Chapter 1

Planning and procurement

Unfortunately, soils are made by nature and not by man, and the products of nature are always complex.

Karl von Terzaghi, 1936

INTRODUCTION

Site investigation is the process by which geological, geotechnical, and other relevant information which might affect the construction or performance of a civil engineering or building project is acquired.

Soil and rock are created by many processes out of a wide variety of materials. Because deposition is irregular, soils and rocks are notoriously variable, and often have properties which are undesirable from the point of view of a proposed structure. Unfortunately, the decision to develop a particular site cannot often be made on the basis of its complete suitability from the engineering viewpoint; geotechnical problems therefore occur and require geotechnical parameters for their solution.

Site investigation will often be carried out by specialists in the field of soil mechanics. Soil, in the engineering sense, is the relatively soft and uncemented material which overlies the rock of the outer part of the Earth's crust. Specialists in the mechanical behaviour of soil are normally civil engineers and in the UK they will often have some postgraduate geotechnical education: such people are termed 'soils engineers' or 'geotechnical engineers'. Geologists with an interest in the relevance of geology to civil engineering or building construction are called 'engineering geologists'.

Soil mechanics in its present form is a relatively recent addition to the field of engineering. Interest in the behaviour of earth and rock for engineering purposes can be traced back to Roman times (Palladius in Plommer (1973)), but significant advances in analysis seem to date back to the eighteenth century, when the need for large defensive revetments led to early work on retaining walls. Coulomb's paper, delivered to the Académie Royale des Sciences in 1773 and published in 1776, represents an early work which showed considerable understanding, *inter alia*, of the behaviour of soil, and whose results are still valid and in use (Heyman 1972). Subsequent papers, principally delivered by the French, did much to refine the available solutions but little to increase fundamental knowledge.

By the first quarter of the nineteenth century, it appears that many concepts now associated with the principle of effective stress were intuitively understood. Telford used pre-loading during the construction of the Caledonian Canal in 1809 'for the purpose of squeezing out the water and consolidating the mud', and Stephenson used drains to lower pore pressures during the construction of the Chat Moss embankment on the Liverpool and Manchester Railway in the years 1826 to 1829 'in order to consolidate the ground between them on which the road was to be formed' (Smiles 1874). During the industrial period preceding the twentieth century, many of the currently used geotechnical processes for the improvement of ground, such as piling, pre-loading, compaction and de-watering appear to have been used (Feld 1948; Skempton 1960b; Jensen 1969). These techniques were applied in a purely empirical manner.

At the turn of the twentieth century, a series of major failures occurred which led to the almost simultaneous formation of geotechnical research groups in various countries. In America, slope failures on the Panama Canal led to the formation of the American Foundations Committee of the American Society of Civil Engineers in 1913 and, in Sweden, landslides during a railway construction resulted in the formation of the State Geotechnical Commission in the same year. Following a number of embankment and dyke failures, a government committee under Buisman was set up in Holland in 1920. Casagrande (1960), however, dates the advent of modern soil mechanics to the period between 1921 and 1925, when Terzaghi published several important papers relating to the pore pressures set up in clay during loading, and their dissipation during consolidation, and also published his book *Erdbaumechanik auf Bodenphysikalischer Grundlage*.

These works largely stemmed from Terzaghi's appreciation of the need to supplement geological information with numerical data, following two years spent collecting geological information on the construction sites of US dams (Terzaghi 1936).

Terzaghi's first professional work in England was in 1939, when he was retained to investigate a slope failure at the Chingford reservoir (Cooling and Golder 1942). As a result, the first commercial soil mechanics laboratory in the UK was established by John Mowlem and became Soil Mechanics Ltd in 1943. Whyte (1976) reports that by 1948 five other contractors and one consultant had soils divisions. Major encouragement was given to soils research in the UK by Cooling, who influenced a number of engineers (for example Skempton, Bishop and Golder) who worked at the Building Research Station in the 1940s. In 1948, *Géotechnique* commenced publication, and by 1955 a great number of significant papers on soil mechanics had been published covering topics such as site investigation, seepage, slope stability and settlement.

According to Mayniel (1808), Bullet was the first to try to establish an earth pressure theory, in 1691. More importantly from our point of view, Bullet notes the importance of *site investigation* for the foundations of earth-retaining structures and recommends the use of trial holes in order to determine the different beds of soil beneath a site, and in order to ensure that poor soil does not underlie good soil. Where trial holes could not be made, Bullet recommended the use of an indirect method of investigation whereby the quality of the soil was determined from the sound and penetration achieved when it was beaten with a 6—8 ft length of rafter.

Whilst the use of trial holes to investigate sub-soil may, not unexpectedly, date from centuries ago, it is more surprising to note that the equipment for boring holes in soft ground also has a long history. Jensen (1969) and Whyte (1976) illustrate types of drilling equipment in use around 1700, and many of the tools bear a striking resemblance to those used in light percussion drilling at the present time in the UK.

Modern site investigation differs from its forbears principally because of the need to quantify soil behaviour. Terzaghi, in his James Forrest lecture to the Institution of Civil Engineers in London (1939) noted that in 1925 sampling methods in the USA were 'primitive', with sealed tube samples being almost unheard of. The work of Casagrande between 1925 and 1936 demonstrated the influence of soil disturbance during sampling (see, for example, Casagrande (1932)) and led to the development in the USA of 'elaborate and ingenious procedures for furnishing almost undisturbed samples up to a diameter of 5-inches' (Terzaghi 1939). At the same time considerable advances were made in Denmark, France, Germany, Sweden and England.

In the UK, Cooling and Smith (1936) reported an early attempt at the acquisition of 'undisturbed' soil samples using a 105 mm dia. split tube forced into the ground from the back of a lorry. By 1937 the tool was a 105 mm dia. tube which was driven into the soil (Cooling and Golder 1942; Cooling 1942), and which had an area ratio (the ratio of displaced soil area to sample area) of about 20%. Boring was by well-boring apparatus, 'sunk in the usual way with augers, chisels, etc.' (Cooling 1942). By 1945 the sampling tube had become the U100 which is still in use today (Longsdon 1945).

In 1949, the first draft *Civil Engineering Code of Practice for Site Investigations* was issued for comment. At that time Harding (1949) delivered a paper to the Works Construction Division of the Institution of Civil Engineers in which he detailed the methods of boring and sampling then available. The recommendations made in that paper, and in discussions on the paper by Skempton, Toms and Rodin form the basis of the majority of techniques still in use in site investigation in the United Kingdom. For example, in his discussion on methods of boring, Harding notes that:

> the boring equipment used in site investigations is criticized by some who have not been exposed to the need to carry it themselves, as being primitive and lacking in mechanization. Whilst it is possible to think of many ingenious contrivances for removing articles at depths below ground, in practice simple methods usually prove to be more reliable.

while Skempton confirmed this view:

> with that simple equipment [shell and auger gear and 102 mm dia. sampler] the majority of site investigations in soils could be carried out and, moreover, sufficient experience was now available to enable the positive statement to be made that, in most cases, the results obtained by that technique (in association with laboratory tests) were sufficiently reliable for practical engineering purposes.

By 1953, Terzaghi stated in connection with site investigation that 'we have acquired all the knowledge which is needed for a rational interpretation of the observational and experimental data'. The reader may reasonably ask what is to be gained from this book, since techniques are so well established. In reality, since 1950, four main changes have taken place. First, many of the methods introduced before and since have been the object of criticism as a result of differences between predictions and subsequent observations. Secondly, a considerable number of the lessons learnt before 1950 have been forgotten: few U100 samplers in use today are of the standard required by Hvorslev (1949) for undisturbed sampling, and much fieldwork remains unsupervised by engineers. Thirdly, few engineers have an experience or understanding of the techniques of boring and drilling holes for site investigations, and most clients remain unaware of the importance of this part of the work. Finally, recent years have seen the introduction of sophisticated and expensive methods of testing and computer analysis which cannot be sensibly applied to samples and predictions of soil conditions of indeterminate quality.

The Civil Engineering Code of Practice No. 1: Site Investigations was issued in 1950, and revised as British Standard Code of Practice CP 2001 in 1957. This code has now been extended, completely rewritten and re-issued as British Standard 5930:1 981. At the time of writing (1992) BS 5930 is under revision. The code contains much valuable information, but it is perhaps necessary to ask whether it is wise to codify in this way. Terzaghi (1951) argued that:

> since there is an infinite variety of subsoil patterns and conditions of saturation, the use of the different methods of subsoil exploration cannot be standardised, but the methods themselves still leave a wide margin for improvement, as far as expediency and reliability are concerned.

OBJECTIVES

The objectives of site investigation have been defined by the various *Codes of Practice* (*BS CP 2001:1950, 1957; BS 5930:1981*). They can be summarized as providing data for the following.

1. *Site selection*. The construction of certain major projects, such as earth dams, is dependent on the availability of a suitable site. Clearly, if the plan is to build on the cheapest, most readily available land, geotechnical problems due to the high permeability of the sub-soil, or to slope instability may make the final cost of the construction prohibitive. Since the safety of lives and property are at stake, it is important to consider the geotechnical merits or demerits of various sites before the site is chosen for a project of such magnitude.
2. *Foundation and earthworks design*. Generally, factors such as the availability of land at the right price, in a good location from the point of view of the eventual user, and with the

planning consent for its proposed use are of over-riding importance. For medium-sized engineering works, such as motorways and multistorey structures, the geotechnical problems must be solved once the site is available, in order to allow a safe and economical design to be prepared.

