Chapter 7

Undisturbed sampling techniques

INTRODUCTION

Of the very large number of sampling techniques devised worldwide since the turn of the century, few are now in current use, and even fewer are in current use in the UK. Here, the most widely used tools are the 100 mm dia. thick-walled open-drive sampler, the 'Standard Penetration Test' 35 mm thick-walled open-drive split barrel sampler, 54mm or 102mm thin-walled fixed-piston samplers, and double-tube swivel type core barrels. The types of sampler adopted in each part of the world depend on the state of development of the area, its sampling tradition, economics, and its principal soil types. In the heavily developed South East and Midlands of England, soil types are typically stiff or very stiff clays and weak rocks. In the valleys, alluvium often consists of coarse gravels. Sampling is therefore based on the use of rugged tools in a large diameter borehole.

When carrying out site investigation abroad, the available drilling equipment is often very different from that used at home, and the familiar sampling tools may be either unobtainable or inappropriate. When drilling at home the solution of new problems may require a reappraisal of the value of commonly used techniques. These factors require an engineer to be aware of as many types of sampler as possible and this chapter therefore sets out to review the main types of equipment now available. In Chapter 6 (Sampling and sample disturbance) the way in which a number of common types of sampler are constructed, and the manner in which they work was described. Samples are obtained in a number of ways:

1. by using a number of techniques in shallow pits, shafts and exposures; and
2. in boreholes, using either drive or rotary techniques.

Drive samplers are pushed into the soil without rotation, displacing the soil as they penetrate. They generally have a sharp cutting edge at their base. In contrast, rotary samplers (often termed 'corebarrels') have a relatively thick and blunt cutting surface, which has hard inclusions of tungsten or diamond set into it. The sampler is rotated and pushed (relatively) gently downwards, cutting and grinding the soil away beneath it. A general classification of samplers is shown in Fig. 7.1.

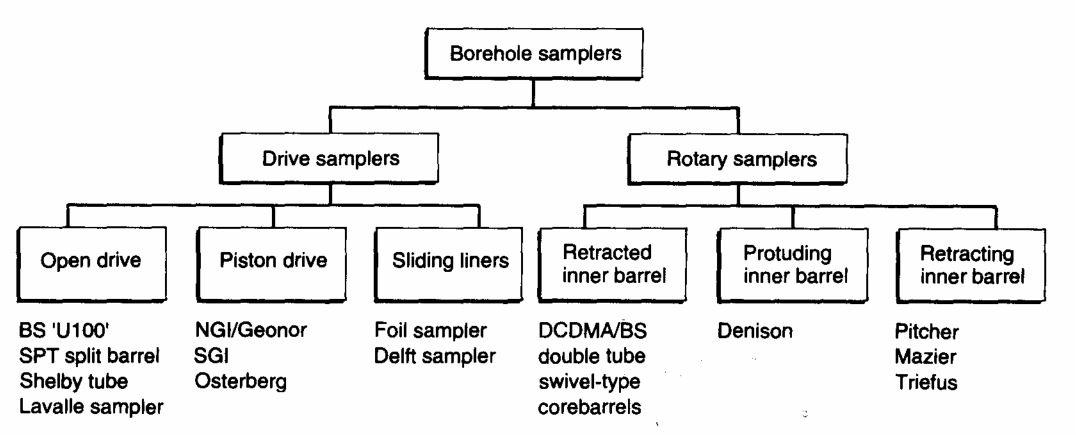


Fig. 7.1 General classification of borehole sampling devices.

It is generally believed that undisturbed sampling is not possible in granular soils. Nonetheless, special techniques for sand sampling have been developed over the years, and these are described in a later section of this chapter. Finally, we consider the selection of appropriate samplers for different purposes, and to suit different ground conditions.

SAMPLES FROM PITS AND EXPOSURES

Trial pits, trenches and shallow excavations are often used in site investigations, particularly during investigations for low- and medium-rise construction, because they provide an economical means of acquiring a very detailed record of the complex soil conditions which often exist near to the ground surface. It is worth remembering, however, that trial pits and other exposures can also be used for *in situ* testing and to obtain high-quality samples.

The types of samples taken will vary according to the needs of the investigation. Disturbed samples of granular soil are likely to be more representative than those that can be taken from boreholes. Disturbed samples are often taken for moisture content or plasticity determination in the laboratory, and in association with determinations of *in situ* density. *In situ* density testing is described in Chapter 9.

Undisturbed samples can be obtained either by drive sampling (see below) or block sampling (as described in Chapter 6). In either case it is important to recognize the disturbance created by excavating the trial excavation, and ensure that disturbed material is carefully removed before or after sampling. To this end, the faces and bottom of the pit should be hand trimmed in the areas to be sampled (or described), particularly when the pit has been machine excavated. In exposures, an attempt should be made to remove the weathered surface of the soil.

In the UK 38mm open-drive tubes are often hammered into the sides and base of trial pits. These tubes normally have no check valve, a high area ratio, and no inside clearance. It is often necessary to dig the sample tube out of the soil in order to avoid losses. When U100 tubes (see under ‘Drive samplers’) are used, they require considerable force and are commonly pushed into the soil with a ‘back-actor’ bucket. Care must be taken to prevent rocking of sample tubes during driving since this causes serious disturbance to the soil at the shoe level. The use of a frame to align the sampler during driving is advisable.

Better quality samples of firm to stiff clay soils can be obtained by trimming the soil in advance of a large diameter (100—200 mm) sampler. This eliminates the disturbance caused by soil displacement ahead of the cutting shoe, but may allow slight lateral expansion of the soil. When the material to be sampled is either hard, stoney or coarse and granular, it is essential that advanced trimming of large diameter samples is used.

When the soil is sufficiently stiff or cemented to stand up under its own weight, a block sample may be taken. The normal technique is to cut a column of soil about 300mm cube, so that it will fit inside a box with a clearance of 10—20 mm on all sides. A box with a detachable lid and bottom is used for storage. With the lid and bottom removed, the sides of the box are slid over the prepared soil block, which is as yet attached to the bottom of the pit. After filling the space between the sides of the box and block with paraffin wax, and similarly sealing the top of the block, the lid is placed on the box. The block is then cut from the soil using a spade, and the base of the sample trimmed and sealed. Block samples allow complete stress relief, and may therefore lead to expansion of the soil, but in very stiff clays this technique is widely regarded as providing the best available samples (see Fig. 6.5).

The Sherbrooke sampler

Block samples can only be taken from depth in heavily overconsolidated soils, such as the London clay. In normally and lightly overconsolidated clays, excavation of a pit or shaft to more than a few metres depth is often impossible because base heave will occur. Lefebvre and Poulin (1979) calculate that, for example, in a clay with an undrained shear strength the depth of a trench or pit will be limited to about 4 m, if a factor of safety of two is to be maintained.

To overcome this problem, Levebvre and Poulin (1979) designed the apparatus shown in Fig. 7.2, which is essentially a down-borehole block sampler. The equipment needs a borehole of about 400 mm diameter, which is best cleaned using a flat- bottomed auger, in order to reduce disturbance and minimize the amount of disturbed material left in the base of the hole before sampling. The hole is kept full of bentonite mud. The sampler is lowered to the base of the hole, and rotated, either by hand or using a small electric motor, at about 5r.p.m. A cylinder of soil, about 250 mm in diameter, is carved out by three circumferential blades, spaced at 120°. They make a slot about 50mm wide, and are fed by bentonite or water to help clear the cuttings. The time taken to obtain a sample obviously depends upon ground conditions, but may be about 30—40min. After carving out a cylinder about 350 mm high, the operator pulls a pin, and the blades (which are spring-mounted) gradually rotate under the base of the sample, as rotation is continued. Closure of the blades separates the sample from the underlying soil, and the sample is then lifted to the surface with a block and tackle. Lifting takes place very slowly for the first 0.5 m, in order to avoid suction at the base of the sample. The sample is coated with layers of paraffin wax, and may be placed in a container packed with damp sawdust or other suitable material. The complete process takes about 3 h, including preparation for shipment.

Tests by Lefebvre and Poulin have shown that this sampler is capable of obtaining soil of comparable quality to that produced by block sampling in the sensitive clays of eastern Canada. The sampler was used in the Bothkennar clay in Scotland, where it provided the highest quality of samples obtainable (Clayton *et al.* 1992). It was found, however, that the apparatus is quite time-consuming and difficult to use. Lefebvre and Poulin (1979) note that it is not intended that this technique should replace tube sampling for routine investigations. But where the highest quality samples are required for testing of soft or sensitive clays, at the time of writing this apparatus provides the best method of obtaining undisturbed samples from depth.

DRIVE SAMPLERS

Drive samplers are samplers which are either pushed or driven into the soil without rotation. The volume of soil corresponding to the thickness of the sampler wall is displaced into the surrounding soil, which is either compacted or compressed.

Drive samplers can be divided into two broad groups: open-drive samplers and piston drive samplers. Open-drive samplers consist of a tube which is open at its lower end, while piston drive samplers have a movable piston located within the sampler tube. Piston samplers can be pushed through a soft soil to the desired sampling level, but open-drive samplers will admit soil as soon as they are brought into contact with, for example, the bottom of a borehole.

Open-drive samplers

Open-drive samplers suffer from several disadvantages, as Hvorslev (1949) pointed out. Poor cleaning of the borehole before sampling, or collapse of sides of the borehole after cleaning may mean that much of the recovered soil is not only highly disturbed, but also non-representative. The use of a large area ratio can induce soil displaced by the sampler drive and causing large-scale remoulding of the sample. The problems of pressure above the sample during the drive, and of sample retention during withdrawal have been noted in the previous chapter.

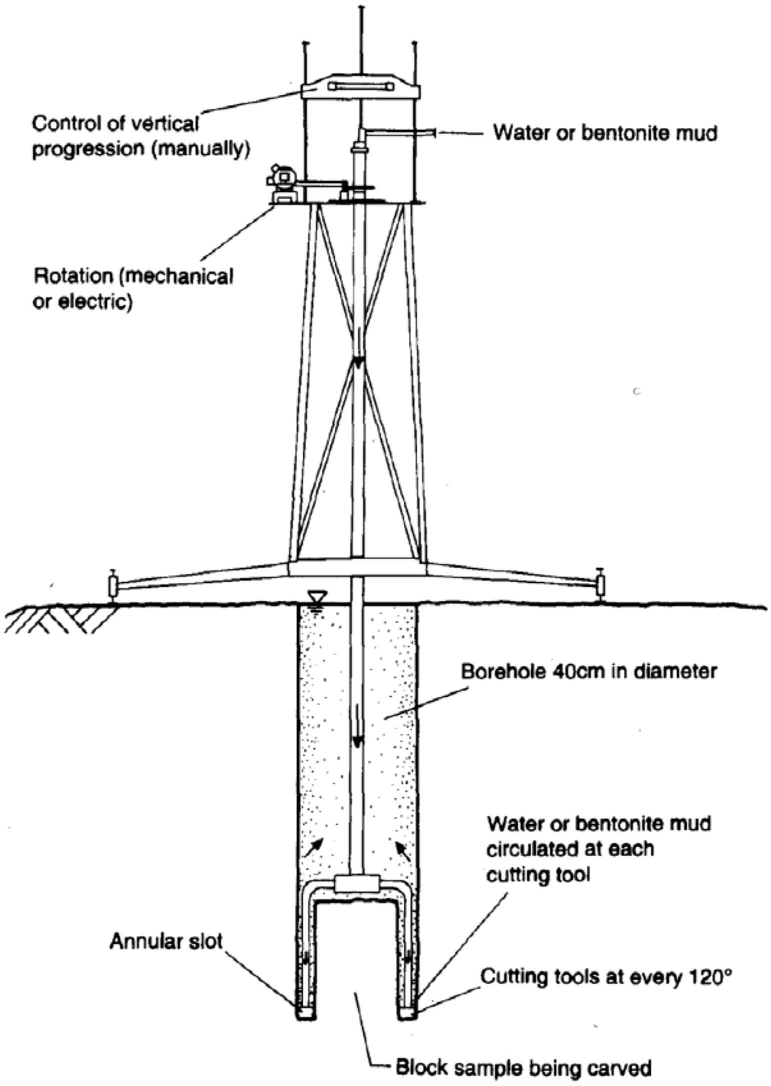


Fig. 7.2 Schematic diagram of the Sherbrooke down-hole block sampler (Lefebvre and Poulin 1979).

The advantages of open-drive sampling are principally those of cheapness, ruggedness and simplicity of operation. Open-drive samplers can be arbitrarily divided into two groups. Thin-wall open-drive samplers have been defined as those with a wall thickness of sampling tube of less than 2.5% of the diameter, corresponding approximately to an area ratio of 10% (Hvorslev 1949). This classification is not a good guide to the amount of sampling disturbance because of the influence of cutting shoe taper and *in situ* stress level in the soil. In the following discussion thin-wall sampling devices are taken to be those with an area ratio of less than 20%, and a suitable cutting shoe taper, while thick-wall samplers are taken to have an area ratio greater than 20%.

