae}\right) \tag{5.4}$$

where *M* = mass of hammer, *M’* = total mass of drive rods, anvil and guide rods, and *e* = average penetration per blow.

Figure 5.20 shows the results of dynamic probe tests carried out to assess the variability of a high porosity chalk site.

Table 5.3 Weights, dimensions and hammer energies for various dynamic probes

Reference	Hammer mass, *M* (kg)	Drop height, *h* (mm)	Cone diameter, *d* (mm)	Cone area, a (cm^2)	Drive length, *1* (mm)	Rate (blows/ min.)	Hammer energy, H_e (J/mm^3 x 10^{-4})	Designation
BS 1377:1990	50±0.5	500±10	43.7 ±0.3	15	100	15—30	16.4	DPH DPSH
	63.5 ± 0.5	750 ± 20	50.5 ± 0.5	20	100	15—30	23.4	
DIN 4094	10	500	25.2	5	100	15—30	9.8	LRS5
	10	500	35.6	10	100	15—30	4.9	LRS1O
	30	200	35.6	10	100	15—30	5.9	MRSAIO
	30	500	35.6	10	100	15—30	14.7	MRSB1O
	50	500	35.6	10	100	15—30	24.5	SRS1O
	50	500	43.7	15	100	15—30	16.4	SRSI5
ISSMFE (1977)	63.5	750	62	30	200	20—60	7.8	DPA
	63.5	750	51	20	200	20—60	11.7	DPB

Swedish weight sounding

The Swedish weight-penetrometer consists of a screw-shaped point (Fig. 5.21), rods, weights, and a mechanism or machine to rotate the rods. The device has rarely, if ever, been used in the UK. It is used as a static penetrometer in soft cohesive soils. When the static penetration resistance exceeds 1 kN the penetrometer is rotated in addition to being loaded vertically. Under these conditions it can then penetrate stiff clays and dense sands.

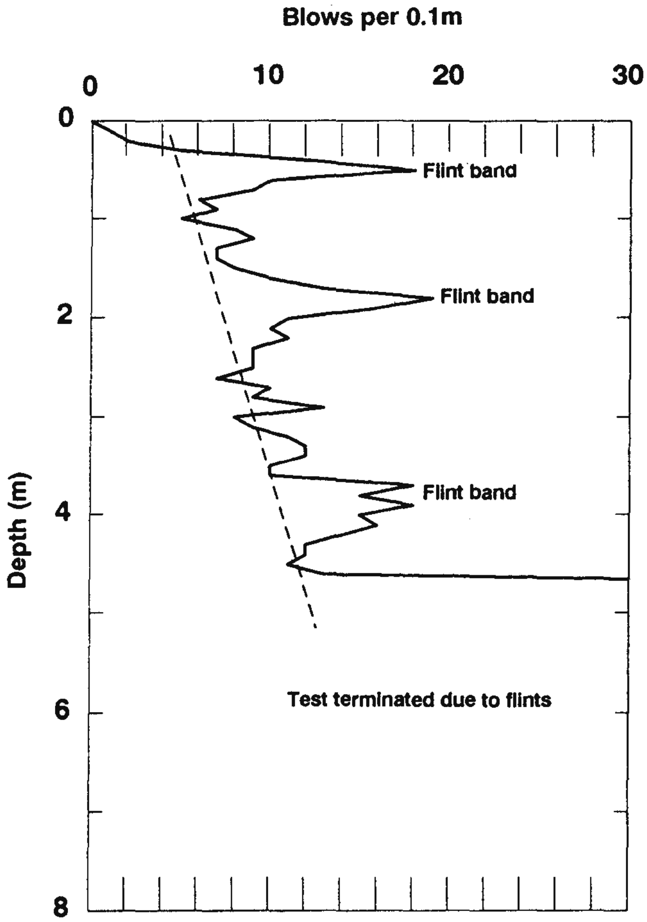


Fig. 5.20 Dynamic probe test results for a chalk site.

The point is attached to rods, and is then loaded in steps using the standard loads in Table 5.4.