3. *Temporary works design*. The actual process of construction may often impose greater stress on the ground than the final structure. While excavating for foundations, steep side slopes may be used, and the in-flow of groundwater may cause severe problems and even collapse. These temporary difficulties, which may in extreme circumstances prevent the completion of a construction project, will not usually affect the design of the finished works. They must, however, be the object of serious investigation.
4. *The effects of the proposed project on its environment*. The construction of an excavation may cause structural distress to neighbouring structures for a variety of reasons such as loss of ground, and lowering of the groundwater table. This will result in prompt legal action. On a wider scale, the extraction of water from the ground for drinking may cause pollution of the aquifer in coastal regions due to saline intrusion, and the construction of a major earth dam and lake may not only destroy agricultural land and game, but may introduce new diseases into large populations. These effects must be the subject of investigation.
5. *Investigation of existing construction*. The observation and recording of the conditions leading to failure of soils or structures are of primary importance to the advance of soil mechanics, but the investigation of existing works can also be particularly valuable for obtaining data for use in proposed works on similar soil conditions. The rate of settlement, the necessity for special types of structural solution, and the bulk strength of the sub-soil may all be obtained with more certainty from back-analysis of the records of existing works than from smallscale laboratory tests.
6. *The design of remedial works*. If structures are seen to have failed, or to be about to fail, then remedial measures must be designed. Site investigation methods must be used to obtain parameters for design.
7. *Safety checks*. Major civil engineering works, such as earth dams, have been constructed over a sufficiently long period for the precise construction method and the present stability of early examples to be in doubt. Site investigations are used to provide data to allow their continued use.

According to US 5930: 1981, site investigation aims to determine all the information relevant to site usage, including meteorological, hydrological and environmental information. Ground investigation aims only to determine the ground and groundwater conditions at and around the site; this is normally achieved by boring and drilling exploratory holes, and carrying out soil and rock testing. In common engineering parlance, however, the terms site investigation and ground investigation are used interchangeably.

GENERAL DESIGN PHILOSOPHY

Site investigation should be an integral part of the construction process. Unfortunately it is often seen as a necessary evil — a process which must be gone through by a designer if he or she is to avoid being thought incompetent, but one which gives little of value and takes precious time and money. This is an unfortunate by-product of the way in which site investigation is often carried out, and it can hardly be surprising that if no effort is put into targeting the investigation to precise issues, then little of value emerges.

Site investigation should be a carefully considered process of scientific discovery, tailored both to the conditions existing on site and to the form of construction which is expected to take place. In order to make the most of site investigation, it is important that the design team (who may be led by architects, quantity surveyors and other non- engineering professionals) obtain at the conceptual design stage the advice, however briefly, of a geotechnical engineer. This geotechnical specialist can give the initial and most important guidance on the likely risks associated with the project, and the way in which they may be investigated and dealt with. For most construction projects, the natural variability of the ground and groundwater conditions represent a major risk, which if not properly addressed can endanger not only the financial viability, but also the physical stability of the construction, either during construction or during the use of the building.

In principal then, all sites must be investigated if construction is to be safe and economical. In practice, the way in which they are investigated can vary very widely, and the costs and time necessary will also be significantly different. The keys in selecting the most effective method of dealing with the inevitable uncertainties which must arise are geotechnical knowledge and experience. Possible approaches which have been successfully used include the following.

Approaches to site investigation

Approach 1: Desk-study and geotechnical advice

The minimum requirement for a satisfactory investigation is that a desk study and walk-over survey are carried out by a competent geotechnical specialist, who has been carefully briefed by the lead technical construction professional (architect, engineer or quantity surveyor) as to the forms and locations of construction anticipated at the site.

This approach will be satisfactory where routine construction is being carried out in well-known and relatively uniform ground conditions. The desk study and walk-over survey (see Chapter 3) are intended to:

1. confirm the presence of the anticipated ground conditions, as a result of the examination of geological maps and previous ground investigation records;
2. establish that the variability of the sub-soil is likely to be small;
3. identify potential construction problems;
4. establish the geotechnical limit states (for example, slope instability, excessive foundation settlement) which must be designed for; and above all, to
5. investigate the likelihood of unexpected' hazards (for example, made ground, or contaminated land).

It is unlikely that detailed geotechnical design parameters will be required, since the performance of the proposed development can be judged on the basis of previous construction.

Approach 2: 'Standard' ground investigation

For most projects a more elaborate approach is needed, and will generally follow the following course.

1. A desk study and walk-over survey must first be carried out, to establish the likely conditions on and below the site, as described above (and see Chapter 3).
2. The details of the proposed construction must be ascertained, in as much as they have been decided. Particular care should be taken to establish the probable loading conditions and the sensitivity of any structures to be built, or those already existing on, around or below the site, to the changes that will occur as a result of construction. For example, services and tunnels passing below or alongside a proposed excavation for a basement may be damaged by the movements caused by excavation, and buildings above a proposed tunnel may be damaged by changes in the groundwater conditions and any ground loss caused by construction.
3. From the combinations of construction and ground conditions, the need for particular foundation types, for retaining walls, for cut slopes, and for special construction processes (such a grouting, dewatering and ground improvement) should be determined. These will bring with them particular limit states, and where limit states cannot be avoided (for example,

by changing the configuration of the proposed construction) there will be a need to carry out geotechnical analyses.

EXAMPLE: POTENTIAL LIMIT STATES

- Bearing capacity failure of foundations
- Differential settlement of foundations leading to structural damage
- Instability of clay slopes
- Sulphate attack on concrete
- Damage by mining subsidence
- Damage to surrounding structures as a result of excavating or dewatering an excavation
- Ground collapse over pre-existing natural solution features
- Collapse of excavations as a result of excessive water inflow.

The identification of potential limit states is a matter of experience, education and pessimism. 'Confidence may impress the Client, but it has little effect on the forces of nature' (Skempton 1948).

4. At this stage the geotechnical designer for the project will need to estimate (from experience, or from published values, in papers, or from previous investigations in the same strata) the likely values of parameters required for analyses of limit states, for the various types of ground expected to occur at the site. Some preliminary geotechnical design of the project is required, in order to recognize that only a few of the possible limit states are likely to have to be faced, and therefore that more detailed investigations will not be required for many parameters:
    - where possible, limit states should be avoided, by choosing an appropriate form of structure (for example, by piling through soft clays, rather than designing for bearing capacity failure of shallow foundations);
    - it will be recognized that certain limit states will not be a problem (e.g. the bearing capacity of shallow foundations on rock).

At this stage critical parameters, essential to the successful completion of the project, must be recognized.

EXAMPLE: PARAMETERS REQUIRED FOR THE DESIGN OF A FOUNDATION IN CLAY

- Bulk unit weight of clay
- Undrained strength of clay
- Compressibility of clay
- Variability of the above, both laterally and with depth
- Groundwater level
- Sulphate content of groundwater
- Acidity of groundwater.

5. From a knowledge of the probable ground conditions and the required parameters, the geotechnical specialist should now identify all possible ways of determining the required parameters. Many tests that might be used (see Chapters 8 and 9) will only work satisfactorily in limited ground conditions, so limiting the available choice.

In principle, the parameters may be obtained:

- based on published data from other sites;
- based on previous site investigation data;
- back-analysis of performance of nearby construction;

- back-analysis of observed performance during construction;
- laboratory testing on samples taken during ground investigation; and
- *in situ* testing during ground investigation.

In order to optimize the investigation, estimates of:

- relative accuracy;
- relative cost;
- availability, and
- relevance to the problem

should be assessed for each way of determining the parameters.

EXAMPLE: DETERMINATION OF THE COMPRESSIBILITY OF FRACTURED WEAK ROCK

SPT	Cheap, readily available, widely accepted, usable at any depth, inaccurate
Plate test	Expensive, readily available, accurate, widely accepted, difficult to use at depth
Surface-wave geophysics	Cheap, not readily available, relatively accurate, shallow only, not widely accepted
Back analysis	Virtually free, readily available, relatively accurate, any depth, may not be relevant if site conditions are unusual.

At the same time the degree of sophistication and the accuracy required for each type of geotechnical analysis should be determined.

For *ultimate limit states* (i.e. where collapse is involved) consider the cost of failure, in terms of:

- legal;
- political; and
- financial consequences.

For *serviceability limit states* (i.e. where collapse does not occur, but the use of the structure is impaired) consider:

- savings which might be made in construction costs if parameters were better known; and
- the reduction in risk that might be achieved by using better analytical methods, based upon sounder engineering, with more sophisticated parameters.

EXAMPLE: ESTIMATION OF GROUND MOVEMENTS AROUND DEEP EXCAVATIONS IN THE CITY OF LONDON

Despite the generally large cost of civil engineering construction it is common to base routine design on basic parameters obtained from the SPT (Chapter 9), and routine undrained triaxial and oedometer testing (Chapter 8), both of which generally give very conservative (i.e. over-safe) estimates of ground movements. It is relatively unusual to base design on back-analysed parameters, or on more sophisticated and well-instrumented laboratory stress-path testing, despite the proven ability of these forms of parameters, in conjunction with finite element analysis, to give good predictions of movements around large excavations in the London clay.

The cost of using higher quality ground investigation and analytical techniques is typically less than

0.1% of the total cost of land purchase, architectural and structural design, and construction. Therefore it is worth considering whether these techniques may be used to justify greater site usage, such as building more basements and/or building closer to neighbouring structures. As will be seen below, increasing expenditure on geotechnical engineering can also be used to reduce the complexity of the construction process, which will lead directly to reductions in construction cost.

6. The details of the ground investigation can now be decided. The investigation boreholes should be of sufficient depth and distribution to establish the position of interfaces between different types of soil (within the zone likely to affect the construction), and the *in situ* testing and soil sampling should be planned so that the soil can be grouped into different categories (for example, rock, clay, sand, organic material — see Chapter 2) as well as tested to provide the specific parameters necessary for design calculations. This facet of the planning and design of a ground investigation is considered later in this chapter.

Approach 3: Limited investigation, coupled with monitoring

In some projects, it may be possible to carry out redesign during construction, in order to reduce costs. Given the natural variability of the ground, geotechnical engineers routinely use 'moderately conservative' soil parameters in design calculations, and do not normally attempt genuine predictions of values such as settlement, ground movements adjacent to excavations, etc. The example below illustrates how the demolition and reconstruction process was modified during construction, on the basis of moderately conservative design using finite element and boundary element analysis, and observations of ground movements.

EXAMPLE: SITE INVESTIGATION AND REDESIGN DURING CONSTRUCTION, FOR A BUILDING OVER A TUNNEL IN CENTRAL LONDON

The development of Grand Buildings, in Trafalgar Square, London, required demolition and reconstruction techniques which could guarantee that damage to underlying Underground railway tunnels would be avoided (Clayton *et al*. 1991). The relative location of Grand Buildings, with respect to the underlying tunnels, can be seen in Fig. 1.1—the closest tunnels, approximately l0m in diameter, lie only 5m below the basement of the new building. It was thought that the effects of construction on the underlying tunnels would be acceptably small if ground movements at the tunnel level were less than 15 mm.