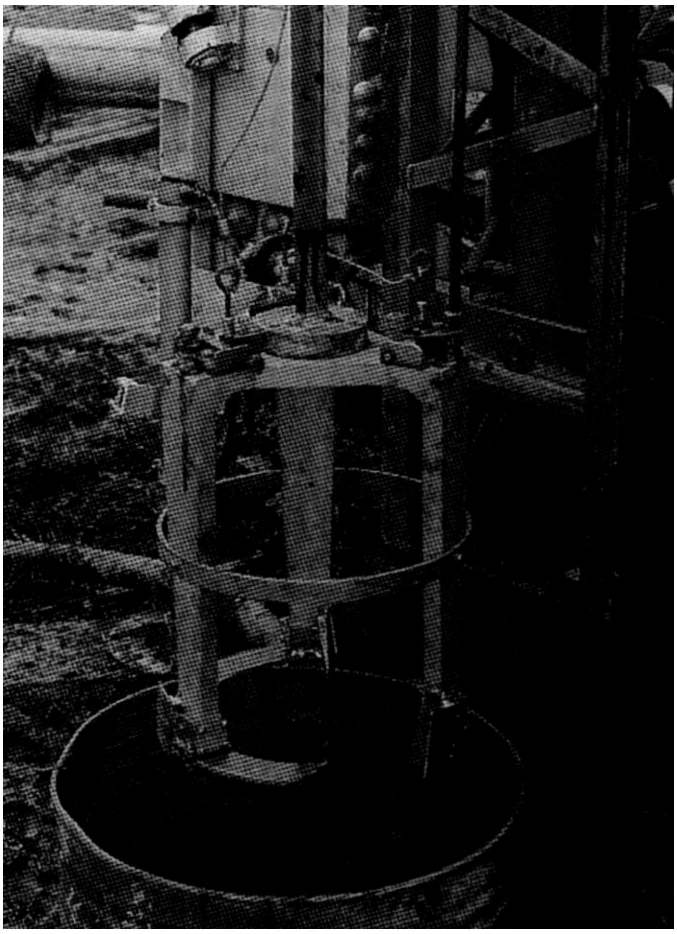


Fig. 7.3 The Sherbrooke sampler in operation (photograph courtesy Dr D.W. Hight).

Thick-walled open-drive samplers

Thick-walled open-drive samplers are widely used throughout the world. In their most common forms they consist of a solid or split sampler barrel, threaded at both ends to take a cutting shoe (typically with inside clearance) and a sampler head provided with either a check valve or vents.

BS general purpose sampler

The British Standard General Purpose 100 mm Sampler (BS ‘5930:1981), commonly termed the U100 sampler, evolved during the 1930s and 1940s (Le Grand *et al.* 1934; Cooling and Smith 1936; Cooling 1942; Longsdon 1945; Rodin 1949). The sampler is rugged, cheap and will provide a core sample in most British clays, which are typically heavily overconsolidated. Its size and form were adopted because of the common borehole size at the time of its development, and because of its ability to sample (however ‘inadequately) in stoney very stiff glacial clays.

The British Standard U100 sampler will fit inside a 150mm dia. borehole. Harding (1949) noted that:

> some believe that the smaller the [casing] tube the cheaper will be the hole. This is a fallacy. In British gravel-laden deposits, nothing less than 6-inches [152 mm] diameter is worthwhile. This permits the average type of stone to be brought up by shell without pounding with a chisel and also allows of 4-inch diameter sampling.

Light percussion drillers will often use 200mm tools in preference to the 150mm size because of their greater weight, and thus their improved ability to make fast progress.

Figure 6.11 shows a typical British 100mm dia. open-drive sampler. It has a 104 mm inside dia. at the base of the cutting shoe, a 27% area ratio, and an inside clearance of 1.4% provided by tapering the inside diameter of the cutting shoe at an angle of 30 to meet the 106mm internal diameter of the sample tube, or by providing a uniform internal diameter to the cutting shoe and thus stepping out, abruptly at the junction of the shoe and sampler tube. The outside cutting edge taper may be 20° up to a thickness of 2.3 mm, and 7° thereafter, or alternatively may initially be 30°, and then 15° up to a 6.5mm thickness. Designs vary according to the manufacturer, but shoes and tubes are always interchangeable. The normal sample tube length is 457 mm, but two tubes are often coupled together in order to allow debris at the bottom of the borehole to pass into the upper tube during driving. Thus the normal length to diameter ratio is about 4.5, with a possible maximum of 9.

The U100 sampler head incorporates vents and a ball valve assembly to allow air or water to leave the top of the tube as soil enters at its base. The ball valve is also intended to improve the sample retention by preventing air or water re-entering the top of the tube if the sample starts to slide out. Because of the conditions under which the vents and ball valve are expected to work, it is important to ensure that the sampler head is cleaned before each sampling operation. Even though the build-up of pressure above the sample can be reduced to an acceptable level, it is doubtful if the ball-valve assembly can be effective in reducing sample losses.

The so-called British Standard sampler is not as completely standardized as, for example the Swedish piston sampler. In CP 2001:1957 the maximum area ratio was specified as 25%, with an inside clearance of between 1% and 3%, and a drawing of a suitable design was given. BS 5930:1981 allows an area ratio of 30%, but other recommendations remain the same. The vent area should be not less than 600mm2 cutting shoe taper is not specified. The sampler may or may not use liners, to allow the specimen to be transported and stored in a lightweight cylinder which does not have to be able to resist driving forces.

In the 1982 edition of this book we wrote that ‘most users of this type of sampler do not fit liners’. It is unfortunate that in the past decade it appears that many UK companies, apparently driven by the need to reduce costs, have taken to using plastic liners inside steel outer tubes, in order to reduce the number of metal tubes they require to hold in stock. We have repeatedly observed the severe distortions induced when plastic liners are used, in comparison with the relatively low level of distortions when they are not. Figure 7.4 shows an example of this, in a laminated clay. The inclusion of a plastic liner, typically about 3mm thck (means that the cutting shoe thickness must be increased. Taking the example of the lower cutting shoe in Fig. 6.11, it can be calculated that the area ratio will increase from 27% to 41%. Examination of cutting shoes used with this type of sampler suggests that a value of area ratio of 45—50% is usual, equivalent to a B/t ratio of about 11. As we have shown, the minimum axial strain (at the centreline) will be of the order of 4—5%, and peripheral strains and shear distortions can be expected to have a very significant effect on soil properties (Georgiannou and Right, 1994).

The U100 sampler is rugged, and easy to use. The sample tubes are screw-threaded to the head and cutting shoe before sampling. The sampler head is screwed to a sliding hammer (also termed a ‘jarring link’) and lowered down to the base of the hole on square rods. The sampler is driven into the soil by repeatedly lifting the rods through about 500mm and allowing them to fall. The number of blows and the distance moved by the sampler head during the drive are recorded by the driller. The sampler may be pulled immediately from the soil, or in stiff cohesive soils it may be left in the soil for a few minutes before it is brought to the top of the hole. After sampling, the tube and soil are carefully separated from the cutting shoe and sampler head. A small quantity of soil is removed from either end of the tube if necessary, and the ends of the sample are waxed, packed and then sealed with either plastic, or screw-threaded metal caps. If damaged or blunt, the cutting shoe is replaced before the sampler is next used.

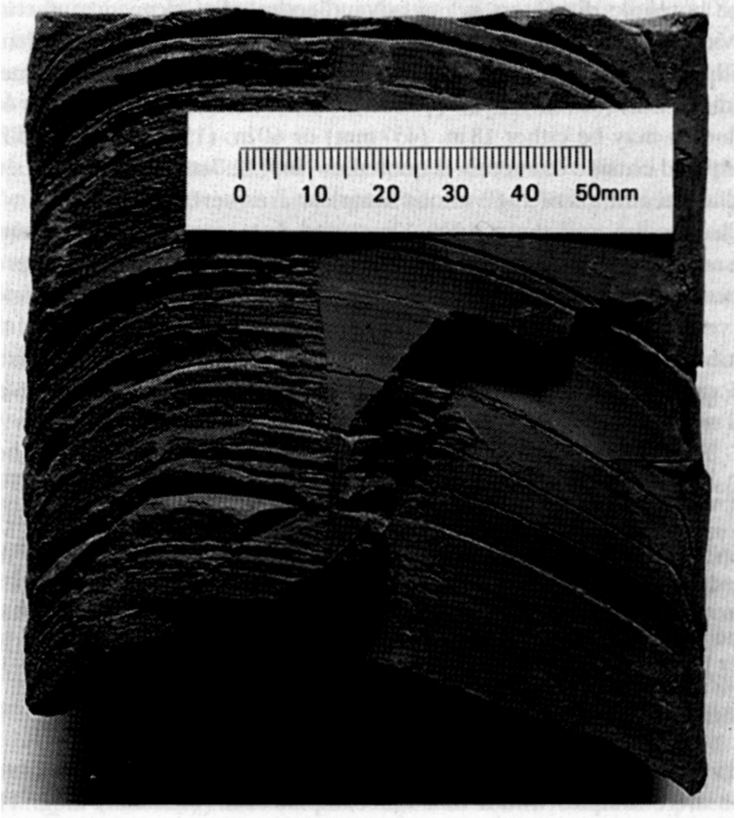


Fig. 7.4 Heavy shear distortion in a clay sample taken using a driven BS U100 sampler with a plastic liner (courtesy Surrey Geotechnical Consultants Ltd).

In many countries the use of light-weight drilling rigs, percussion equipment and large borehole diameters is not advantageous. American manufacturers of samplers provide a very wide range of sampler diameters, with a variety of lengths. The Acker Solid Tube Sampler is available in a great many sizes. Its inside diameter may be 1in. (38mm), 2in. (52mm), 2km. (64mm), 3m. (76mm), 4in. (102mm) or 5in. (127mm). Its length may be either l8in. (457mm) or 60in. (1524mm). The difference between inside and outside diameters is quoted as ½ in. (12.7 mm) and the area ratios and length to diameter ratios of the various samplers are therefore as listed in Table 7.1.

Table 7.1 Open-drive sampler characteristics for a tube thickness of 0.5 in.

Internal tube diameter (in.)	Area ratio (%)	Length/diameter ratio	
		L=l8in.	L=60in.
1 ½	78	12	40
2	56	9	30
2 ½	44	7.2	24
3	36	6	20
4	27	4.5	15
5	21	3.6	12

Clearly, most of these tubes have excessive area and length/diameter ratios, and will not provide undisturbed soil for laboratory testing to give soil properties relevant to *in situ* conditions. However, in soil conditions where small diameter boreholes can be very much more economical than holes of 150mm dia. and larger, they are particularly useful. Terzaghi (1939) indicated the importance of what he described as the ‘variation survey’, a completely sampled profile of soil along several vertical lines of a site:

> In 1925, under the illusion that soil strata really are fairly homogeneous. I had the habit of requesting

> one ‘dry [i.e., tube] sample’ for every 5 or 10 feet of test borings through homogeneous strata. Since that time the painstaking investigations of Mr A. Casagrande have destroyed my cherished illusion. No longer is there any doubt that homogeneous beds of clay are very rare Due to the universal absence of homogeneity the essential prerequisite for selecting representative samples consists in securing complete data on the variation of at least one property of the soil along several vertical lines. The samples for the more elaborate soil tests are then selected in such a manner that the properties of the most frequent soil types are determined. The weighted average of the test results is obtained by statistical methods.

The variation survey was originally accomplished by obtaining continuous 2 in. (50 mm) open-drive samples with a thin-wall sampler 30in. (450mm) long. The samples were cut into 6 in. sections before being tested for moisture content or compressive strength.

In the UK, despite the advice from Terzaghi and from others (for example, Rowe (1968, 1972)), few site investigations involve taking continuous samples of any sort.

Presumably this is because of a desire to reduce the cost of site investigation. Such an attitude must be considered very short-sighted.

Both of the sampler types discussed above have ‘solid’ tubes; their sampler barrels are continuous around the circumference.

Thick-walled split barrel samplers

A further common sampler is the thick-walled open-drive split barrel sampler. Here the sampler barrel is split longitudinally into two halves. During driving these are held together by the shoe and head which are screwed on to each end. The split barrel allows easy examination and extraction of the sample, but makes the sampler considerably weaker. To compensate for this, such samplers are usually short, and have a high area ratio.

One of the most common thick-walled open-drive split barrel samplers is used during the Standard Penetration Test (see Chapter 9). During this test the sampler is driven into the soil by repeated blows of a 65 kg hammer falling freely through 760 mm, and the number of blows required to drive the sampler a distance of 300mm is recorded as the SPT N value. The N value is assumed to be dependent on relative density in granular soils, and undrained shear strength in cohesive soils.

Figure 7.5 shows the apparatus used in the UK for the SPT test. The dimensions of the sampler are defined in BS 1377:1975. Any sample obtained from this sampler will be highly disturbed, because the SPT split barrel sampler has an area ratio of about 100% and a length to diameter ratio of 13. No inside clearance is used. Samples of fine soils obtained from the apparatus should be considered as remoulded.