Table 5.4 Standard loads for Swedish weight-penetrometer

	Mass (kg)
Rod weight alone	0
Clamp	5
Single 10kg weight	15
Two 10kg weights	25
Two 10kg weights +25 kg weight	50
Two 10kg weights + two 25 kg weights	75
Two 10kg weights + three 25 kg weights	100

The penetrometer is used as a static penetrometer in soft soils, with the loads being added or removed to give a penetration of about 50mm/s. Although loads are normally added, it is sometimes necessary to remove them, for example after penetrating a desiccated crust. Once the static penetration resistance exceeds 1 kN, or the penetration rate under 1 kN load is less than 20mm/s, the rod is rotated. The load of l kN is maintained, and the number of half turns required to give 0.2 m of penetration is measured. The rate of rotation should be between about 30 r.p.m., when carrying out mechanized weight sounding. Figure 5.22 shows an example of the results obtained.

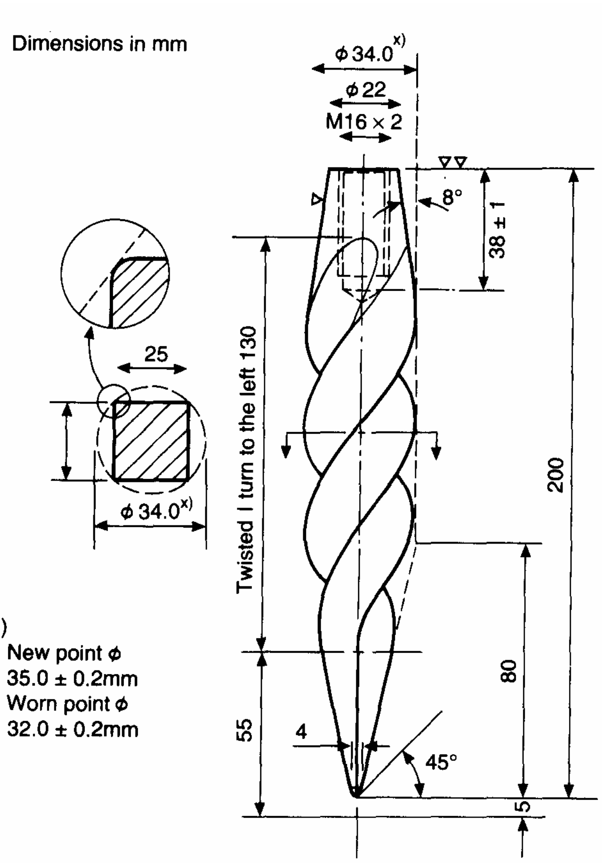


Fig. 5.21 Swedish weight sounding point.

EXAMINATION *IN SITU*

Trial pitting

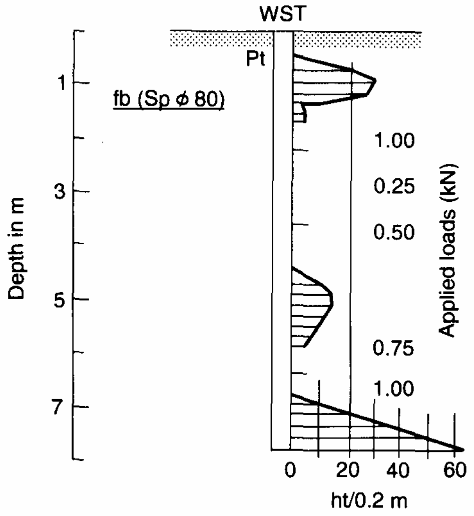
Trial pits provide the best method of obtaining very detailed information on strength, stratification, pre-existing shear surfaces, and discontinuities in soil. Very high quality block samples can be taken only from trial pits.

It is as well to note that every year many people are killed during the collapse of unsupported trenches. Remember to be careful — do not enter trenches or pits more than 1.2m deep without either supporting the sides or battering back the sides. Even so, if a pit is dug and remains stable without support, a quick means of exit such as a ladder should be provided.

Trial pits may be excavated by either hand digging or machine excavation. In general, machine excavation is used for shallow pits, whereas hand excavation is used for deep pits which must be supported. In the limited space of a trial pit, which is often 1.5m x 3m in plan area at ground level, it is usually impossible to place supports as machine excavation proceeds. Shallow trial pits provide a cheap method of examining near-surface deposits *in situ,* but the cost increases dramatically with depth, because of the need to support.