Initial designs were based upon limited and rather routine' ground investigation, involving just two boreholes. Strength and compressibility values were determined from standard triaxial and oedometer testing (see Chapter 8). These values were not, however, used in estimating ground movements around the structure, since it is known (Fig. 1.2) that in this part of the London clay deposit they very significantly underestimate the stiffness of the ground. Instead, the movements were calculated using finite element and boundary element computer methods, incorporating the ground stiffness values back analysed from observations of movements at the Hyde Park Cavalry Barracks, a site some distance away, but still in similar London clay.

Even using these, much higher, stiffness parameters the estimated ground movements were large. In order to limit the predicted tunnel movements a complex 20-stage sequence of demolition and construction was developed, which involved construction of foundations from within the existing building, in a number of small areas, with underpinning, and the intermixing of construction with demolition, the provision of some kentledge to limit the effects of unloading, and extensive temporary works to support the partly demolished building.

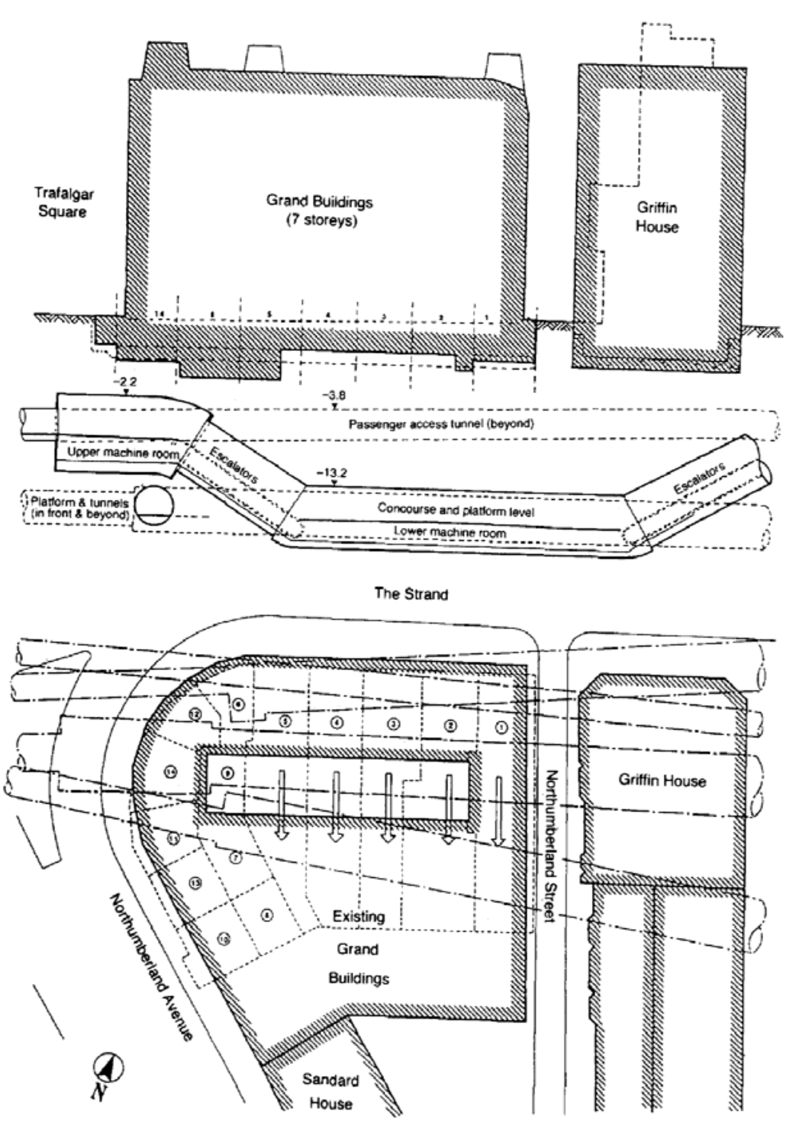

Fig. 1.1 Elevation showing a W—E section through Grand Buildings (above), and plan showing proposed demolition and raft construction sequence (below).

During planning of the construction process it soon became apparent that the proposed sequence of demolition and reconstruction would prove very complex and time consuming in execution, and that therefore economies of time and cost might be achieved through a redesign. In the absence of good-quality site-specific soil parameters for use in further analyses, an observational approach was developed. This was not the Observational Method *sensu stricto* (see below), but a strategy based firmly upon measurement of a critical parameter, vertical displacement, at the level of the most critical tunnel. The strategy involved:

1. assessment of the available information on the London clay, including experience gained by the design-and-build contractor in constructing the adjacent Griffin House;
2. adoption of moderately conservative soil stiffness parameters, and a conservative demolition and reconstruction scheme starting at the least-sensitive (Griffin House) end of the existing Grand Buildings;
3. boundary element analysis to predict the movements at various levels beneath the structure, and especially at the most critical tunnel location, and along the Passenger Access Tunnel which runs at the same level from the Upper Machine Room towards Griffin House;
4. incorporation in the plans of elements of work which could be abandoned if the predicted ground movements were proved to be pessimistic;

5. monitoring of movements within the Passenger Access Tunnel, especially during the early stages of demolition; and
6. re-assessment of ground stiffness parameters, and re-design of the demolition and reconstruction programme, as the demolition proceeded.

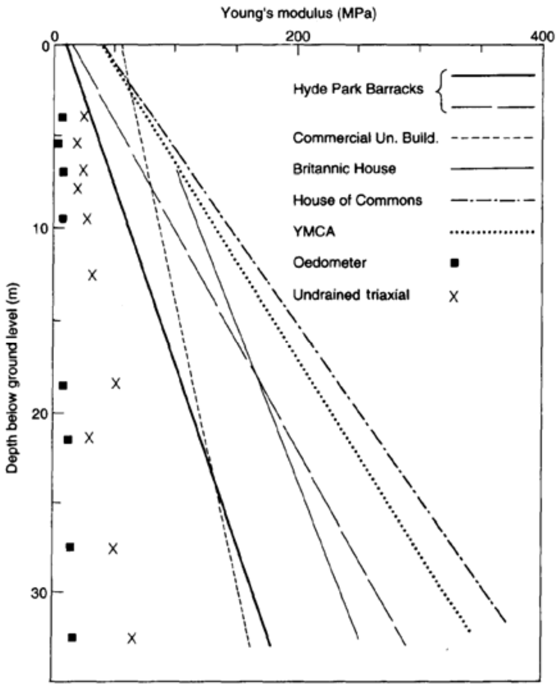

Fig. 1.2 Comparison of Young's modulus values for the London clay at Grand Buildings, obtained from routine undrained triaxial and oedometer testing, with values back analysed from observed movements around other excavations in the London area.

The resulting demolition areas (in numbered circles, according to sequence) are shown in Fig. 1.1. As a result of early measurements, during the demolition and excavation of strip 1, it became clear that the design analysis had significantly overestimated the heave. Therefore the planned 'back-load' kentledge was not used, except on strip 5 and immediately above the Upper Machine Room, and demolition was allowed to proceed simultaneously over the entire site. Monitoring continued throughout demolition and reconstruction. A maximum heave of the order of 4.3mm was measured, compared with values of the order of 10—15mm predicted by finite element and' boundary element analyses for the original design.

Approach 4: The observational method

This is a carefully considered approach to geotechnical design, developed by Peck (1969).

Peck (1969) ascribed Terzaghi's great success to his use of observation, coupled with his insistence on full, personal responsibility and authority on critical jobs. Clearly variations in financial constraints, the complexity of soil conditions, and time restrictions mean that very different approaches can be taken during site investigation. Peck argued that the methods available for coping with the inevitable uncertainties which arise as a result of the natural variability of soil and rock conditions broadly form three groups.

1. *Method 1*: Carry out limited investigation, and adopt an excessive factor of safety during design.
2. *Method 2*: Carry out limited investigation, and make design assumptions in accordance with general average experience.

3. *Method 3*: Carry out very detailed investigation.

In the first two methods only the vaguest approximations to the values of the physical properties of the sub-soil can be obtained. The variability of the soil properties, together with the degree of continuity of the individual layers of soil are almost certainly unknown, and groundwater conditions will not usually be adequately defined. Under these conditions it is almost certain that method 1 will be wasteful, while method 2 can frequently be dangerous. Only in the cases of investigations of major projects is there any likelihood that sufficient funds will be available for very detailed investigations, and in many cases the financial return will not merit this approach. Peck (1969) gives the ingredients of the ‘observational method’ as follows:

1. exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail;
2. assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role;
3. establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions;
4. selection of quantities to be observed as construction proceeds, and calculation of their anticipated values on the basis of the working hypothesis;
5. calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions;
6. selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis;
7. measurement of quantities to be observed and evaluation of actual conditions during construction; and
8. modification of the design to suit actual conditions.

A simple example of the observational method is given by Peck (1969). The pressures applied by soil to a strutted excavation are, to this day, a matter of considerable uncertainty. Conventional design methods assume worst conditions, as determined by various instrumented sections (for example, Peck (1943)). The Harris Trust building was to be constructed in Chicago, and the contractor had to design a bracing system (Fig. 1.3) for the excavation for foundations. He had at his disposal various measurements of strut loads on similar ground in Chicago and could therefore predict with some certainty the maximum strut loads that would occur.

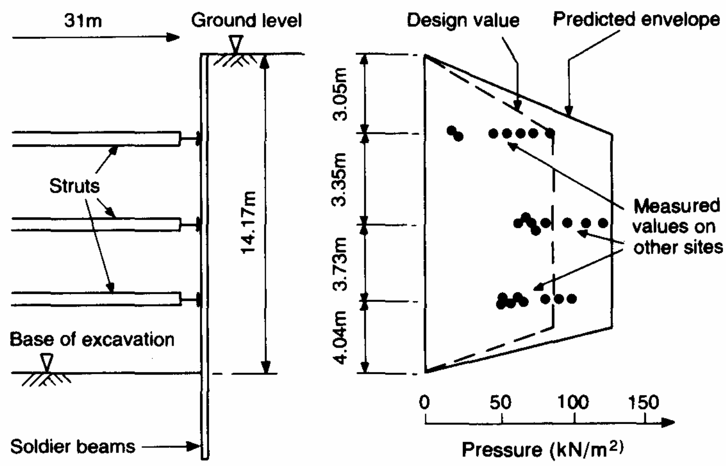

Fig. 1.3 The Harris Trust Excavation (Peck 1969).