Samples f coarse granular soils must be considered unrepresentative, because the coarser particles will not be able to enter the barrel during driving. For this reason the Report of the Subcommittee on the Penetration Test for use in Europe allows the sampler cutting shoe to be replaced by a solid steel cone with a J0 apex angle, when drilling in gravelly soils. This avoids cutting shoe damage, and prevents high penetration resistances due to the lodgement of large particles in the end of the shoe.

Because of its design, the SPT thick-wall open-drive split barrel sampler will give low recoveries in most soils. It is therefore unsuitable for obtaining continuous representative samples for a variation or reconnaissance survey. In the UK the resulting sample is normally broken into lengths of about 75 mm and placed in a small disturbed sample container such as a glass jar.

Samplers using liners inside the sample tube were termed ‘composite samplers’ by Hvorslev (1949). Liners allow considerable savings to be made because the structural outer sampler barrel, which transmits the driving force to the cutting shoe, can be used repeatedly. Only the liner is removed, complete with sample, and sealed and transported to the laboratory. Where cohesionless or very soft soils are to be sampled it is, of course, necessary that they are not removed from the sampler tube before they are to be examined. We have already noted (above) the increase in the use of plastic liners in the BS U100 sampler in the UK during the last decade. In other countries better-designed liners are typically made of metal.

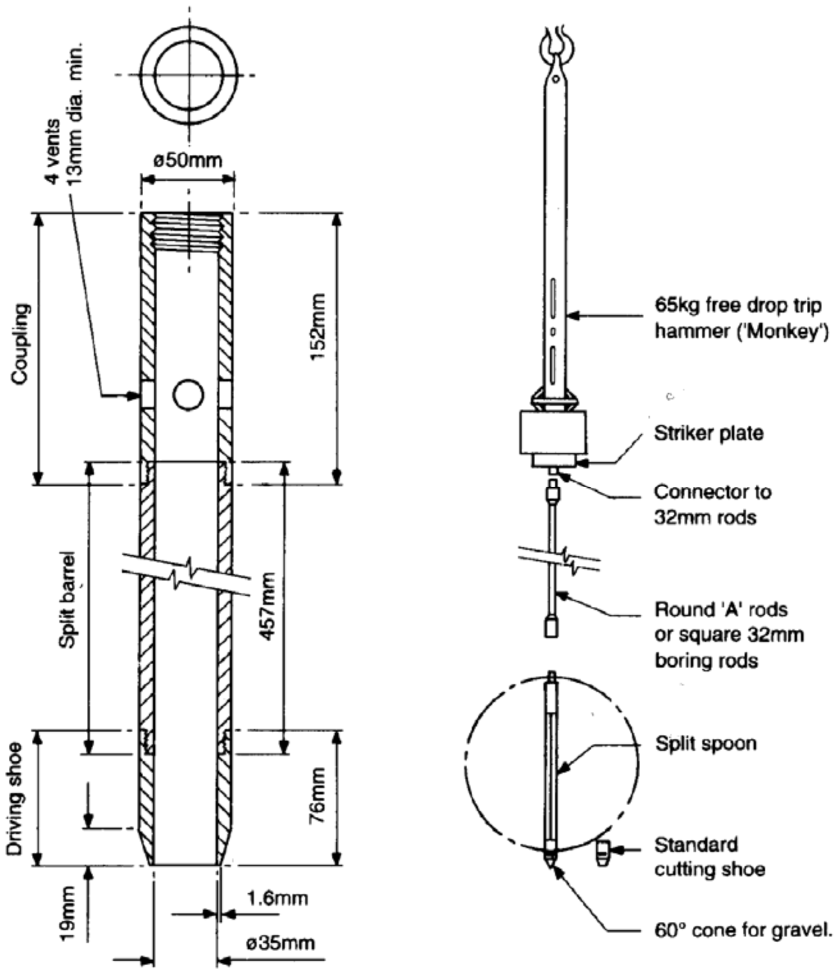


Fig. 7.5 Standard Penetration Test’ equipment.

The Acker-split tube sampler is available with either solid or sectional liners. Sectional liners can be very useful in reducing the need for a laboratory extruder to remove soil from the tube, and they also allow the soil to be examined in the field, if necessary. If an extruder is not required for sample extraction, the liners can be used successfully in a wider range of soils. The inside diameter of the cutting shoe is 2 $^{15/32}$ in. (62.7mm), while its outside diameter is 3 ¼ in. (82.6mm), giving an area ratio of 74%. The inside diameter of the liner is 2 ½ in. (63.5mm), giving an inside clearance of 1.6%.

Thin-walled open-drive samplers

The thin-walled open-drive sampler, or ‘Shelby Tubing’ sampler was introduced in the USA in the late 1930s (Terzaghi 1939; Hvorslev 1940, 1949). ‘Shelby Tubing’ is a trade name for hard-drawn, seamless steel tube manufactured by the National Tube Company of the USA. Early devices took two forms. The US Engineer Office, Boston District, sampler (Fig. 7.6) attached the thin-wall sampler tube to the head by spot welding it to a short length of heavy tube, which in turn threaded into the head. Another method of fixing the tube to the head, suggested by H. A. Mohr. uses tubing which is a close fit over the lower section of the sampler head, and which is fixed to the head by two Allen set screws which, when engaged, lie flush with the outer surface of the sampler tube. This design has been incorporated into a large number of samplers, and is now in use worldwide (see, for example ASTM D 1587—74).

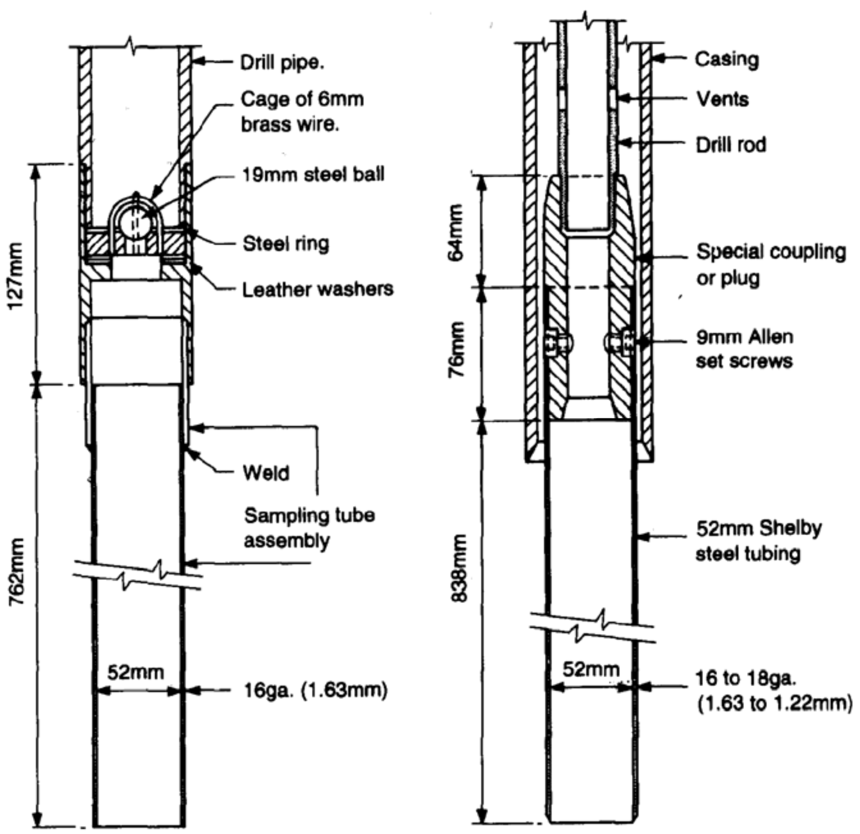


Fig. 7.6 Two early thin-walled open-drive samplers (from Hvorslev 1940).

Early thin-walled samplers, such as those in Fig. 7.6 had relatively small area ratios (approximately 10—14%), but had length to diameter ratios of 15—20 and did not use inside clearance. The cutting edge was either cut square, or bevelled. Most modern thin-walled tubes are drawn in, in order to provide a suitable inside clearance (Fig. 7.7) and are sharpened.

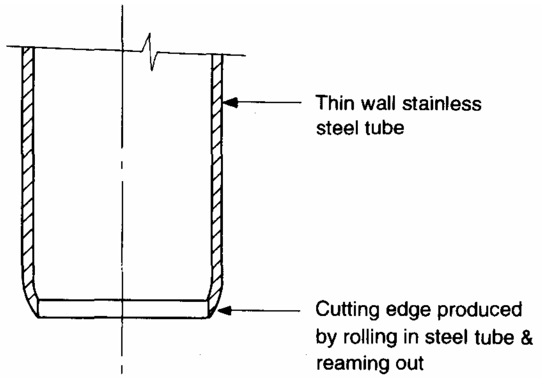


Fig. 7.7 Typical detail of thin-walled open-drive sampler, showing drawn in, sharpened cutting edge.

Thin-walled open-drive sample tubes are readily damaged, either by buckling or blunting or tearing the cutting edge, when they are driven into very stiff, hard, or stoney soils. Pushing, rather than hammering, tends to reduce the chances of damaging the tube. When the cutting edge is damaged, the tube must be sent to the metal workshop for reforming.

In the UK, thin-walled open-drive samplers have, during the past decade, become used for the high quality tube sampling of very stiff and hard clays, such as the London clay. Such a sampler, which is hydraulically jacked (from a frame at ground surface) into the bottom of the hole has been described by Harrison (1991). They are in wide use elsewhere, and can, with a certain amount of care, be used to obtain undisturbed samples from very soft soils with undrained shear strengths of the order of 5 kN/rn2. In very soft sensitive soils sampling will normally need to be carried out with a piston sampler.

Thin-walled open-drive sample tubes are typically 24—3Oin. (i.e. 610—762mm) long, and give a maximum sample length 2—3 in. (52—70 mm) less than this. They may be expected to have an inside clearance of up to 1— 1%. Available in a wide variety of diameters, they typically have area ratios similar to those in Table 7.2.

Table 7.2 Thin-walled open-drive sample tubes

Internal tube diameter (mm)	Area ratio (%)	Length/diameter ratio
48	15	11.5
60	13	9.1
73	12	7.5
86	10	6.4
121	8	4.9

It can be seen that for this type of sampler, the 121 mm internal diameter tube provides an excellent combination of low area ratio and low length to diameter ratio, which would give acceptable results with a minimum of inside clearance. At the other end of the scale, the small diameter sampler is very similar to that used by Terzaghi for his variation surveys, with the improvements of a sharpened cutting edge and inside clearance.

Laval sampler

Probably the most effective tube sampler available for sampling soft and sensitive clays is the Laval sampler (La Rochelle *et al.* 1981). The use of such an expensive, time-consuming and delicate sampling process for routine sampling probably cannot be justified, but it has been shown (not only by the originators, but also as a result of trials at Bothkennar in Scotland, reported by Clayton *et al.* (1992)) that this sampler recovers soft and sensitive soil almost of the quality that can be achieved using block sampling techniques.

The Laval sampler is shown in Figs 7.8 and 7.9. The device consists of a thin-walled sampling tube mounted on a sampler head, and housed within an external corebarrel. The sampling tube contains a screw-type head valve which ensures that an effective vacuum can be achieved above the sample during withdrawal from the ground. The external corebarrel is used to remove soil around the sampling tube, after tube penetration, to ensure that no vacuum exists at the bottom of the cutting edge during sample withdrawal. No inside clearance is required because, in the soil types in which it is intended to be used, the shearing action between the tube and the soil leads to positive excess pore pressures, a reduction locally in effective stress, and a consequent lubricating effect. The inclusion of inside clearance was thought by La Rochelle *et al.* to introduce unnecessary ‘squeezing in’ of additional soil, and consequent disturbance. The sampling tube is precision machined from ZW-1035 carbon steel tubing with an i.d. of 200mm and an o.d. of 218 mm, to give a uniform circular internal cross-section along its length, and an internal diameter of 208 ± 0.03 mm. With a wall thickness of 5mm, the area ratio is 10% and the B/t ratio is 42. The cutting edge angle is 5°.

Fig. 7.8 The Laval sampler (photograph courtesy Dr D.W. Hight).

The operation of the Laval sampler is shown in Fig. 7.10. A borehole is made to the required depth, either open-hole using a fishtail bit, or as a result of previous sampling. No casing need normally be used, since bentonite mud flush provides wall support. The sampling assembly is lowered to the bottom of the hole with the sampler hooked on to the collar inside the top of the corebarrel (Fig. 7.10). With the head valve open, the sampling tube is gently unhooked by lifting and turning the inner rod at the surface. The sampler is pushed slowly into the soil, stopping some 50mm before contact is made between the bottom of the sampler head and the upper surface of the soil (Fig. 7.l0b). The head valve is then closed, and the corebarrel is used in conjunction with mud flush to clear soil from around the outside of the sampler tube, and to a depth of approximately 20mm below the bottom of its cutting edge (Fig. 7.l0c). The sample tube is rotated through about 90° in order to shear the soil at its base, and is then pulled gently out of the soil and hooked back on to the internal collar (Fig. 7.9). The assembly is finally removed from the borehole. The sample is extruded immediately, and is cut into slices 130mm or 200mm high which are placed on waxed plywood board and sealed in several layers of Saran paper sandwiched between brushed paraffin wax/vaseline mixture. The cost of the steel sampling tubes is such that they cannot economically be used for sample storage.