Shallow trial pits can be excavated by wheeled offset back-actor excavators such as the JCB 3c, MF50, etc., which have a digging depth of only about 3.5—4.0m, and may not be able to move easily across wet steeply sloping sites. Deeper pits, or pits where access is difficult can be excavated by 360° slew-tracked hydraulic excavators. Machine types commonly used in trial pitting are the JCB 6c, Hymac 580c, and Poclain L60. These machines have a digging depth of about 6 m, and an available digging force about 50—100% greater than the back-actor type excavator.

Very deep pits can only be economically excavated by machine if their sides are very stable, when they can be dug to the required depth without requiring support. In some soil conditions (for example, chalk) it has been found possible to excavate pits to a 12 m depth using a 22RB tracked rope-operated excavator with a heavy rope grab, but under these conditions an elaborate safety cage must be provided to protect engineers and geologists engaged upon logging the face of the excavation. An example of the resulting engineer's trial pit record is shown in Fig. 5.23.



WST	Weight sounding test
ht/0.2m	Number of halfturns per 0.2m of penetration
Pt	Dry crust of clay
fb (Sp ϕ 80)	Preboring to this level with 80mm diam auger

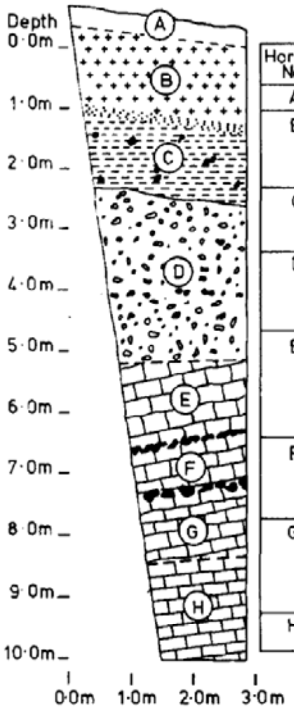
Fig. 5.22 Example of the results of Swedish weight sounding (ISSMFE 1977).

Large bored shafts

Shafts bored by piling rigs may be used for *in-situ* examination of soil. The shaft is usually auger bored, abut 1.00m dia., and inspected from a cage lowered by crane. The cage is just big enough to hold a man, and is normally equipped with air, light and telephone.

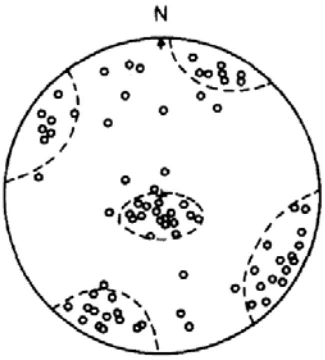
There are several problems with this method. First, the equipment is very expensive to hire, particularly as it may have to stand idle while inspection of the hole is carried out. Secondly, the action of auguring creates a smear zone around the edge of the hole, which leads to difficulties when trying to assess the soil description. In addition, the taking of block samples is very difficult because of the extremely confined working space, and discontinuities in rock are less easily recognized and recorded than in a square pit.

In the two instances where this method is known to have been used, the material was chalk. In one a 46 m deep road cutting was proposed, and in the other several 22 m wide silo foundations were being investigated. The method is, however, relatively common in South Africa.



Horizon No	Depth from/to	Chalk grade	Engineering description
A	0·0/0·3	-	Thin organic top soil.
B	0·3/1·65	-	FILL: Very stiff to hard, light, white, brown, structureless made ground consisting of very well compacted chalk and angular f.m.c. flints in a silty chalk matrix.
C	1·65/2·90	-	FILL: Stiff dark brown structureless CLAY with f.m.c. blue grey flint gravel and some chalk fragments.
D	2·90/4·95 3·1 3·9 4·0	V	Very stiff to hard off white iron stained coarse CHALK GRAVEL with some f.m.c flints in a matrix of chalky silt and clay m.c. FLINT bands.
E	4·95/5·70 5·70	IV	Very stiff to hard extremely friable white highly fractured CHALK with some f.m.c. flints. Material insitu i.e. not transported Continuous blue/grey FLINT band
F	5·70/6·70 6·70	IV	Very stiff to hard extremely friable white with fe staining highly fractured CHALK with m c blue grey flints Some fractures infilled with clay. Continuous coarse blue grey FLINT band.
G	6·70/8·05 8·05	III	Hard non friable off white iron stained blocky CHALK well jointed and fractured some infilled with clay m c flints occurring in bands. Almost continuous coarse blue/grey FLINT band.
H	8·05/10·0	III to II	Hard blocky to massive white CHALK jointed and fractured.