The design of the struts could have been based on the trapezoidal diagram, providing a safe but uneconomical design since most of the struts would have carried much less load than their capability.

The contractor proposed to design the struts at a relatively low factor of safety, for loads of about two-thirds the envelope values, or about average measured load conditions. This achieved considerable economy. To guard against higher loads the contractor measured the axial load in every strut during construction, and had available extra struts for immediate insertion if necessary. Only three struts were required in addition to the thirty-nine originally designed for the whole project.

Not only did this approach produce a large saving in construction costs; it also, and perhaps more importantly gave the absolute certainty that no strut in the system was overloaded.

The observational method is now frequently claimed to be used, when in fact all the essential components described above have not been adhered to. In 1985 Peck noted that:

> the observational method, surely one of the most powerful weapons in our arsenal, is becoming discredited by misuse. Too often it is invoked by name but not by deed. Simply adopting a course of action and observing the consequences is not the observational method as it should be understood in applied soil mechanics. Among the essential but often overlooked elements are to make the most thorough subsurface explorations that are practicable, to establish the course of action on the basis of the most probable set of circumstances and to formulate, in advance, the actions that are to be taken if less favorable or even the most unfavorable conditions are actually encountered. These elements are often difficult to achieve, but the omission of any one of them reduces the observational method to an excuse for shoddy exploration or design, to dependence on good luck instead of good design. Unhappily, there are far too many instances in which poor design is disguised as the state of the art merely by characterizing it as an application of the observational method.

IMPLEMENTATION

It has already been noted that early site investigation in Britain was associated with work by the Building Research Station, and by contractors. During this period the response of contractors rather than consultants in setting up geotechnical organizations meant that by the late 1940s a high proportion of the experience, expertise and facilities available for site investigation was held by contracting firms. As a result, site investigation in the UK became a contractual operation. At the present time, much of the work of site investigation is carried out on the basis of a competitive tender.

At the present time then, most site investigation in Britain is commissioned by local authorities, government organizations or consulting engineers, on behalf of their clients. Typically the engineer produces conditions of contract, a specification, and a bill of quantities, and the tenderer receives a plan showing the proposed borehole locations. Provisional borehole depths and sampling routines are normally given, and the contractor will be told whether he is to provide a factual report, or whether both factual and interpretative reports on the project are required. Whether interpretation is required or not, it can be seen that the contractor is under great pressure to work quickly and efficiently, for the company will have quoted fixed prices for work to be carried out in uncertain ground and groundwater conditions.

It has been found that the best site investigations involve a considerable number of activities, some of which may become relatively unimportant in some cases, but should never be forgotten. An ideal order of events might be as shown in Table 1.1.

The sequence of geotechnical site investigation might be:

1. preliminary desk study, or fact-finding survey;

2. air photograph interpretation;
3. site walk-over survey;
4. preliminary subsurface exploration;
5. soil classification by description and simple testing;
6. detailed subsurface exploration and field testing;
7. the physical survey (laboratory testing);
8. evaluation of data;
9. geotechnical design;
10. field trials; and
11. liaison by geotechnical engineer with site staff during project construction.

Table 1.1 Order of events for site investigations

Project design team	Geotechnical designers	Geotechnical contractor
Definition of project	Geotechnical advice on likely design issues	
Site selection	Preliminary desk study to advise on relative geotechnical merits of different sites	
Conceptual design	Geotechnical advice on optimizing structural forms and construction methods, in order to reduce sensitivity of proposed construction to ground conditions	
	Detailed desk study and walk-over survey to produce a report giving: • expected ground conditions • recommended types of foundations • geotechnical design problems needing analysis	
	Ground investigation plan	
		Ground investigation: • profiling • classification • determination of parameters
Detailed structural / architectural design	Detailed geotechnical design	
Construction	Comparison of actual and anticipated ground conditions-assessment of new risks	Additional ground investigation
Performance	Geotechnical monitoring	Instrumentation

Unfortunately, in practice, British site investigation today more closely resembles the dream of engineers working on soil mechanics before World War I. According to Terzaghi (1936):

> engineers imagined that the future science of foundations would consist in carrying out the following program: Drill a hole into the ground. Send the soil samples obtained from the hole through a laboratory with standardized apparatus served by conscientious human automatons. Collect the figures, introduce them into equations, and compute the result.

After a period of optimism between the wars, the inevitable pressures of competitive tendering have reduced the average level of British site investigation to the state where reputable companies, with considerable geotechnical experience and expertise to offer, find financial survival difficult.

The financial pressures faced by British site investigation contractors are inevitable, whilst clients do not understand the value of good ground investigation, and prefer economy to sound engineering.

The major part of the college training of civil engineers consists in the absorption of the laws and rules which apply to relatively simple and well-defined materials, such as steel or concrete. This type of education breeds the illusion that everything connected with engineering should and can be computed on the basis of *a priori* assumptions (Terzaghi 1936).

PLANNING GROUND INVESTIGATIONS

The process of all site investigation should be, above all, one of scientific method. Sufficient factual information should be gathered (from the desk study and walk-over survey) to form hypotheses regarding the ground conditions, and from this and a reasonable knowledge of what is to be built on the site, the problems likely to be encountered both during the construction and the life of the development must be predicted. The design of the proposed construction should then, ideally, take into account the project's geotechnical setting, in order to avoid as many difficulties as possible, and minimize the remainder. Finally, ground investigation should be carried out in order, if necessary, to determine the actual ground conditions on the site, and where necessary to obtain parameters for engineering calculations.

Field investigation, whether by geophysics, or by boring or drilling, must have clearly identified aims if it is to be worthwhile. In some situations it may be necessary to make extensive and detailed ground investigations, but it is also perfectly conceivable that in other situations very few (if any) trial pits or boreholes or soil testing will be required before the start of construction. At present, ground investigation is poorly targeted, and it is because of this that it is sometimes regarded as a necessary but rather unrewarding expense. Yet it must be remembered that the majority of unforseen costs associated with construction are geotechnical in nature. Tyrell *et al.* (1983) carried out an appraisal of 10 UK highway construction projects where cost over-runs were substantial, averaging some 35% of the tender sum. They went through contract records to determine the cause of the additional costs, and found that approximately one-half of the increase in cost could be attributed to just two factors:

1. inadequate planning of ground investigation; and
2. inadequate interpretation of the results of ground investigations.

Because the planning of ground investigation is so important, it is essential that an experienced geotechnical specialist is consulted by the promoter of the project and his leading technical designer very early during conceptual design (see Procurement, below). The planning of a ground investigation is broken down into its component parts in Table 1.2. The geotechnical specialist may be an independent consultant, but more often in the UK will work for a specialist geotechnical consultancy practice, for a - general civil engineering consultancy, or for one of the larger specialist ground engineering contractors. In the UK, the British Geotechnical Society's 1992 *Geotechnical Directory of the United Kingdom* obtainable from the BGS at the Institution of Civil Engineers in London, gives a list of suitable individuals and the companies that employ them. The qualifications and experience required, before an individual may achieve an entry in the Directory, are shown in Table 1.3.

Table 1.2 Planning a ground investigation

Stage	Action	Carried out by
I	Obtain the services of an experienced geotechnical specialist	Developer/client
II	Carry out desk study and air photograph interpretation, to determine the probable ground conditions at the site	Geotechnical specialist
III	Conceptual design: optimize construction to minimize geotechnical risk	Architect, structural engineer, geotechnical specialist
IV	Identify parameters required for detailed geotechnical calculations	Geotechnical specialist
V	Plan ground investigation to determine ground conditions, and their variation, and to obtain geotechnical parameters	Geotechnical specialist
VI	Define methods of investigation and testing to be used	Geotechnical specialist
VII	Determine minimum acceptable standards for ground investigation work	Geotechnical specialist
VIII	Identify suitable methods of procurement professional	Geotechnical specialist, lead design, developer/client

The most important step in the entire process of site investigation is the appointment, at a very early stage in the planning of a construction project, of a geotechnical specialist. At present, much site investigation drilling and testing is carried out in a routine way, and in the absence of any significant plan. This can result in a significant waste of money, and time, since the work is carried out without reference to the special needs of the project.

Table 1.3 Requirements for organizations and individuals to appear in the British Geotechnical Society's Geotechnical Directory of the UK

Organizations	Individuals
For an organization to appear in the Directory it must be active in the UK offering services in geotechnical engineering (as opposed to manufacturing geotechnical equipment, for example). It must also employ at least one person whose name appears as an individual entry in the Directory. Organizations which belong to one of the Trade Associations featured in the Directory are identified in the lists by means of the Association's logo.	For an individual's name to appear in the Directory, he or she must be resident in the UK and be a member of the British Geotechnical Society, the Engineering Group of the Geological Society or a regional Geotechnical Society. He or she must also fulfil one of the three sets of criteria given below. Chartered Engineer through Corporate Membership of the Institution of Civil Engineers, the Institution of Structural Engineers, the Institution of Mining and Metallurgy or be a Chartered Geologist or a Corporate member of an equivalent overseas Institution and a minimum of five years' experience as a practising geotechnical specialist or: a professional qualification, as above and a further degree (a Master's degree or Doctorate) in a relevant subject area, for example soil mechanics, geotechnical engineering, foundation engineering or engineering geology and a minimum of three years' experience as a practising geotechnical specialist or: a minimum of twenty years' experience as a practising geotechnical specialist

Once a geotechnical specialist has been appointed, work can start on determining the ground conditions at the site. The first stages of this process are the desk study, air photograph interpretation, and a site walk-over survey (see Chapter 3). In geotechnical work, descriptions of soil and rock are made in accordance with very specific guidelines (Chapter 2), which have been devised to indicate their performance under engineering conditions, in terms of strength, compressibility and permeability. If previous site investigation reports exist for construction in the same soil, this allows the geotechnical engineer to judge (albeit in a general way) the likely performance of the ground under and around the proposed development. In any case, geological maps coupled with experience will give a considerable amount of information, of great value in the initial stages of design.