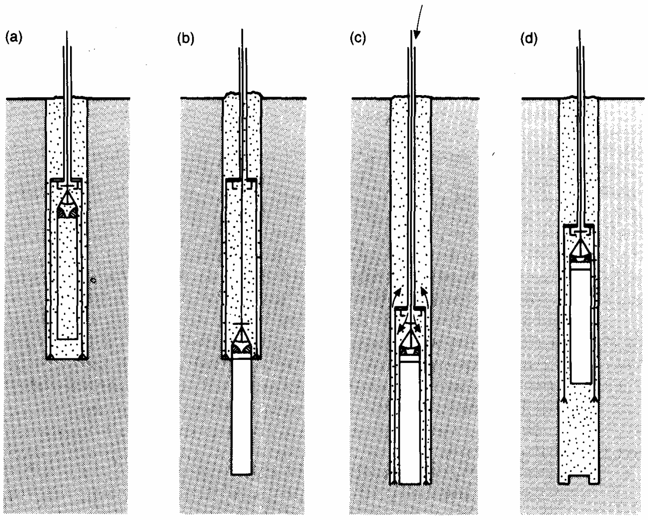


Fig. 7.10 General operation of the Laval sampler (La Rochelle *et al.* 1981).

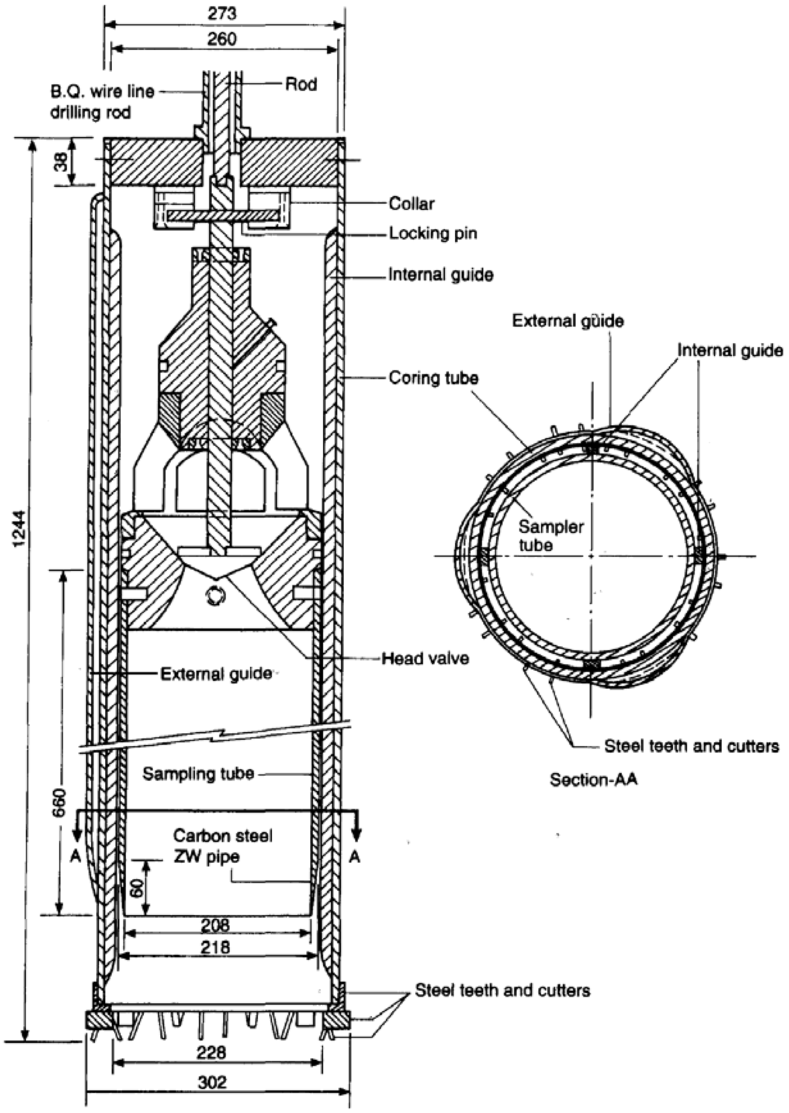


Fig. 7.9 The Laval 200mm diameter tube sampler (La Rochelle, Sarrailh, Tavenas, Roy and Leroueil 1981).

Piston drive samplers

Piston samplers were developed in both Europe and the USA in the period between 1900 and 1940. All piston samplers have a piston contained within the sample tube, which is moved upwards relative to the sample tube at some stage of the sampling process. Because there may be various reasons for including this piston in the design, however, the mechanisms associated with the piston movement are numerous.

Pistons have been included in sampler designs in order:

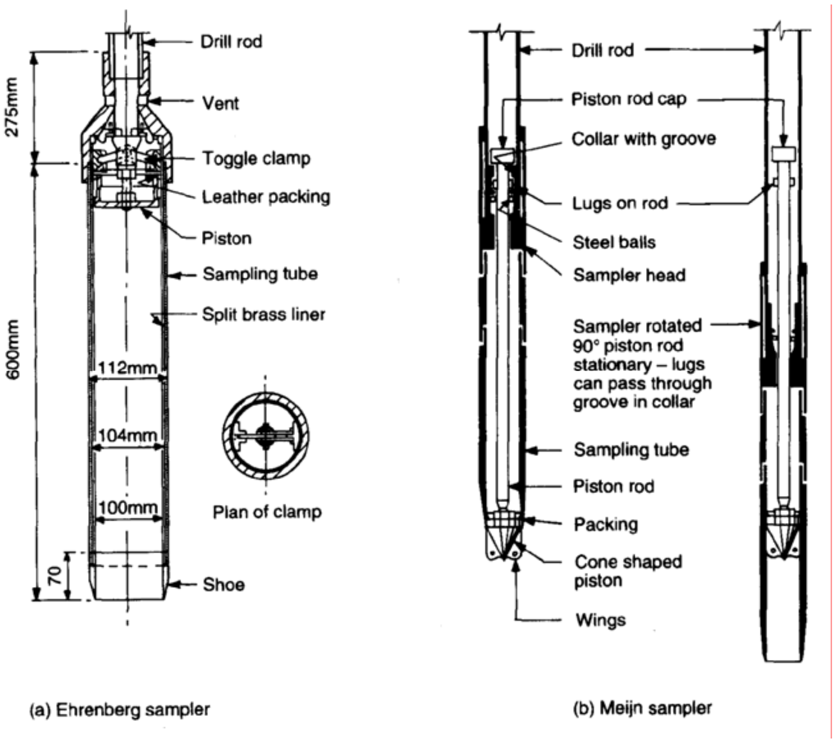
1. to prevent soil entering the sampler tube before the sampling position is reached. Many piston samplers have been specifically designed to be pushed, without a pre-drilled borehole, through the soil to the desired sampling depth (Bastin and Davis 1909; Olsson 1925, 1936; Petterson 1933; Porter 1936, 1937, 1939; Stokstad 1939), although it should be remembered that when this is done the upper part of the sample will normally be highly remoulded.

2. to reduce losses of samples, by providing an efficient airtight seal to the top of the soil in the tube during withdrawal. Any tendency of the sample to slide out of the tube is counteracted by pressure decrease above the sample, (for example, see Ehrenberg (1933)).
3. to reduce the entry of excess soil into the tube during the early stages of sampling, as a result of using a relatively high area ratio, and to prevent too little soil entering the sampler at the end of the drive, as a result of the build-up of internal friction; and
4. to increase the acceptable length to diameter ratio. Adhesion between the tube and the soil entering it will tend to reduce recovery once large length/diameter ratios are reached, but the movement of the top of the sample away from the underside of the piston will form a vacuum which will tend to increase the recovery.

Early American piston samplers, such as the Davis peat sampler (Bastin and Davis 1909), differed from early Swedish piston samplers (for example, Olsson (1925)) because the piston in the former was retracted to the top of the sample tube before it was driven, while in the latter case the piston remained fixed at the same level relative to ground surface throughout the drive (Hvorslev 1940). Hvorslev (1949) defined three main groups of piston sampler: (i) free piston samplers; (ii) retracted piston samplers; and (iii) fixed piston samplers.

Free piston samplers

Free piston samplers have an internal piston which may be clamped during withdrawal of the sampler, and during driving of the sampler to the required sampling depth. However, when the sample tube is being pushed into the soil during sampling the piston is free to move both with respect to the sample tube and to ground level. Figure 7.11 shows the Ehrenberg piston sampler and the Meijn piston sampler. In the former, the piston is free to move upwards at all times, but it cannot move downwards relative to the sample tube. It is not suitable for pushing through soft soil in order to reach the desired sampling level. In contrast, the Meijn sampler holds the piston at the bottom of the sample tube with two lugs on the inner rod which locate below a grooved collar in the sampler head. When the sampler reaches the correct level the sampler head and tube are rotated through 90° and the lugs clear the collar. After pushing the sample tube into the soil, loss of material is prevented during withdrawal by a cone clamp in the sampler head which prevents the piston rod sliding downwards through the head.



(a) Ehrenberg sampler

(b) Meijn sampler

Fig. 7.11 Two types of free piston sampler (Ehrenberg 1933; Huizinga 1944).

Free piston samplers overcome most of the disadvantages of the open-drive type of sampler, but they remain easy to use. Their main advantages are that they can be designed so that they can be pushed through debris at the base of a borehole, and that sample losses are greatly decreased by the provision of an efficient seal at the top of the sample. Despite this they are not used in the UK, perhaps because of fears that friction between the piston packing and the inside of the sample tube may cause sample compression or significantly reduce recovery.

Retracted piston samplers

Retracted piston samplers use the piston primarily to prevent the entrance of unwanted soil during the process of pushing the sampler to the required sampling depth (Bastin and Davis 1909; Porter 1936, 1937, 1939; Stokstad 1939). Once this depth is reached the piston is retracted to the top of the tube, and the sampler is then driven into the soil. The retraction of the piston may cause soft soil to flow upwards into the tube, and during driving a large area ratio may lead to the entry of excess soil into the tube. This type of sampler is not in use in the UK. It retains several of the disadvantages of the open-drive sampler, and is more difficult to use.

Fixed piston samplers

Fixed piston samplers can be used with or without a borehole. The sampler is pushed to the level at which sampling is to start with the piston rod fixed relative to the sampler head and tube, and located at the base of the tube to prevent the entry of soil. At this point the piston is freed at the sampler head, but refixed at the ground surface to the drilling rig or to a suitable frame in order to prevent it moving vertically during sampling. The sample tube is then pushed ahead of the piston into the soil. After sample driving, the inner rods extending to the ground surface from above the sampler head can be removed, since the piston is prevented from moving downwards relative to the sample tube by a clamp located in the sampler head.

Fixed piston samplers have all of the advantages discussed above: they prevent the entry of debris before sampling, they reduce the entry of excess soil during sampling and they largely eliminate sample losses. Hvorslev (1949) commented that ‘the drive sampler with a stationary piston has more advantages and comes closer to fulfilling the requirements for an all-purpose sampler than any other type’. Its disadvantages lie principally with its cost and complexity in use.

The original fixed piston sampler developed by Swedish engineer, John Olsson (Olsson 1925, 1936) controlled the movement of the piston before and during sampling by extending the piston rod to the ground surface inside the outer rods, and clamping it either to the outer rods or a frame at ground level. Modifications and improvements were tried over a period of many years (Petterson 1933; Bretting 1936; Kjellman 1938; Fahlquist 1941; Hvorslev 1949; Osterberg 1952; Hong 1961). In 1961, the Swedish Committee on Piston Sampling produced their findings (*Swedish Geotechnical institute Report No. 19*) and Kallstenius gave precise details of the apparatus in use. Since that time, work has been carried out to assess the effectiveness of piston samplers in obtaining good quality undisturbed samples (Berre *et al.* 1969; Schjetne 1971; Holm and Holtz 1977) and modifications to the apparatus have continued (for example Osterberg (1973) and Tornaghi and Cestari (1977)). The Japanese Society for Soil Mechanics and Foundation Engineering have subsequently published a Draft Standard for stationary piston sampling (Mon 1977).

Piston samplers with fixed pistons are available with a variety of sampler barrels. These may be thin-walled (made of either seamless steel tubing or of aluminium tube) or of the composite type.

Figure 7.12 shows a thin-walled seamless steel tube type fixed piston sampler similar to those described by Hvorslev (1949). The sampling tube has a rolled and reamed cutting edge. The sampler may be pushed through soft soils to the desired sampling level and, during this process, the conical piston is held at the base of the sampler tube. This is achieved by attaching the piston rod to the upper part of the head via a few turns of the left-hand thread of the piston rod screw clamp. When the sampling level is reached, the piston rods are turned clockwise at ground surface, tightening the rods above the sampler but disengaging them at the screw clamp. The piston rod is then fixed to the rig or a frame at ground level, and the hollow outer rods are pushed smoothly downwards to drive the sampling tube ahead of the piston into the soil. After sampling, the piston rods can be unclamped and the sampler pulled to the surface using the outer rods. The piston is held up by the ball cone clamp in the sampler head. Once the sampler is at ground surface, the tube is released from the head by screwing the Allen set screws inwards. The ball cone clamp must be released by turning a screw on the side of the head through 900 before the sample tube can be pulled from the head. The vacuum release screw must be slackened before the piston can be pulled out of the sample tube. The various screws must be reset before the next sample is taken.