(a) One of the detailed logs produced by geologists to describe soil types, fracture spacing, bedding, weathering and so on



(b) Dip and strike of exposed joints, bedding planes, fractures plotted on a polar net

Fig. 5.23 Results obtained from a l0m deep pit in Upper Chalk in Hampshire (Anon 1974).

Tunnels and drifts

This method is extremely expensive, and most projects do not merit its application. The most common use of tunnels and drifts is during preliminary exploration for underground power stations, where it is necessary to determine the in-situ stress regime in order to design the roof of the main hail.

TV and borehole cameras

TV and borehole cameras can be placed inside a relatively small hole (75—150mm) and can, therefore, be used with conventional drilling methods to examine deep features.

TV cameras are usually used to examine the sides of a borehole for jointing and other features, and to investigate the extent of old mine workings. Simple borehole cameras can be constructed by placing fairly conventional photographic equipment within a drill barrel (for example see Anon. 1970), but this type of equipment is only of use in examining subsurface cavities, because of the focal length of the apparatus. Trantina and Cluff (1964) have described a borehole camera which overcomes the focal length problem by using a vertically aligned camera viewing a conical mirror. This apparatus can be used to examine the joint patterns on the walls of an NX drillhole (Fig. 5.24).

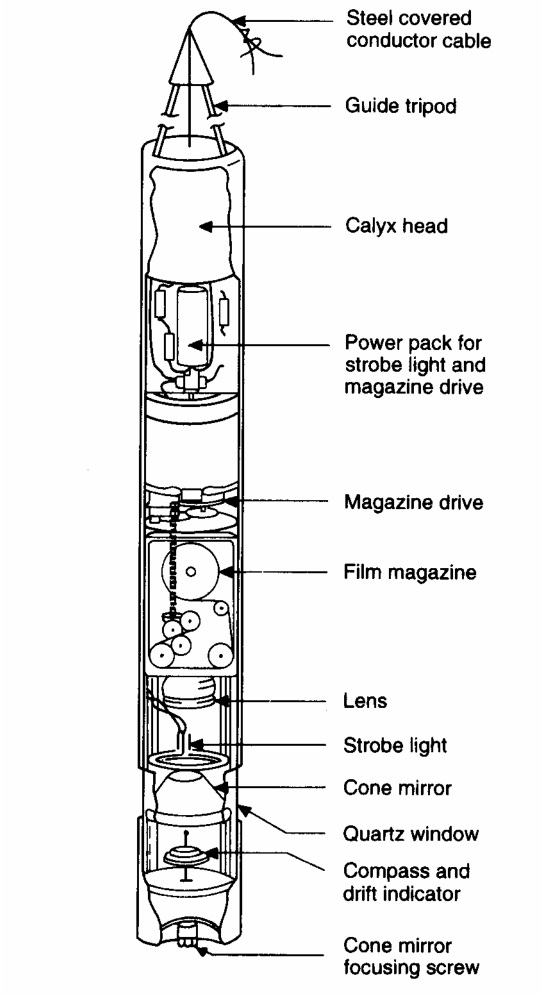


Fig. 5.24 NX borehole camera (after Trantina and Cluff, 1964).

Optical methods of examining the sides of boreholes or drillholes can only be relied on under the most favourable conditions, when the hole is dry. These devices cannot give results in the muddy conditions which normally exist in water-filled holes. They are often expensive to use, and it is therefore doubtful if their use is worthwhile until it is known that the groundwater lies below the level of interest.