At this stage there should also be interaction between the client and all of his design professionals. Where possible, the design should be modified to reduce possible geotechnical problems. For example, if a large site is to be developed as a business park, the buildings might be re-aligned with their long sides parallel to the contours; this will reduce the amount of cut and fill, thus keeping the cost of foundations and retaining structures to a minimum, while also reducing the risks of slope instability. Structures may be relocated to avoid areas of potentially difficult ground, such as infilled quarries, pre-existing slope instability, or where old foundations or contaminated ground may exist below previously demolished structures. Appropriate foundation types and structural connexions can be chosen.

From a knowledge of the probable ground and groundwater conditions, and the required structural form(s), the geotechnical engineer should predict the types of foundations and earth-retaining structures required on the project, and any possible problems (such as slope instability, chemical attack on foundation concrete, construction difficulties) which can be foreseen, and which may therefore require further investigation. The planning of a ground investigation requires a knowledge both of the ground conditions at and around the site, and of the form of the proposed construction. If the design of the construction is to be optimized, then the form of construction should, as far as possible, take the expected ground conditions into account.

At the end of the desk study, air photo interpretation and walk-over survey, the geotechnical specialist should make a written report, giving he expected ground conditions across and around the site, the uncertainties in these predictions, and the extent of ground investigation proposed for their investigation. In addition, he or she should make proposals for suitable types of foundations for any proposed structures, and should identify areas where other geotechnical structures (such as retaining walls or slopes) will be expected. For these areas there will be a need to obtain geotechnical parameters for design. Other potential problems requiring investigation should also be identified. The parameters to be obtained during ground investigation, and the methods to be used to obtain those parameters, should be described, and justified, in detail.

Planning trial pitting, boring and drilling

Drilling and trial pitting are normally carried out for a number of reasons, such as:

1. to establish the general nature of the strata below a site;
2. to establish the vertical or lateral variability of soil conditions;
3. to verify the interpretation of geophysical surveys;
4. to obtain samples for laboratory testing;
5. to allow *in situ* tests to be carried out; and
6. to install instruments such as piezometers, or extensometers.

Frequently, most if not all of these objectives will control the method of drilling on site. All the objectives must be achieved with the minimum of expense and disruption to occupiers of the site.

In the UK, drilling, sampling and testing are normally carried out by a specialist site investigation contractor. The most convenient method of organizing the work is for the engineer controlling the contract to decide on the position and depth of boreholes, the sampling routine for each soil type that is likely to be found, and the number and type of *in situ* and laboratory tests that are required. A number of contractors can then provide competitive bids, the cheapest price can be selected, and the work carried out.

The scheme described in the preceding paragraph is ideal from the contractual viewpoint, because it allows a fixed price to be obtained by competitive tender. As a method of achieving the aims of site investigation, it is rarely satisfactory, however, because soil conditions are not very well known at tender stage and because competitive tendering favours contractors who have the lowest overheads and are therefore less likely to be able to bring a high level of engineering expertise to bear on the work. When specifying and controlling drilling, it is important that the drilling and testing programme can be modified while work is in progress, as new information is made available by each borehole or test pit. Therefore both office and site staff should be aware of the reasons for the decisions made during the initial planning of the work, in order that they do not hesitate to alter drilling and testing schedules where this is appropriate.

The principal factors which allow a logical drilling programme to be planned and successfully executed are:

1. a relationship between structure, borehole layout, frequency and depth;
2. a need for sample quality and quantity related to the required geotechnical parameters and the soil type and variability;
3. site supervision, to ensure that drilling and sampling are carried out to a high standard and that good records are kept; and
4. prompt sample description and preparation of borehole and pit records in order that the drilling programme can be modified as the work proceeds.

These factors are considered in turn below.

Borehole layout and frequency

Borehole layout and frequency are partly controlled by the complexity of the geological conditions. The complexity of geological structure and the variability of each of the soil or rock units should be at least partially known after the fact-finding or desk study. If soil conditions are relatively uniform, or the geological data are limited, the following paragraphs will give an initial guide. Borehole layout and frequency may need to be changed as more information emerges.

Investigation will normally be carried out by machine or hand-excavated trial pits, where only shallow depths are to be investigated, for example for low-rise housing projects, or for shallow instability problems. The use of pits in these situations allows a detailed engineering description of soil conditions, and will also permit block samples to be taken. Most boreholes will be considerably deeper than can be excavated by an open trial pit, and these will normally be carried out by light percussion or hollow stem auger drilling.

Most projects will fall into one of the following categories:

a) *isolated small structures*, such as pylons, radio masts, or small houses, where one borehole may be sufficient;
b) *compact projects*, such as buildings, dams, bridges or small landslips, will require at least four boreholes. These will normally be deep and relatively closely spaced;
c) *extended projects*, such as motorways, railways, reservoirs and land reclamation schemes will require shallower, more widely spaced boreholes, but these will normally be expected to verify the depth of ‘good’ ground. In the case of road projects this will mean either rockhead, or a soil with a ‘stiff’ consistency. In the case of reservoirs, borings should be continued until an adequate thickness of impermeable ground is found. The frequency of borings on extended sites must be judged on the basis of the uniformity or otherwise of the site geology and its expected soil variability. On a highway project the recommendations for borehole spacing

vary from 30 to 60 m (Hvorslev 1949) to 160 m in changeable soils and 300m in uniform soils (*Road Research Laboratory* 1954).

Many projects, such as highways, are a combination of the categories described above. Structures on extended projects should be treated as compact projects. For example, a typical investigation for a motorway in the UK might use 5—l0m deep borings every 150m along the proposed road line, with four 25—30m deep borings at the proposed position of each bridge structure. Additional boreholes might be placed on the basis of soil information found during the fact-finding survey, on the basis of:

1. the geological succession in the area. Thin beds of limited outcrop may require closer boreholes;
2. the presence of drift deposits such as alluvium or glacial till, whose vertical and lateral extent may require close inspection;
3. problem areas, for example where pre-existing slope instability is suspected.

The layout of the borings should aim not only to provide soil profiles and samples at positions related to the proposed structures and their foundations, but should also be arranged to allow the hypotheses formed during the fact-finding survey to be checked. The borings should be positioned to check the geological succession and to define the extent of the various materials on site, and they should be aligned, wherever possible, in order to allow cross-sections to be drawn (Fig. 1.4). Where structures are to be found on slopes, the overall stability of the structure and the slope must obviously be investigated, and to this end a deep borehole near the top of the slope can be very useful.

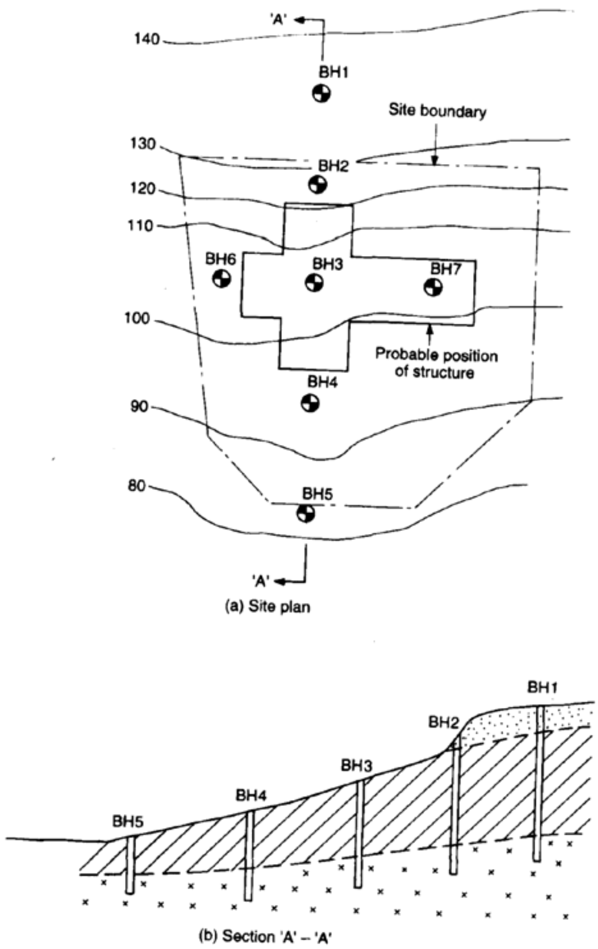

Fig. 1.4 Alignment of boreholes.

Depth of borings

It is good practice on any site to sink at least one deep borehole to establish the solid geology. On extended projects several of these may be necessary, partly in order to establish the depth of weathering, which may be up to 100 m below ground level and may be irregular, and also to establish the depth to which cavernous or mined areas descend.

Hvorslev (1949) suggested a number of general rules which remain applicable:

> The borings should be extended to strata of adequate bearing capacity and should penetrate all deposits which are unsuitable for foundation purposes — such as unconsolidated fill, peat, organic silt and very soft and compressible clay. The soft strata should be penetrated even when they are covered with a surface layer of high bearing capacity.
>
> When structures are to be founded on clay and other materials with adequate strength to support the structure but subject to consolidation by an increase in the load, the borings should penetrate the compressible strata or be extended to such a depth that the stress increase for still deeper strata is reduced to values so small that the corresponding consolidation of these strata will not materially influence the settlement of the proposed structure.
>
> Except in the case of very heavy loads or when seepage or other considerations are governing, the borings may be stopped when rock is encountered or after a short penetration into strata of exceptional bearing capacity and stiffness, provided it is known from explorations in the vicinity or the general stratigraphy of the area that these strata have adequate thickness or are underlain by still stronger formations. When these conditions are not fulfilled, some of the borings must be extended until it has been established that the strong strata have adequate thickness irrespective of the character of the underlying material.
>
> When the structure is to be founded on rock, it must be verified that bedrock and not boulders have been encountered, and it is advisable to extend one or more borings from 10 to 20 ft into solid rock in order to determine the extent and character of the weathered zone of the rock.
>
> In regions where rock or strata of exceptional bearing capacity are found at relatively shallow depths — say from 100 to 150 ft — it is advisable to extend at least one of the borings to such strata, even when other considerations may indicate that a smaller depth would be sufficient. The additional information thereby obtained is valuable insurance against unexpected developments and against overlooking foundation methods and types which may be more economical than those first considered.
>
> The depth requirements should be reconsidered, when results of the first borings are available, and it is often possible to reduce the depth of subsequent borings or to confine detailed and special explorations to particular strata.