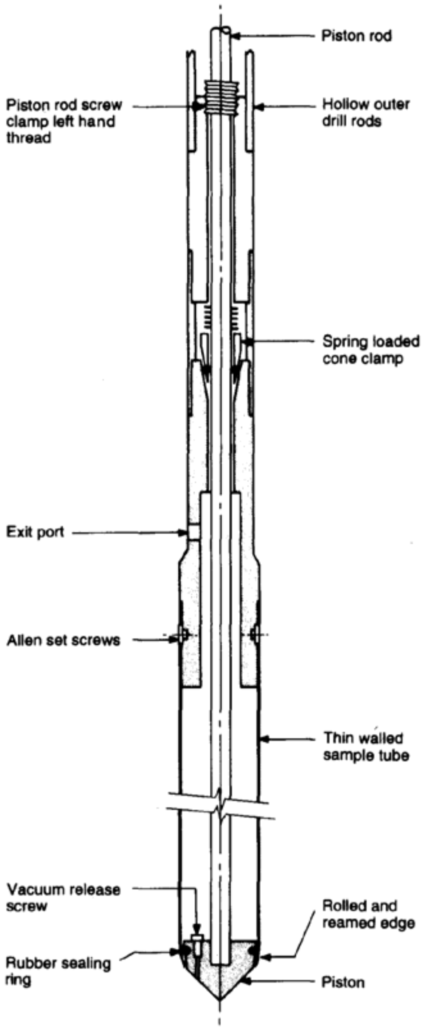


Fig. 7.12 Thin-walled seamless steel tube fixed piston sampler.

A device such as that described above has been widely and successfully used in very soft and sensitive clays in Norway. The Norwegian Geotechnical Institute 54mm dia. sampler has the following characteristics (Void 1956; Berre *et al.* 1969):

maximum tube length	880 mm
maximum sample length	725 mm
outside diameter	57mm
area ratio	11—12%
inside clearance	1.0—1.3%
maximum length/diameter ratio	13.4

outside cutting edge angle	120

The NGI sampler has also been built in a 95mm version, giving 1000mm long samples (Berre *et al.* 1969). Evidence from oedometer tests suggests that 50cm2 specimens from 95 mm dia. piston samples give much less scattered test results than specimens from 54mm piston samples, in soft to firm clay. This may be a consequence of small-scale heterogeneity, or of reduced sampling or extrusion disturbance.

An adaptor kit is available from the UK company, Engineering Laboratory Equipment Ltd, to allow the 54mm NGI/Geonor sampler to take 101mm dia. sample tubes with lengths of either 457mm or 1000mm. These tubes are aluminium, with an outside bevel and no inside clearance. They have the following characteristics:

maximum sample length	330 or 875mm
outside diameter	105mm
area ratio	8%
length/diameter ratio	3.3 or 8.8.

These types of piston sampler have been used widely and reasonably successfully in the UK, where typically they are pushed into the soil at the base of a borehole. Their major disadvantage lies in the slow speed with which they can be used. Inner and outer rods are screwed on in I m lengths, and the complex holding mechanisms require careful use. To speed the sampling process several researchers have proposed mechanisms which allow a fixed piston sampler to be used with only one set of rods. Bretting (1936) developed a sampler with an integral hydraulically actuated piston, intended for use in a cased borehole. The piston was fixed to the outer barrel of the sampler and held at the required level by drill rods extending to the ground surface. The sample tube extended over the fixed piston to a second (upper) piston, which could be forced downwards by the application of water pressure to the inside of the drill rods at ground level. This principle was subsequently also used by Osterberg (1952, 1973) for his hydraulic piston sampler (see Fig. 7.13).

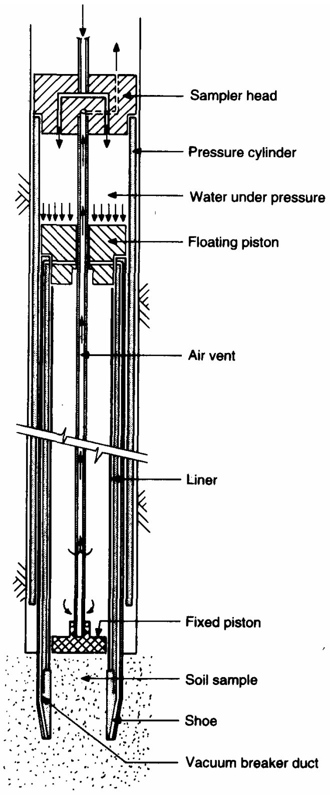


Fig. 7.13 The Osterberg composite hydraulic fixed piston sampler (Osterberg 1973).

The original Osterberg thin-walled hydraulic piston sampler was available in 127mm dia. (6% area ratio) and 72mm dia. (6.3% area ratio) forms. Raymond *et al.* (1971) and Raymond (1977) used this sampler with a restricted sample length of 600mm in the sensitive Leda clay and found it to give results second only to block sampling. The improved Osterberg composite hydraulic fixed piston sampler (Osterberg 1973) gives a maximum sample length of 1625mm with a diameter of 127 mm. It has an area ratio of 18%, inside clearance of 0.4%, a length to diameter ratio of 12.8 and a cutting edge angle of 7°. It has vents in the sample tube to allow vacuum relief below the tube when pulled from the soil, and the sampler can be rotated before pulling, in order to shear the soil at the base of the tube.

Fixed piston samplers are also widely used in Europe and the USA with liners. These composite fixed piston samplers have the advantages that they can be made more rugged and therefore more suitable for displacement boring, but the tube used to retain and store the soil after sampling can still remain lightweight and cheap. Evidence from sampling the soft, sensitive Leda clay (Raymond *et al.* 1971) suggests that the use of liners may be essential in small diameter samplers in some soil types, since both extrusion forces and the vibrations caused by sawing seamless steel tubing cause severe disturbance.

The Swedish composite fixed piston sampler (Kallstenius 1961) has a 700 mm stroke and a 50mm dia. at the cutting edge. Its outside diameter is 60mm, with plastic sectional liners of 170mm length and 50.2 mm inside diameter used to retain the sample. The base of the piston is 50° cone ended. Its characteristics are therefore:

maximum sample length	700mm
internal diameter at cutting shoe	50mm
area ratio	44%
inside clearance	0.4%
length to diameter ratio	14

Swedish experience has shown that very high quality samples can be obtained even with such a high area ratio and length to diameter ratio. Kallstenius (1958) showed the importance of cutting shoe design: for the Swedish standard piston sampler the taper is specified as 45° up to a thickness of 0.3mm and 5° thereafter. Similarly, in the USA, the Lowe—Acker composite fixed piston sampler (Lowe 1960) eliminates the effects of the high area ratio of a composite barrel by coupling a 150mm length of thin-walled tube to a 75mm long tapered coupling at its base. Despite a 70mm sample diameter and an area ratio of about 60%, Lowe (1960) has claimed that the effect of the thicker walled barrel section of the sampler is negligible.

The Swedish standard piston sampler is of rather small diameter compared with many modern devices, and the importance of a large diameter specimen in reducing sample disturbance and obtaining representative samples has already been noted. Holm and Holtz (1977) have presented the results of a study in which the Swedish Standard 50mm dia. device was compared with the NGI 95mm sampler, the Osterberg 127mm hydraulic piston sampler, and a 124mm dia. research sampler developed at the Swedish Geotechnical Institute. The results of this study indicate no significant differences between either the ratio (preconsolidation pressure/*in situ* vertical stress) or undrained shear strength derived from laboratory tests on specimens obtained by the various devices, but there are indications that:

1. results of oedometer tests on 50mm samples are more scattered, supporting the findings of Berre *et al.* (1969); and
2. the undrained modulus obtained from 50mm samples may be significantly lower.

Foil and stockinette samplers

Several devices have been developed to allow very long samples to be taken. Long samples are particularly desirable when soil is highly variable, containing for example interbedded clays and sands. Begemann (1974) has argued that in these conditions the calculation of settlement or predictions of the effectiveness of vertical sand drains cannot be made without a full, undisturbed, detailed picture of the soil, and this view is certainly supported by the work of Rowe (1968a, b, 1972).

Inside friction can be reduced by the cautious use of inside clearance; it cannot be eliminated without causing serious disturbance to the soil inside the sampler as a consequence of the reduced support. The provision of sliding liners within the sampler barrel means that lateral restraint can be maintained while frictional forces between the soil and its container are eliminated. Two types of device are available: that developed by the Swedish Geotechnical Institute and described by Kjellman *et al.* (1950) inserts aluminium foils between soil and sampler, whilst a sampler developed at the Delft Soil Mechanics Laboratory by Begemann (1961, 1971) surrounds the soil with a nylon stocking reinforced plastic skin and supports it with bentonite fluid.

The principles of operation of the Swedish foil sampler are shown in Fig. 7.14. According to Broms and Hallen (1971), two types of sampler exist, giving sample diameters of either 68mm or 40mm. There are sixteen rolls of very thin high strength steel foil in the sampler head of the 68mm sampler. Each foil is 12.5mm wide, and about 0.1mm thick. The thickness may be varied depending on the required maximum sample length and the anticipated frictional forces to be resisted. The sampler is pushed into the soil without a borehole. As the sampler is pushed downwards the foils, which are attached to a stationary piston, unwind from their rolls and completely surround the sample.

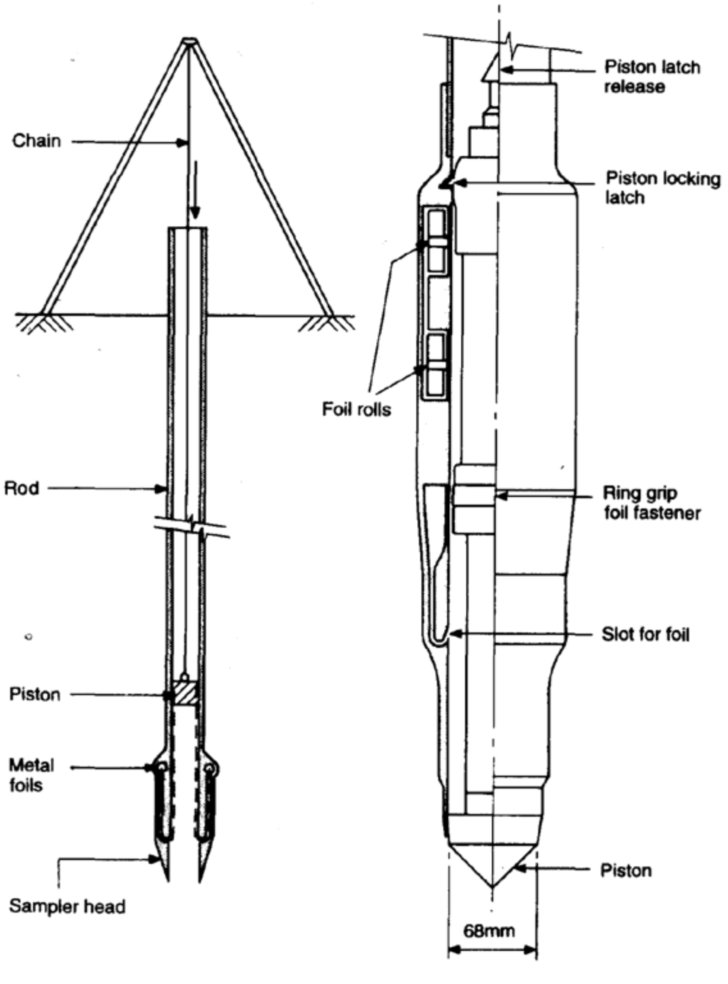


Fig. 7.14 Principle of operation of the Swedish foil sampler, and detail of the Mark V sampler head (Broms and Hallen 1971; Kjellman, Kallstenius and Wager 1950).

The maximum sample length that can be obtained depends on the strength of the foils and the size of the foils and their magazines. The 40mm foil sampler can hold a maximum length of 12m of foil, while the 68mm sampler can store 30m.

The friction between the foils and the sampler can be reduced by lubrication when sampling clays, and it has then been found possible to obtain continuous cores more than 20m long in very soft to soft soil. In sands, lubricants may penetrate the soil and cannot therefore be used; the length of sample is reduced.

The sampler is generally pushed or driven into soft cohesive soils. When silty or sandy soils are met, jetting may be needed to reduce the driving resistance. Ramming and jetting reduce the quality of the sample. Broms and Hallen (1971) describe a drilling rig for use with the foil sampler to obtain continuous samples of hard materials where rotary drilling is required. Using this equipment it has been possible to obtain cores of sand or hard boulder clay (till) up to l0m long.