As a rough guide to the necessary depths, as determined from considerations of stress distribution or seepage, the following depths may be used.

1. *Reservoirs*. Explore soil to: (i) the depth of the base of the impermeable stratum, or (ii) not less than 2 x maximum hydraulic head expected.
2. *Foundations*. Explore soil to the depth to which it will be significantly stressed. This is often taken as the depth at which the vertical total stress increase due to the foundation is equal to 10% of the stress applied at foundation level (Fig. 1.5).
3. For *roads*. Ground exploration need generally only proceed to 2—4 m below the finished road level, provided the vertical alignment is fixed. In practice some realignment often occurs in cuttings, and side drains may be dug up to 6 m deep. If site investigation is to allow flexibility in design, it is good practice to bore to at least 5 m below ground level where the finished road level is near existing ground level, 5 m below finished road level in cut, or at least one-and-a-half times the embankment height in fill areas.
4. For *dams*. For earth structures, Hvorslev (1949) recommends a depth equal to one-half of the base width of the dam. For concrete structures the depth Of exploration should be between one-and-a-half and two times the height of the dam. Because the critical factor is safety against seepage and foundation failure, boreholes should penetrate not only soft or unstable materials, but also permeable materials to such a depth that seepage patterns can be predicted.

5. For *retaining walls*. It has been suggested by Hvorslev that the preliminary depth of exploration should be three-quarters to one-and-a-half times the wall height below the bottom of the wall or its supporting piles. Because it is rare that more than one survey will be carried out for a small structure, it will generally be better to err on the safe side and bore to at least two times the probable wall height below the base of the wall.
6. For *embankments*. The depth of exploration should be at least equal to the height of the embankment and should ideally penetrate all soft soils if stability is to be investigated. If settlements are critical then soil may be significantly stressed to depths below the bottom of the embankment equal to the embankment width.

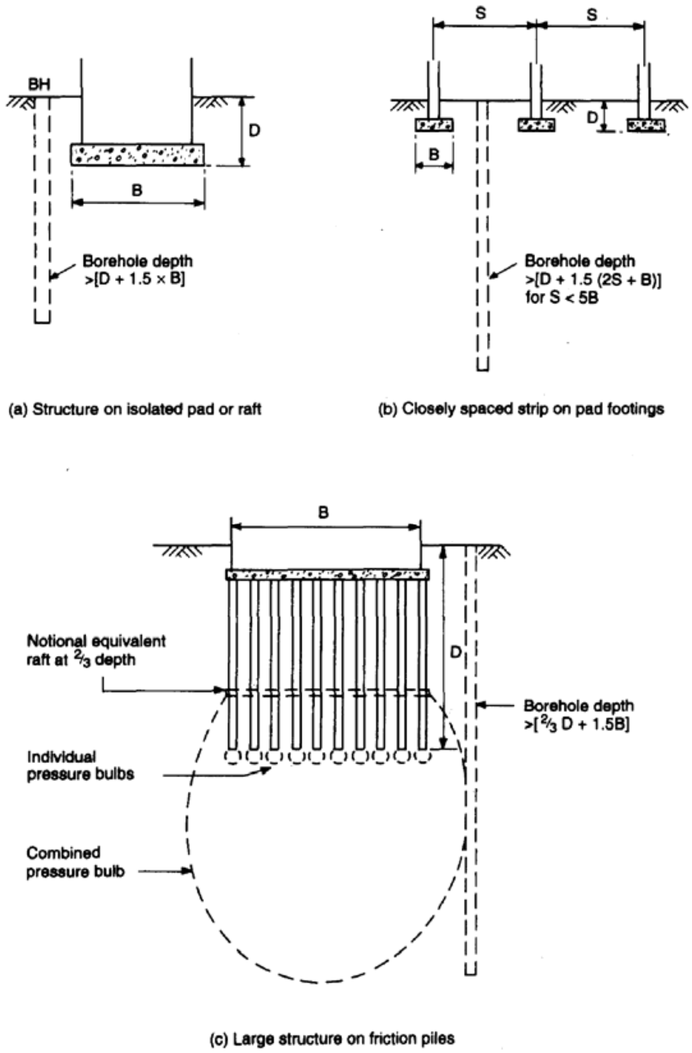

Fig. 1.5 Necessary borehole depths for foundations.

Because many investigations are carried out to determine the type of foundations that must be used, all borings should be carried to a suitable bearing strata, and a reasonable proportion of the holes should be planned on the assumption that piling will have to be used.

Sampling, laboratory testing and in situ testing requirements

As will be seen in the Chapters 6, 7 and 9, which deal with sampling disturbance, sampling techniques, and *in situ* testing, most available sampling and *in situ* testing techniques are imperfect, and often represent a compromise. The normal sampling and *in situ* testing routines in use in the UK, represent the results of just such a compromise. They result from the fact that stiff clays, stoney glacial tills and gravelly alluvium are so often found in the UK, and that prices for ground investigation are relatively low. In routine ground investigations samples are taken or *in situ* tests made only every 1.5 m down boreholes, and only about 25% of the soil at every borehole location is sampled, however imperfectly. Even in the most intensely investigated site, it is unlikely that more than one part in 1000000 of the volume of ground affected by construction will be sampled.

The sampling routine should be aimed at:

1. providing sufficient samples to classify the soil into broad soil groups, on the basis of particle size and compressibility;
2. assessing the variability of the soil;
3. providing soil specimens of suitable quality for strength and compressibility testing; and
4. providing specimens of soil and groundwater for chemical testing.

Soil and rock are not normally found in pockets, each of a distinct type, but often grades gradually from one soil type (for example, sand) to another (for example, clay). It is therefore necessary artificially to divide the available soil and rock samples into groups, each of which is expected to have similar engineering behaviour. Engineering soil and rock description (Chapter 2), and index tests and classification tests are used for this purpose (Chapter 8).

Geotechnical parameters are obtained by testing specimens which have been selected to be representative of each of the soil groups defined by soil description, and classification and index testing. Where soil grouping cannot be carried out, perhaps because of time or financial constraints, it is often found to be necessary to carry out much larger numbers of the more time-consuming and sophisticated tests required for determining geotechnical design parameters. Therefore this is a false economy.

Thus, if 450 mm long samples are to be taken every 1.0 to 1.5 m down the borehole in cohesive soils, every test specimen should be subjected to determinations of water content and plasticity. Where an undrained shear strength profile is required, tests should be made on every specimen of the appropriate diameter in the depth range required for the profile. For proposed spread foundations, embarkments and temporary works cuttings, these depths should not be less than the height of the cut or fill, or the width of the foundation. If soil conditions are unfavourable, piles may be required; in anticipation of this, shear strengths should then be determined to much greater depths.

Large numbers of undrained triaxial strength tests are required in order to establish a shear strength — depth profile in firm to hard clays, because of the scatter in their results which is induced by fissuring. In the past, it has often been assumed that much smaller numbers of effective strength test results will be needed, because fissuring effects are less important. It now appears that this is not the case. Fissures appear to have little effect on small-strain stiffness, but unfortunately give rise to a large scatter in effective strength parameters (c’ and p’) even when 100mm diameter specimens are used. Current UK practice tends to underestimate the need for a sufficient number of effective stress tests; when long-term slope or retaining wall stability problems must be analysed, at least five sets of tests, each with three specimens, should be made on each soil type. Compressibility tests, normally by oedometer compression, will be required from every specimen within the probable depths of soil to be significantly stressed. Clearly, soil is normally variable, and when a two-stage investigation (a variation survey followed by detailed exploration) is not carried out, the only logical course is to test more extensively those specimens that are obtained.

In the UK *in situ* testing is carried out when:

1. good quality sampling is impossible (for example, in granular soils, in fractured rock masses, in very soft or sensitive clays, or in stoney soils);
2. the parameter required cannot be obtained from laboratory tests (for example, *in situ* horizontal stress);

3. when *in situ* tests are cheap and quick, relative to the process of sampling and laboratory testing (for example, the use of the SPT in London clay, to determine undrained shear strength); and most importantly,
4. for profiling and classification of soils (for example, with the cone test, or with dynamic penetration tests).

The most commonly used test is the Standard Penetration Test (SF1') (Chapter 9), which is routinely used at 1.5 m intervals within boreholes in granular soils, stoney soils, and weak rock. Other common *in situ* tests include the field vane (used only in soft and very soft cohesive soils), the plate test (used in granular soils and fractured weak rocks), and permeability tests (used in most ground, to determine the coefficient of permeability).

Marsland (1986) has stated that:

> the choice of test methods and procedures is one of the most important decisions to be made during the planning and progress of a site investigation. Even the most carefully executed tests are of little value if they are not appropriate. In assessing the suitability of a particular test it is necessary to balance the design requirements, the combined accuracy of the test and associated correlations, and possible differences between test and full-scale behaviour.

The primary decision will be whether to test in the laboratory or *in situ*. Table 1.4 gives the relative merits of these options.

Table 1.4 Relative merits of *in situ* and laboratory testing

In situ testing	Laboratory testing
Advantages	
Test results can be obtained during the course of the investigation, much earlier than laboratory test results	Tests are carried out in a well-regulated environment.
Appropriate methods may be able to test large volumes of ground, ensuring that the effects of large particle sizes and discontinuities are fully represented.	Stress and strain levels are controlled, as are drainage boundaries and strain rates.
Estimates of *in situ* horizontal stress can be obtained.	Effective strength testing is straightforward.
	The effect of stress path and history can be examined.
	Drained bulk modulus can be determined.
Disadvantages	
Drainage boundaries are not controlled, so that it cannot definitely be known whether loading tests are fully undrained.	Testing cannot be used whenever samples of sufficient quality and size are unobtainable, for example, in granular soils, fractured weak rock, stoney clays.
Stress paths and/or strain levels are often poorly controlled.	Test results are only available some time after the completion of fieldwork.
Tests to determine effective stress strength parameters cannot be made, because of the expense and inconvenience of a long test period.	
Pore pressures cannot be measured in the tested volume, so that effective stresses are unknown.	

The ground investigation planner requires a detailed and up-to-date knowledge of both laboratory and *in situ* testing, if the best choices are to be made. Table 1.5 gives a summary of the current situation in the UK — but this will rapidly become out of date. Whatever is used depends upon the soil and rock encountered, upon the need (profiling, classification, parameter determination), and upon the sophistication of geotechnical design that is anticipated.

Table 1.5 Common uses of *in situ* and laboratory tests

Purpose		Suitable laboratory test	Suitable *in situ* test
Profiling		Moisture content Particle size distribution Plasticity (Atterberg limits) Undrained strength	Cone test Dynamic penetration test Geophysical down-hole logging
Classification		Particle size distribution Plasticity (Atterberg limits)	Cone
Parameter determination:			
	Undrained strength, cu	Undrained triaxial	SPT Cone Vane
	Peak effective strength, c' φ'	Effective strength triaxial	
	Residual strength, c_r' φ_r'	Shear box Ring shear	
	Compressibility	Oedometer Triaxial, with small strain measurement Triaxial consolidation	Self-boring pressuremeter Plate test
	Permeability	Triaxial permeability	*In situ* permeability tests
	Chemical characteristics	pH Sulphate content	Geophysical resistivity

Geophysics

Geophysical methods (Chapter 4) may be used for:

1. geological investigation, for example in determining the thickness of soft, superficial deposits, and the depth to rock, and in establishing weathering profiles, usually to provide cross-sections;
2. resource assessment, for example the location of aquifers, the delineation of saline intrusion, the exploration of the extent of sand and gravel deposits, and rock for aggregate;
3. detecting critical buried features, such as voids (mineshafts, natural cavities, adits, pipelines) and buried artefacts (old foundations, wrecks at sea, etc.); and
4. determining engineering parameters, such as dynamic elastic moduli, and soil corrosivity.

In some instances (for example, the determination of small-strain stiffness) they may be used in the same way as other *in situ* tests, but generally they are used as a supplement to direct methods of investigation, carried out by boreholes and trial pitting.

The planning of geophysical surveys has been described in detail by Darrocott and McCann (1986). They note that clients have often voiced their disappointment with the results of geophysical site investigation, and note that in their experience the failure of the techniques can usually be attributed to one or more of the following problems:

1. inadequate or bad planning of the survey;
2. incorrect choice or specification of the technique;

3. the use of insufficiently experienced personnel to conduct the survey.

Geophysical surveys should be planned as an integral part of the site investigation. The desk-study information must be available so that the most effective techniques are used, and (as with direct methods of investigation, such as boring and trial pitting) the 'targets' of each part of a geophysical survey must be clearly understood. Table 1.6 shows how a geophysical survey should be planned. This is discussed in more detail in Chapter 4.

Table 1.6 Stages of a geophysical survey as part of a ground investigation

Stage	Action	Details
I	Preliminary meeting between geophysicist and geotechnical specialist	Determine: (a) the precise result(s) expected (the 'targets'); (b) whether geophysical methods can be expected to achieve (a); (c) which technique(s) are likely to be successful; (d) consider cost-effectiveness of geophysics relative to other techniques.
II	Carry out desk study	Determine: (a) ground conditions; (b) groundwater conditions; (c) sources of background interference.
III	Plan geophysical survey	Determine: (a) which techniques are likely to be successful, given the ground conditions, the targets',and the background interference; (b) probability of success with each technique; (c) cost-effectiveness of geophysics relative to other techniques; (d) if geophysics appears possible, chose equipment and plan layout for chosen techniques, and identify suitable personnel.
IV	Carry out geophysical trials	This will only be possible in unusual circumstances.
V	Main geophysical survey	
VI	On-site interpretation	The plan for the geophysical survey (for example, the layout of instruments) may need revision in the light of early data, to improve results
VII	Correlation boreholes	The borehole programme should include holes to allow checking and 'calibration' of the geophysics. If possible these data should be made available to the geophysical survey team during their field work.
VIII	Final interpretation	Final interpretation should be made jointly by experienced geophysicists and geotechnical engineers, drawing together all the data, including that from direct investigation methods.
IX	Reporting	Reporting should include raw data, in electronic form, as well as filtered, processed and interpreted results.
X	Feedback	The success of the work, as found during construction, should be conveyed to the geophysical team.

Specification

As noted in Table 1.2, it is necessary to define, in one way or another, the minimum standards of the work to be carried out during the ground investigation. This is particularly important for all elements of work that are to be procured on the basis of competitive tender, since the specification document is central to the prices offered by contractors when bidding. The principal features of the specification contract documents in common use in the UK are given below.

1. *Entry, access and reinstatement*. Whilst the engineer is responsible for arranging access, the contractor must give sufficient notice of entry. Only agreed access routes to the site of the boreholes can be used, and avoidable damage must be made good by the contractor at his own expense. The contractor must include in his rates for stripping topsoil in the area of the borehole, and for making good damage in the area of the borehole and along the access route. Unavoidable damage to crops and hedges or fences is normally paid for by the client.

2. *Services*. Services are to be located by hand digging a pit 1.5 m deep, where it is thought that service pipes, cables or ducts may be present in the area of a borehole.
   Precautions should be taken to protect field personnel from safety hazards, such as underground electrical cables and gas pipes. Engineers involved in ground investigation should recognize that they are responsible for the safety of those working for them. Public utility companies (gas, electricity, telephone, water, etc.) must be contacted to ensure that, as far as possible, risks to health and safety are properly identified before drilling is started.

3. *Trial pits*. The contractor should excavate trial pits by hand or machine in order that soil can be examined *in situ* and samples taken. The plan area of any such excavation should not normally be less than 2m2. Pits should be kept free from water, where encountered, by pumping. The contractor should supply, fix and remove, on completion, sufficient support to the side of the pits to protect anyone entering the hole. Topsoil should be stripped from the pit area before the start of work and should be stockpiled separately until completion. At the end of work, the pit should be filled with compacted spoil, any surplus being heaped proud over the site and covered with the topsoil. Where pits must be left open overnight the contractor must provide temporary fencing around the excavation.

4. *Boring and drilling*. For light percussion boring the minimum borehole diameter is normally 150 mm, but the contractor is responsible for starting the hole at a sufficiently large size to allow him to complete the hole to the required depth. If he fails to do this, the contractor is responsible for reboring the hole at his own expense.
   Claycutters should not be used in soft alluvial soils, where they may cause significant disturbance ahead of the hole.
   In some specifications the weight of the claycutter (see Chapter 6) has been limited as shown in Table 1.7.
   Shells used for boring in granular soils must not be tight fitting if this causes the soil to blow into the base of the hole. Under these conditions the borehole must be kept full of water at all times, and the shell should have a diameter not more than 90% of that of the inside of the borehole casing.

Table 1.7 Specifications for claycutter

Diameter of boring (mm)	Maximum weight of claycutter and sinker bar (kg)
150	150
200	180

In a document produced by the Association of Ground Investigation Specialists in 1979, it was specified that a shell diameter at least 25mm less than that of the casing should be used (AGIS 1979), and in the current British Standard for the SPT it is a requirement that the outside diameter of the drilling tools should not exceed 90% of the inside diameter of the casing.

The addition of water to borings is variously specified, with some documents preventing the addition of water except in 'dry granular soils and stiff clays'. In one document the limit for addition of water to clays is fixed by testing the 'immediate undrained cohesive strength' with a 'small field penetrometer'. Water can only be added to the borehole if the strength exceeds 140 kN/m2. Ideally, water should not be added to boreholes when drilling in clays above groundwater level, whatever their consistency. Once the groundwater table is reached, then rapid drilling in stiff fatty clays may not allow time for swelling to take place. If this action is adopted, the first 1.0 m of the day's drilling should not be sampled as it will have had time to swell as a result of stress relief. In all soils below the water table, the borehole should be kept full of water or drilling mud in order to reduce the effects of stress relief. In very soft or soft soils, this is also necessary to prevent failure of the soil up into the cased borehole. When casing is used, it should never be advanced ahead of the borehole. The bottom of the casing should preferably be kept within 150mm of the bottom of the hole at all times in order to prevent excess loosening of surrounding soil, or the formation of voids.

In soft ground, both light percussion boring and auger boring are normally acceptable in the UK. Washboring or jetting is not permitted.

Rotary core drilling may be carried out by open-holing through soft materials, or by drilling ahead of a soft ground boring which has already been made. Clauses are normally included to point out that the material to be cored may be friable or soft, or may contain mixtures of hard rock with interlayered soft materials. The contractor is normally responsible for selecting equipment which will satisfy the other requirements of the specification (for example, recovery, diameter, etc.). Some specifications require the use of hydraulic feed rigs, which are in almost exclusive use in the UK. The introduction of top drive rigs, however, has the advantage that larger runs can be made without rechucking.

The Bill of Quantities is often arranged so that rotary core payment can be made for open-holing and for the recovery of core. In this case it seems sensible to specify that the contractor shall use the necessary equipment, feed pressures and rates, and run lengths so that 100% recovery in any run can be achieved. Where less than 80% recovery is obtained, payment should be at the rate for open-holing for that run length.

Drilling equipment should in general conform to BS 4019, although sampler barrels other than the double-tube ball-bearing swivel type with knock-on spring core catcher box and face discharge bit should not be discouraged since these may give good results. The minimum core diameter and the depth to which it is to be used should be specified, since the cost of deep larger diameter holes will increase significantly when small highly mobile rigs are in general use. The minimum size in sound rock should be N (or 76mm metric), with H (or 101 mm) used in soft or highly weathered rocks, and P (or 116 mm) used in drift such as stiff clays and glacial till.

The maximum run length should be 3m, but where recovery is reduced to less than 80% the length of the next run is often specified as 1 m. If blocking of the flush ports or loss of flush return is detected at any stage, the barrel and core must be removed from the hole immediately. Clear water is the normally specified flush-fluid in the UK, with bentonite mud sometimes being specified in glacial drift and compressed air being used in soft rocks where water flush causes serious deterioration of the core.

There has been a trend in the UK, in recent years, towards the use of rotary coring to obtain samples of heavily overconsolidated clays, and for this purpose bentonite or polymer muds are sometimes specified.

All boreholes and drillholes should be backfilled and compacted in such a way that subsequent settlement of the backfill is avoided. Under artesian groundwater conditions, special sealing devices may be required.