The 66mm dia. *Delft continuous soil sampler* is shown in Fig. 7.15. In the early 30mm dia. version of this sampler (Begemann 1961, 1971) the soil entering the tube was primarily prevented from collapsing by bentonite fluid pressure. A stocking stored on the ‘stocking tube’ was surrounded by red vulcanizing fluid held in the chamber between the stocking tube and the outer sampler tube. The end of the stocking was secured to a cone-ended piston fixed at ground level. The inside of the sampler was filled with bentonite—water slurry. As the sampler was pushed into the ground the stocking unrolled from the stocking tube and rolled on to the outside of the soil. Contact between the slurry and the red vulcanizing fluid caused it to solidify, thus making a water-tight container, and preventing lateral strain of the soil.

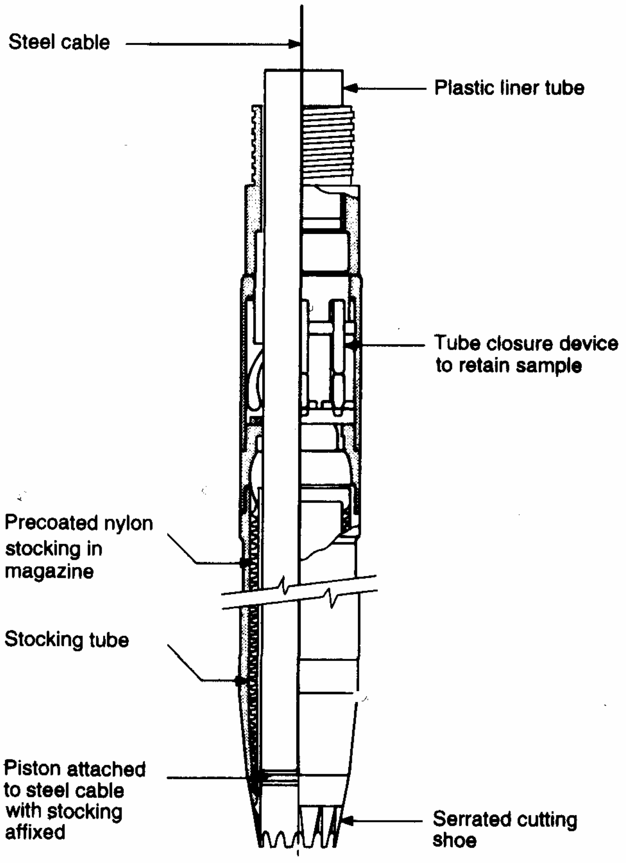


Fig. 7.15 66mm dia. Delft stocking sampler (Begemann 1974).

The sampler was originally pushed into the ground with a 10 tonne penetrometer, such as is used for the cone penetration test. The maximum sample length was determined by the maximum penetration force available, and the length of stocking that could be stored. This varied between l0m and 20m. The sampler was advanced in 1 m drives, and after each section of tube was added it was filled with bentonite slurry. When the desired depth was reached, the bottom of the sample was closed by a diabolo valve operated by rotating the tubes at ground surface, to prevent loss of bentonite and soil during withdrawal.

The 66mm diameter continuous sampler (known in The Netherlands as a Begemann boring) provides samples large enough for laboratory consolidation and triaxial testing (Fig. 7.16). A bentonite flush, weighted with barytes to increase its density, is used in order to provide support for the sample as it passes the opening through which the stocking emerges. In soft soils the density apparently may need to be modified so that the imposed horizontal stress does not exceed that in the soil. The larger sampler includes a plastic liner which virtually eliminates the space between the soil and the inside of the extension tubes. These liners also provide support as the samples are transported to the laboratory. The maximum sample length for the 66mm sampler is 19 m according to Begemann (1974), and a 17 tonne penetrometer has been used.

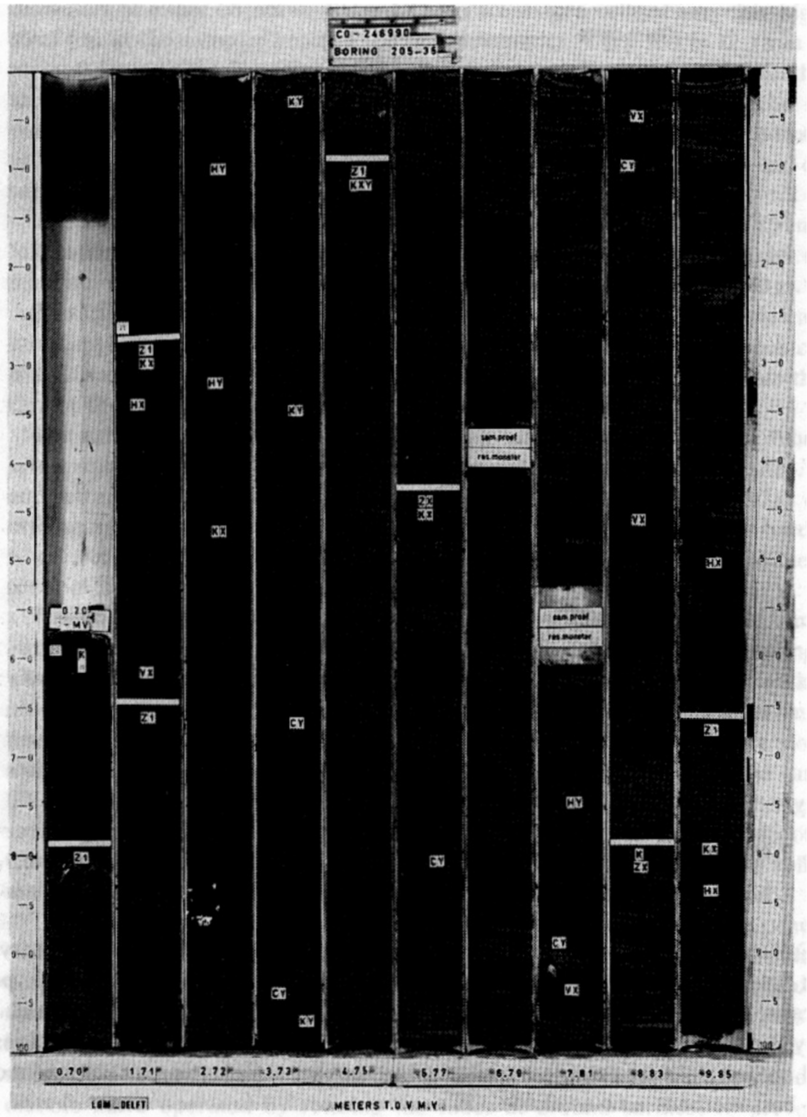


Fig. 7.16 Continuous l0m long sample in soft soil obtained using the Delft sampler (photograph courtesy Delft Geotechnics Laboratory).

Foil and stockinette samplers are relatively expensive, and are best reserved for soft, primarily cohesive soil types. They are no widely used in the UK, perhaps because large thicknesses of soft, fine sediment are not particularly common. Whilst they are very useful in providing a continuous record of complex soil conditions, they will not normally be expected to give as high quality samples as may be obtained using the best methods now available.

ROTARY SAMPLERS

Chapter 5 described the general principles of rotary coring, as carried out routinely during site investigation. The main tool used for rotary sampling of hard rocks in the UK and most of the world is the rotary corebarrel (Fig. 5.11) but rotary samplers are increasingly being adapted to sample virtually all types of soil and rock. In this section we describe the three principal types of rotary corebarrel used on stiff and hard clays, and weak, fractured and weathered rocks. Also described is a simple rotary sampler designed to give very high quality samples in soft sensitive clays.

Rotary corebarrels designed to sample the harder materials encountered during site investigations can be classified into three broad groups:

1. corebarrels with retracted inner barrels, such as the conventional double-tube swivel type corebarrel (Fig. 5.11), here termed ‘retracted corebarrels’;
2. corebarrels where the inner barrel protrudes ahead of the outer barrel, in an attempt to protect the ground being sampled from the deleterious effects of flush fluid, here termed ‘protruding corebarrels’; and
3. corebarrels where the inner barrel is spring mounted, so that it protrudes in relatively soft ground, but retracts when harder layers are encountered, here termed ‘retractor barrels’.

Refracted corebarrels

Double-tube swivel type corebarrels

British site investigation practice uses large diameter double-tube swivel type core- barrels, normally with face discharge diamond bits and a built-in core catcher. Common barrel sizes in use in the UK are NW, HWF, PWF and SWF, giving core diameters of 54.0, 76.2, 92.1, and 112.7 mm. The double-tube corebarrel contains a stationary inner barrel supported on a swivel. Flush fluid is pumped down the inside of the rods which run from the drilling rig at ground level to the top of the corebarrel. Once inside the barrel the flush fluid passes down between the inner and outer barrels and discharges through ports in the cutting face of the bit. The inner barrel is extended with a core catcher box which contains a split ring core catcher. When the barrel is pulled from the bottom of the hole, the catcher spring prevents loss of core by moving down the inside taper of the catcher box and progressively gripping the core more tightly if it slips downwards.

Double-tube swivel type corebarrels of large diameter can be used with great success not only to provide good quality core of sound rock, but also to provide samples of very stiff or hard clays. Once the core enters the inner barrel it is protected from erosion of the flush water and from the torsional effects of rotation. The top of the inner barrel is vented to prevent build-up of pressure over the top of the core. Should this vent become blocked, the pressure in the inner barrel may prevent core entry after as little as 0.5 m of coring, and in softer formations the core may be washed away or ground away.

Wireline drilling techniques, coupled with polymer mud, are now frequently used in the stiff and hard Eocene formations of the London area (the London clay, the Woolwich and Reading beds, and the Thanet sand), as an alternative to thin-wall tube sampling, when higher quality samples than can be obtained using the BS U100 tube sampler are required.

Corebarrels tend to have a larger area ratio and inside clearance than is generally accepted for drive samplers. The former is an advantage, because one of the problems when drilling in soft formations is to keep the pressure between the bit and rock or soil low enough to prevent the barrel fracturing or displacing the material beneath it. The larger inside clearance, which might be 2.4% for an HWF barrel, can cause serious problems. Although the core is protected from erosion by the flush fluid once it enters the inner barrel it is still in contact with that fluid and shales, mudstones and clays may deteriorate significantly if water flush is in use. Because the core is not well supported in the inner barrel, the effects of vibrations will be severe.

It is clear that when the highest possible recovery is required, the normally accepted rules to obtain fast economical progress with a diamond drill cannot be followed. Low bit pressures may reduce bit life by polishing the diamonds, and the low rotational speeds necessary to prevent vibrations from damaging the core will reduce the penetration speed. The main disadvantage of the double-tube swivel type corebarrel is that considerable skill and experience are required to use it successfully. When soil conditions are difficult both equipment and technique must be chosen with care: flush fluid, rig stroke, barrel length, diameter and design, and bit type will all be important.

The correct flush fluid can slow or even prevent the disintegration of the core. A long- stroke rig helps to reduce erosion and softening of the core by reducing the need for rechucking of the drill rods, and also lessens the chances of blocking if the flush pump is stopped during rechucking. Short barrels (say 1.0— 1.5 m long) of large diameter may be preferable to long thin barrels, because the effects of vibration and softening will be reduced. The use of liners of either rigid plastic or flexible plastic (Mylar) helps to reduce the effects of flush fluid, and largely eliminates damage to the core during withdrawal from the inner barrel. They can reduce inside clearance, and their smooth surface allows easy entry of the core.

Much damage can be done to good core during its extraction from the barrel. It is not uncommon to see core removed by holding the corebarrel almost vertical on a wire rope, and repeatedly hitting the inner barrel with a hammer. This method is not only likely to damage the inner barrel, but also will often damage the core. There is little or no chance of the driller being able to maintain the pieces of core in the same relative orientation as they occupy in the barrel while he struggles to place them in a corebox. Core should be extruded with the corebarrel held horizontally, using a coreplug in the inner barrel. Pressure should be smoothly applied to the back of the coreplug so that the core is extended with a minimum of vibration into a plastic receiving channel of about the same diameter as the core. After extrusion both core and plastic channel should be wrapped in clear polythene sheet and securely taped before being placed in the corebox.

Iwasaki *et al.* (1977) and Seko and Tobe (1977) have carried out comparative trials between double-tube swivel type corebarrels and a variety of other sampling devices. Iwasaki *et al.* found that a double-tube swivel type corebarrel with a face discharge bit, modified with a built-in check valve rather than a spring core catcher, an inner tube stabilizer and a reduced inside clearance of about 1.4% would give better results than a Denison sampler (see later) for clays with undrained shear strengths in excess of 150 to 200 kN/m2. Seko and Tobe carried out comparative sampling trials in the very stiff and sometimes hard clays of the Tokyo area: they used the samplers listed in Table 7.2.

Table 7.2 Samplers used in comparative sampling trials

Type of sampler		Diameter of core (mm)
1	Double-tube swivel type corebarrel with a tungsten bit	60
2	Denison sampler	70-80
3	Retractor barrel, without a core catcher	
4	Retractor barrel, with core catcher	
5	Wireline Denison sampler	
6	Single-tube corebarrel	
7	Thin-wall hammered open-drive sampler	

All the rotary samplers were used with mudflush. It was found that the double-tube swivel type corebarrel gave the best specimens, based on unconfined compressive strengths and modulus of elasticity values. Types 2, 4 and 5 were classed as second best, but thought unreliable, often causing serious disturbance. Surprisingly, the retractor barrel without the core catcher gave worse results than that with a spring core catcher. Significantly, the single-tube corebarrel and the hammered thin-walled open-drive sampler were described as ‘entirely unsuitable’.

Protruding corebarrels

In order to reduce the effects of flush fluid and torsional forces on the core, a number of devices have been developed in which the inner barrel extends below the bottom of the rotating corebit. The first of these devices was developed by the Ministry of Railways in Japan in the mid-1930s (Hvorslev 1940; Iwasaki *et al.* 1977). Subsequently Johnson (1940) reported the development of a similar corebarrel with a protruding inner barrel for taking samples of dense but erodible soils in the Denison District, Texas.

Denison corebarrel

The Denison corebarrel (Fig. 7.17) is a triple-tube swivel type corebarrel, with a shoe with a sharp cutting edge threaded onto the inner barrel and extending below the cutting teeth of a tungsten corebit. The length of the corebit must be changed to alter the amount by which the shoe extends below the corebit. According to Hvorlev (1949) and Lowe (1960) a 50—75 mm inner barrel protrusion is suitable for relatively loose or soft soils, whilst the cutting edge should be flush with the corebit in ‘very stiff, dense and brittle’ soils. The Denison corebarrel uses a ‘basket’ type spring core catcher, where a number of curved, thin, flexible springs are fixed to a base ring by rivets, or by welding. According to Hvorslev (1949) the use of such thin springs means that the core catcher is frequently damaged and must be replaced. The inner barrel encloses a liner, often of brass. The original inner barrel design by Johnson (1940) had a 32% area ratio, and a 0.6% inside clearance. The use of a high area ratio means that samples of hard clays and dense sands or gravels will be greatly disturbed, and better sampled by a conventional retracted inner barrel type sampler. Very soft to firm clays can be more effectively sampled with a fixed piston sampler. According to Lowe (1960) the Denison sampler is designed for use in stiff to hard cohesive soils and in sands. It is rarely used in the UK, where stiff clays are sampled using the 100mm thick-walled open-drive sampler, and the undisturbed sampling of sands is rarely attempted.

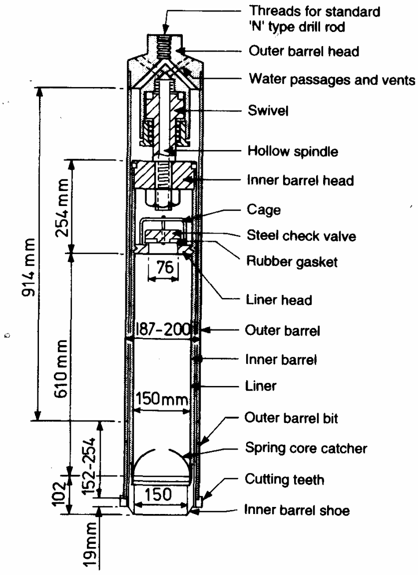


Fig. 7.17 Denison triple-tube corebarrel (Johnson 1940).

Retractor barrels

One of the problems facing the Denison corebarrel user is that the inner barrel protrusion must be pre-selected. To overcome this problem, several corebarrels have been developed which include spring mounted inner-barrels.

Pitcher sampler

The pitcher sampler (Terzaghi and Peck 1967; Morgenstern and Thomson 1971) is shown in Fig. 7.18. The inner barrel consists of a thin-walled sampler tube with a rolled and reamed cutting edge which is fixed to the inner head by set screws. The outer barrel has a tungsten insert corebit. The inner head is not fixed to the outer barrel; when the device is lowered to the bottom of the hole the head is supported immediately above the bit and flush fluid can be passed down the drill rods through the centre of the sample tube to remove any debris left at the bottom of the hole. Once the sample tube beds on to the soil at the bottom of the hole, the central tube on the top of the inner head mates with the outer barrel head. Flush fluid is now routed via the outside of the sampling tube, and the space above the sample is vented via the top of the sampler. The lead of the tube cutting edge is governed by the spring stiffness and the hardness of the soil.

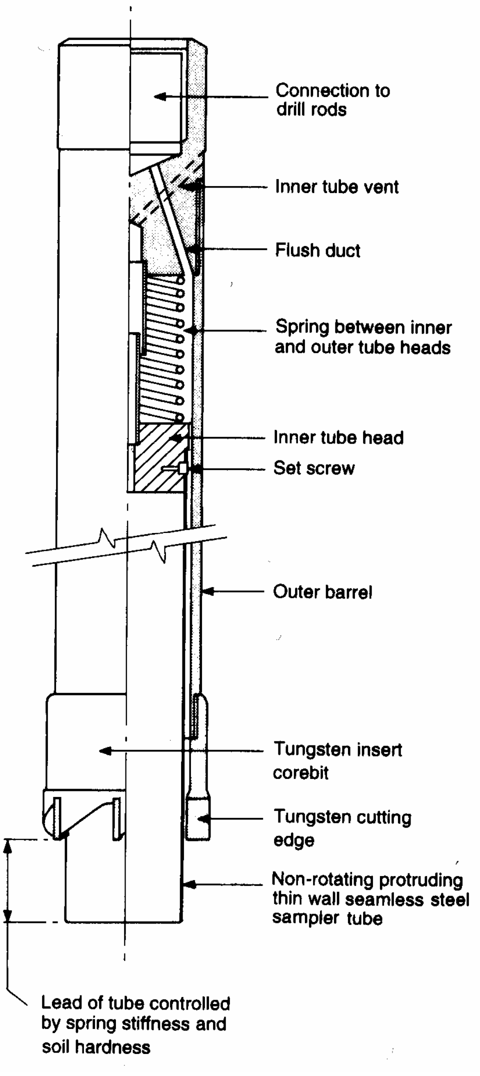


Fig. 7.18 Principal features of the Pitcher sampler.

In theory this type of sampler is ideally suited for drilling in soils with alternate hard and soft layers. In practice it has been found that hard friable soils, such as the weathered Keuper marl, can be sampled very successfully but frequently damage the rather light sampling tube. Thus this device is likely to be unsuitable for sampling inter-layered soil and rock, for example inter-layered clay and limestone. More rugged forms of retractor corebarrels have been developed in Australia by Triefus, and in France by Soletanche (Cambefort and Mazier 1961; Mazier 1974).

Mazier corebarrel

The Mazier corebarrel (Fig. 7.19) is a triple-tube swivel type retractor barrel, whose effectiveness (as with the Pitcher sampler) relies on the fact that the amount of inner barrel protrusion is controlled by a spring placed in the upper part of the device. The inner barrel contains a brass liner which can be used to transport samples to the laboratory, or for storage. The cutting shoe on the bottom of the inner barrel is substantial, making it much less easily damaged than a thin-walled seamless tube, but introducing the problems of disturbance when the high area ratio shoe travels ahead of the corebit.

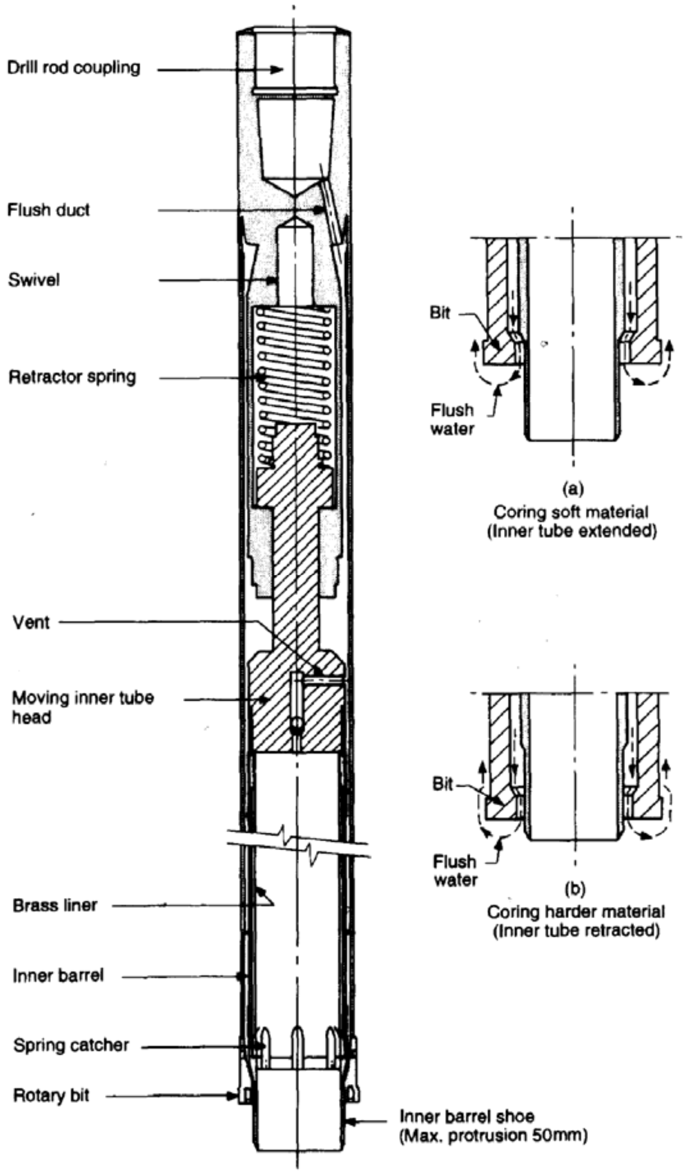


Fig. 7.19 Detail and principle of operation of the Mazier corebarrel.

Triefus triple-tube retractor corebarrel

The Triefus triple-tube retractor corebarrel uses the same principles as the Mazier device, but the maximum projection of the cutting shoe ahead of the corebit is much smaller (between 3mm and 16mm). This means that the absolute minimum of flush fluid should be used, in order to prevent washing and scour of soft or friable formations. Unlike the Mazier barrel, no core catcher is used and the base of the barrel must be sealed by dry blocking (i.e. drilling without flush fluid) at the end of the run. The liner tubes in the Triefus barrel can be either split steel, or solid transparent plastic, the latter allowing inspection of the core in the field without removal from its tube.

Additional major advantages of the Triefus barrel are that most of its components are interchangeable with those of their triple-tube standard corebarrels (allowing the standard barrel to be converted to a retractor barrel in the field), and that both these barrels are fitted with a core extractor plug (blow-out valve) to allow the core in its liner to be pushed gently from the barrel whilst in a horizontal position.

Retractor barrels find their best use in formations of variable hardness, where piston drive sampling cannot penetrate and when standard rotary coring provides insufficient protection to the soil. In general, thin-walled sampler retractor barrels such as the Pitcher sampler are susceptible to tube damage, while those with thick cutting shoes are much more likely to cause serious disturbance to the soil. Where soil conditions are relatively uniform and the soil is of sufficient undrained shear strength (>150—200kN/m2) the results of Iwasaki *et al.* (1977) and Seko and Tobe (1977) indicate that a double-tube swivel type rotary corebarrel can provide less disturbed samples than either protruding or retracting inner tube barrels, or driven thick-walled open-drive samplers.

SAND SAMPLING

‘Practical undisturbed’ samples, in Hvorslev’s terms, can be obtained from sand deposits: but despite the fact that the soil structure, water content, void ratio and constituents remain unaltered such samples are not normally suitable for compressibility testing. Indeed, Broms (1980) asserts that such samples cannot be obtained of a sufficiently high quality to allow determinations of potential liquefaction problems. The effects of total stress relief on granular soils usually result in very large reductions in effective stresses, and the properties of such soils tend to be highly dependent both on stress history and current effective stress level. But in addition, small changes in shear stress can also destroy the ‘memory’ of previous stress applications, leading to considerable reduction in stiffness, in sands.

Undisturbed sand sampling can be very expensive, and is normally only required in special circumstances, for example to obtain values of *in situ* density for earthquake liquefaction problems or for compressibility studies. In Japan, for example, the havoc created by earthquake damage has caused a considerable interest in the sampling of granular materials and has lead to widespread research and publication (for example, Yamada and Uezawa 1969: Hanzawa and Matsuda 1977; Isihara and Silver 1977; Seko and Tobe 1977: Tohno 1977 and Yoshimi *et al.* 1977).

Hvorslev (1949) outlined a number of techniques for sampling sand using:

1. thin-wall fixed piston samplers in mud-filled holes;
2. open-drive samplers under compressed air;
3. impregnation;
4. freezing;
5. core catchers.

Fixed piston sampling

A study of the effectiveness of thin-walled fixed piston sampling has been carried out at full-scale in the laboratory by Marcuson *et al.* (1977). Using a 1.22m dia. x 1.83m high specimen of fine sand, and mud flush rotary drilling, they obtained samples using a 76.2mm dia. piston sampler with an area ratio of 11%. By comparison between soil densities when placed and after sampling it was found that samples of dense sand were slightly loosened and samples of loose sand densified, but the results suggest an accuracy within ±3.5% of the placed density for sands with relative densities of between 20% and 60%. Bearing in mind the difficulty of creating uniform samples (the authors suggest a variability of density at the time of placement of about + 3.2% to —1.6%) these results seem encouraging, and support the view of Friis (1961) regarding the value of thin-walled fixed piston sampling under drilling mud in sand.

The use of compressed air to displace water from around the sampler tube in the borehole, and thus reduce the losses of samples in sand was first suggested by Glossop to Bishop (1948) and independently by Vargas to Hvorslev (1949).

Bishop's sand sampler

Bishop's sand sampler (Bishop 1948; Nixon 1954; Serota and Jennings 1957) consists of a 63.5mm thin-walled open-drive sampler held by set screws to a head containing a rubber diaphragm check valve and vents (see Fig. 7.20). This assembly is mounted within a compressed air bell which is connected to an air pump at the ground surface. The sampler is used in the following manner.

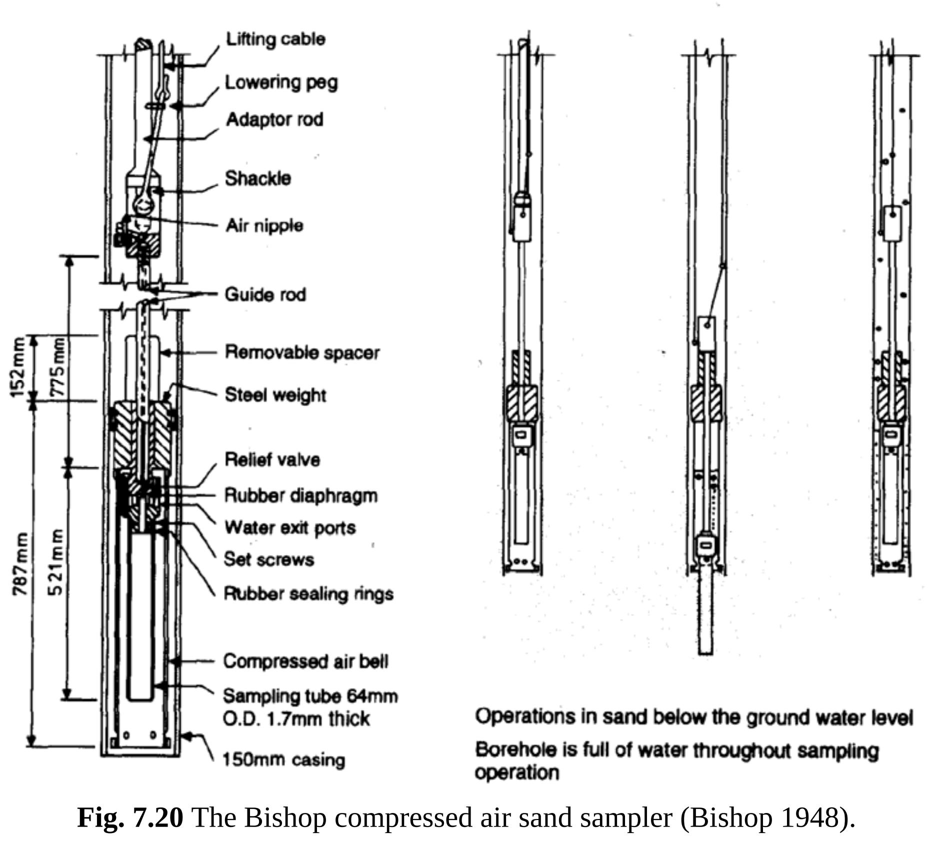


Fig. 7.20 The Bishop compressed air sand sampler (Bishop 1948).

1. Lower the sampler inside the compressed air bell to the base of a cleaned borehole.
2. Push the sample tube ahead of the bell into the soil, using the rods.
3. Remove the rods, and force compressed air into the bell via the relief valve in the sampler head. The relief valve vents to the inside of the bell at a pressure difference of about 150 kN/m2, and this pressure bears on the upper surface of the diaphragm, ensuring that it works efficiently.

4. Once air bubbles rising to the surface of the water in the borehole indicate that the water in the bell has been expelled, the sample tube is pulled from the soil into the bell, and then rapidly brought to ground surface using the lifting cable.
5. Remove the spacer, push the sample tube and head out of the bell, and release the sample tube set screws.
6. Cap the base of the tube and release the check valve before removing the sample tube from the head.

The Bishop sand sampler uses arching and the small capillary suctions set up at the sand/air interface to reduce sample losses. This principle has since been used by Yamada and Uezawa (1969).

Soil impregnation

Van Bruggen (1936) described the use of soil impregnation with a dilute emulsion of asphaltic bitumen, in order to impart cohesion to granular soils and thus allow them to be sampled. The bitumen was subsequently removed by washing through with a solution of carbon disulphide and acetone. Such a process would certainly change the properties of the soil. Hvorslev (1949) describes the use of chemical injection around the cutting shoe of an open-drive sampler to solidify soil and help to retain samples of granular material. Subsequently Karol (1970) and Borowicka (1973) have reported the use of various resin and silica grouts to prevent disturbance to the soil structure during sampling. Impregnation and injection are expensive and relatively difficult to use: the soil to be sampled cannot be impregnated unless the chemicals and so on, can be effectively removed at a later date, and in addition, most grouts and emulsions will not penetrate relatively impervious sand or silt soils. The method is therefore rarely used.

Freezing

In contrast, freezing has been widely used to seal the bottom of sample tubes (once driven), to prevent disturbance to the soil during transporting to the laboratory, and to freeze soil before sampling, (for example, Fahlquist 1941; Hvorslev 1949; Ducker 1969 and Yoshimi *et al.* 1977). These techniques are very expensive, and yet the need for undisturbed silt and sand samples has resulted in their continued use, particularly in the earthquake areas of the Far East and the USA. A relatively economical method of obtaining frozen sand samples is shown in Fig. 7.21. A 73mm thin-wall steel tube is inserted into the ground, while removing soil from its interior with an auger. Once the desired depth of freezing is reached, the lower end of the tube is sealed with cement grout and the plastic ‘freezing tube’ inserted down the centre of the steel tube. Circulation of an ethanol and crushed dry ice coolant at -40 to -60°C results in a frozen column of soil which can be extracted by pulling the steel tube from the ground. At ambient air temperatures of 23—30°C and a ground temperature of 22°C at 0.9 m depth, Yoshimi *et al.* (1977) acquired columnar samples 5.8 m long and 380mm dia. after 16 h of coolant circulation.

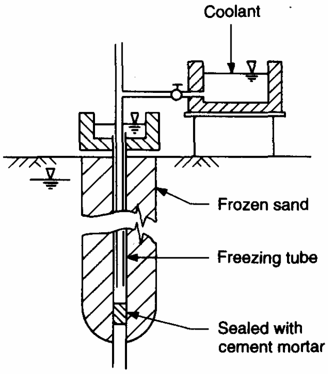


Fig. 7.21 Method of sand sampling by freezing adopted by Yoshimi, Oh-Oka (1977).

The value of samples obtained by freezing depends on the amount of density and soil structure change caused by the process. The amount of strain taking place during freezing increases with increasing relative density, decreasing applied pressure, and increased freezing time. Tests by Yoshimi *et al*. on specimens of soil placed in the laboratory and on samples obtained using the freezing tube technique described above indicate that soil adjacent to the freezing tube was significantly altered by freezing; loose sand was densified, but medium dense and dense sands loosened. Densities in the outer half of the sample, however, showed no alteration and indicated values mostly within ±2% of the average placed or field dry density.

Core catchers

Core catchers can be used with great success to retain granular soils, but their design may introduce considerable disturbance during the sampler drive. Spring systems such as used in rotary samplers are examples of the types of catching device which should be used with great caution. The catchers described by Yamada and Uezawa (1969) and Isihara and Silver (1977) are examples of systems which should lead to a minimum of disturbance.

SAMPLER SELECTION

For reasons of economy it is sensible to adopt the cheapest sampling techniques compatible with the aims of an investigation. To do this, the reasons for drilling and sampling must be clearly defined. In many cases only very simple methods of sampling will be necessary — the priority will be the proper identification of soil type and soil fabric, and there will be little need to obtain realistic soil parameters. In other instances, for example when complex computer analyses are to be undertaken during design, much higher quality samples will be required so that sophisticated laboratory tests can be carried out.

The German Standard DIN 4021 defined five quality classes of soil sample, and quality classes have also been discussed by Idel *et al*. (1969), and by Rowe (1972), and have been defined in BS 5930:1981. In principle they identify the range of samples shown in Table 7.3.

Table 7.3 Soil sample quality classes

Quality class	State of soil sample
1	No geometric distortion. Shear strength and compressibility are unaffected.
2	Geometric distortion. Density and water content unaffected.
3	Density altered. Water content and particle size distribution unaffected.
4	Water content and density altered. Particle size distribution unaffected.
5	Particle size distribution altered by loss of fines or grain crushing.

Based upon the research of the past decade, this classification no longer seems relevant and, indeed, it does not appear to have been used in practice. We can note, for example, that Quality class 1 samples cannot be obtained with routine tube samplers, and that the shear strength and compressibility of even the best quality block samples are likely to be affected as a result of changes in effective stress during sampling. It is difficult to envisage how water content can remain unaffected when density changes, given that most soils are likely to be saturated when *in situ*. And inadequate particle size distributions may result as much from a poor choice of sample size as from poor sampling technique.

In the UK the typical ‘routine’ soil sampling associated with light percussion drilling is as follows.

1. *All soils.* Small disturbed sample (jar sample) immediately each new stratum is detected. Water samples from every water strike.
2. *Sand.* Standard penetration test (SPT), with a jar sample taken from the split spoon, immediately on entering the stratum, and at 1.5 m intervals thereafter. If no sample is recovered by the split spoon a large disturbed sample (bulk bag) should be taken from the same level. Bulk bags should be taken at 1.5m intervals midway between the SPT tests.
3. *Sand and gravel, or gravel.* Standard penetration test with 60° cone (SPT cone), immediately on entering the stratum, and at 1.5m intervals thereafter. A large disturbed sample (bulk bag) should be taken from the level of the SPT (cone) test.
4. *Chalk, marl or silt.* Alternate 100mm thick-walled open-drive samples (UlOOs) and SPT tests with jar samples taken from the split spoon sampler, at 1.5 m intervals. In hard marls and cemented silts an ‘H’ size double-tube swivel type corebarrel with air flush is sometimes used.
5. *Hard clay.* U100 samples may be possible, but otherwise SPT tests are carried out. Exceptionally, mud flush and rotary coring is used.
6. *Stiff clay.* U100 sample immediately upon entering the stratum and then at 1.5 m intervals. A small disturbed sample is taken from the cutting shoe of the U100 samples, and at 1.5 m intervals midway between the U100 samples.
7. *Very soft clay or peat.* 54mm or 100mm dia. thin-walled fixed piston samples, either continuously in a shallow deposit, or at 1 m intervals in a deep deposit.
8. *Rock.* Continuous rotary core from a double-tube swivel type corebarrel, with water flush. The minimum size is usually ‘N’.

This scheme leaves the ‘variation survey’, that is the assessment of soil variability, as well as many of the decisions about sampling, and the recognition of strata changes, to the drilling foreman. He is the only person to see the majority of the soil profile, and must watch the disturbed material produced by the drilling process most carefully so that subtle (but perhaps significant) features are not to be missed. This type of ground investigation, and the routine testing practices associated with it can now be viewed as barely adequate. The ground profile is not properly examined, the samples obtained are typically of low quality, and the testing carried out may often be unnecessary, or inappropriate for the engineering needs of the project.

When proper design of ground investigation is carried out there is a need to match the sophistication of sampling (and *in situ* testing) to the sophistication of the analysis and design of the project. Empirical and semi-empirical methods of design are certainly acceptable, and should be used in conjunction with the appropriate sampling and test methods upon which they were originally based. But more fundamental methods of analysis, for example for the constitutive modelling of soil behaviour via finite element or finite difference analyses, will require high-quality sampling and testing methods. From the range of sampling methods described, the methods shown in Table 7.4 are the best available.

Table 7.4 Recommended sampling methods

Soil type	Recommended sampling technique	Likely disturbance
Very soft, soft, firm, or sensitive clays	Laval open-drive overcored sampler	Minor destructuring
	Sherbrooke down-hole block sampler	Reduction in effective stress due to borehole fluid penetration
Inter-layered sand, silt, clay	Delft sampler	Major loss of effective stress. Some destructuring
Firm, stiff and very stiff clays	Thin-walled hydraulically jacked open-drive tube samples	Minor destructuring, with significant increases in effective stress
Very stiff and hard clays, mudrocks, and stoney clays	Wireline coring, using bentonite mud or polymer muds with anti-swelling agents, or double-tube swivel type corebarrel with bentonite mud flush	Significant decrease in effective stress
Sand	Piston sampling in mud-filled borehole	Total loss of effective stress. Major destructuring. Density approximately maintained
Gravel	Sampling from pits	Only particle size and density can be obtained
Weak rocks, chalk	Triple-tube swivel-type corebarrel with mud or msf flush, or retractor barrel	Minor core loss Discontinuities opened
Decomposed granite	Treifus or Mazier retractor barrel	Minor core loss. Effective stress loss
Hard rock	Double-tube swivel-type corebarrel	Discontinuities opened