5. *Sampling*. The contractor is commonly required to take disturbed samples, open-drive samples, piston-drive samples and rotary core from boreholes and drillholes. All samples from

soft ground borings or trial pit excavations should be clearly labelled with the following information:

(i) contract name and reference number;
(ii) reference number of hole;
(iii) reference number of sample;
(iv) date of sampling;
(v) depth of top and bottom of sample below ground level; and
(vi) top (if undisturbed).

In addition to labelling the outside of the sample tube, a similar label, but additionally marked 'top' should be placed inside the top of the tube. All labelling should be protected from the effects of damp and water.

Small disturbed samples are normally specified at the top of each stratum, from between undisturbed samples in fine-grained soils, and from the cutting shoes of all thick-walled open-drive samplers. They should contain not less than 1kg of soil which should, as far as possible, fill an airtight container. Large disturbed samples are normally taken from the test section of borehole used for the SPT (cone) test in gravels and other materials containing coarse particles. Their minimum weight should be 25 kg, although larger samples may be required for specific testing requirements.

Thick-walled open-drive 'undisturbed' samples are standard in firm to very stiff clays in the UK. Most specifications make reference to the British Standard for Site Investigation, and in addition some specify minimum sample tube length (450mm), maximum area ratio (about 25%), inside diameter (100mm) and cutting edge taper ($\ngtr 20°$). The cutting edge should be sharp and free from burrs. The sample tube and cutting shoe should be free from rust, pitting or burring. The use of oil on the inside of the tube should be limited to the minimum practicable.

Thick-walled open-drive sample tubes should either be jacked into the ground or driven from ground level using a standard penetration test automatic trip hammer. Before lowering the sampler tube down the hole, the bottom of the boring should be cleaned of loose materials. Under extreme circumstances, the use of hand-rotated augering is specified for the 600mm of boring above the sample depth. In order to improve recovery, specifications sometimes require either sampler rotation (if practicable) or a waiting period in order to increase adhesion between the soil and the inside of the sampler tube. Thick-walled open-drive samplers must have a ball valve fitted in the sampler head to prevent the build up of pressure over the sample during the sample drive. This should be kept clean at all times. Flap-type core catchers inserted between the cutting shoe and sample tube are normally only permitted when all else fails. Over-driving should normally be avoided.

The undisturbed sample should be pulled slowly from the soil and brought to the top of the hole. After removing the cutting shoe and the head, disturbed material from the top of the sample should be removed and sufficient soil taken from the base of the tube to allow a 10mm thick wax seal to be placed. The sample should immediately be sealed with at least three brush-coated layers of low melting point microcystalline wax. Following this, an oversize metal foil disc is sometimes specified, which is then covered with further wax. The ends of the tubes should be filled with a damp packing material (sawdust, newspaper or rags), and metal or plastic caps applied. The sample tube should be labelled immediately. In the UK, thick-walled open-drive samples are normally specified at a minimum of one every 1.0m for the first 5 m of drilling, and 1.5 m thereafter.

Piston-drive sampling is normally only vaguely specified, usually for very soft or sensitive soils: 'Equipment shall be of a pattern approved by the Engineer'. If piston samples are required then the equipment should be of the fixed piston type, and samples should be taken continuously or at 1 m intervals. Clearly, much more stringent specifications are required for sampling sensitive soils, and therefore the following points should be included.

Piston samples should be of the fixed piston type, with an area ratio compatible with their cutting edge angle (see the ISSMFE recommendations (1965) in Chapter 6). The maximum cutting edge angle should be 7°. In alluvial soils the minimum diameter should be 100mm, with a minimum length of 450 mm. The maximum inside clearance should be 0.75—1 .00%, although in very soft and sensitive soils there will be no necessity to include any inside clearance. Where possible, piston samplers should be of a design using short sectional liners made of an inert substance such as plastic or impregnated paper. They may be pushed to the desired sample depth or used from the base of a borehole. During the sample drive the inner (piston) rod must be securely fastened at ground surface so that no downward movement is possible. After sampling, the sampler should be rotated before being carefully brought to the surface. The liners should be removed, immediately labelled, and sealed with wax and push-on caps.

When undisturbed sampling is attempted but no recovery results, the borehole should be cleaned out to the full depth to which the sampler has penetrated, and a fresh attempt to sample should be made immediately. The disturbed soil removed from the borehole should be saved as a large disturbed sample. In some specifications reduced payment is made to the contractor for undisturbed sampling attempts which give samples of less than 100mm length, or if the sample is of no use, provided the contractor is not at fault. When full recovery is not achieved the actual sample length and reason for partial recovery must be recorded.

Rotary core should not be removed from the core-barrel by suspending it from a winch rope and hammering the inner barrel. Corebarrels should be held horizontally whilst cores are extruded using a coreplug by applying a constant pressure, and the cores should leave the barrel and travel on a transparent polythene sheet placed on a rigid plastic receiving channel of approximately the same diameter as the core. After extrusion the core should be sealed in the plastic sheet with waterproof adhesive tape, and bound to the rigid plastic receiving channel. It should then be placed in a corebox such as shown in Fig. 1.6. Wooden spacer blocks should indicate the top and bottom levels of each run.

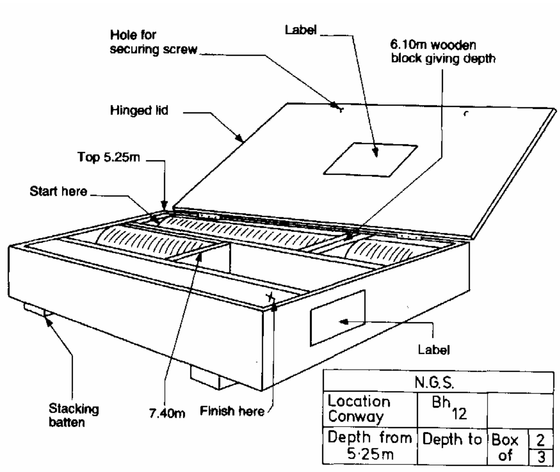

Fig. 1.6 General layout for a corebox (from Redford 1981).

Alternatively, a clear rigid plastic liner (in the UK, sometimes sold under the brand name ‘Coreline’) may be used as a third liner within the corebarrel. This reduces frictional forces between the inner barrel and the core, and in addition allows the core to be withdrawn from the inner barrel whilst it is held in the horizontal position. When a clear rigid plastic liner is used, end caps and plastic tape can be used to protect the core, and coreboxes need not be so carefully made.

In general, it is common to see considerable detail relating to boring and drilling in specification documents, simply because there are currently no national or international standards available for guidance. This is regrettable because, as will be seen in later chapters, drilling technique can have an enormous impact on the quality of samples and *in situ* tests. The advice given in Chapter 7 can be used to make improvements to current specification documents.

In the USA the following American Society for Testing and Materials (ASTM) standards are available for site investigation and sampling:

ASTM D420—87: *Standard guide for investigating and sampling soil and rock*,
ASTM D1452—80: *Soil investigation and sampling by auger borings*,
ASTM D1587—83: *Thin-walled tube sampling*,
ASTM D3550—84: *Standard practice for ring-lined barrel sampling of soils*,
ASTM D2113—83 (reapproved 1987) *Standard practice for diamond core drilling for site investigation*,
ASTM D4220—83: *Standard practices for preserving and transporting soil samples*. In the UK the provisions given in BS 5930 (which in any case describes itself as a code of practice, rather than a standard) for drilling and sampling generally are not suitable for inclusion in a contract specification (see, for example, Clayton (1986) for criticisms).

6. *Groundwater*. The groundwater regime is often not very well determined by ground investigation. Since pore water pressure is usually a very important factor in any engineering calculation, any seepages or inflows into the borehole should be closely monitored. Each time that groundwater is detected, the depth of entry should be measured and the speed of inflow described. Boring should be suspended and groundwater levels observed in an attempt to determine the static groundwater level. Some specifications allow for standing time (i.e. unproductive time) while the groundwater stabilizes in the borehole. Others require that the driller should only suspend work for a maximum of 20 mm. At the end of this period, if the water level is still rising, its depth is to be recorded and drilling recommenced.

   Each groundwater inflow should be sampled. Where water has previously been added for boring purposes, it should be bailed out before sampling. The sample should not be less than 11.

7. *Storage, handling and transporting of soil samples*. All samples and cores should be protected at all times from the adverse effects of weather. They should, as soon as practicable, be placed in a sample store with a humid atmosphere and a temperature between 7 and 18°C. Samples should be handled carefully at all times and should be transported to a soils laboratory for testing within two weeks of sampling.

8. *In situ testing*. BS 1377:1991 and ASTM Part D18 (dealing with Soils and Rocks) give specifications for the most common *in situ* tests, including the SPT, the cone test, vane testing and permeability testing. In addition, German standards and ISSMFE (International Society for Soil Mechanics and Foundation Engineering) Reference Test Procedures are available to cover other forms of testing (for example dynamic penetration testing). Details of these are given in Table 1.8. It is normal in the UK simply to state at the start of a Specification that all the ground investigation work is to be carried out to the British Standards for 'Site Investigation' (currently BS 5930:1981) and 'Testing of Soils for Civil Engineering Purposes' (currently BS 1377: 1991). It is a much better practice to refer specifically within the Specification to the clauses of required standard dealing with the particular test. British Standards are normally complex, and to avoid omission, specific points to be noted and adhered to by the ground investigation contractor should be highlighted within the Specification document.

Table 1.8 Standards available for *in situ* testing

Test	British Standard	American Standard
Density tests (sand replacement, water replacement, core cutter, balloon, and nuclear methods)	BS 1377:part 9:1990, clause 2	ASTM D1556—82 ASTM D2937—83 ASTM D2167—84 ASTM D2922—91
Apparent resistivity	BS 1377:part 9:1990, clause 5.1	ASTM G57—78 (re-approved 1984)
In situ redox potential	BS 1377:part 9:1990, clause 5.2	
In situ California bearing ratio	BS 1377:part 9:1990, clause 4.3	ASTM D4429—84
Standard penetration test	BS 1377:part 9:1990, clause 3.3	ASTM D1586—84 ASTM D4633—86 (energy measurement)
Dynamic penetration tests	BS 1377:part 9:1990, clause 3.2	
Cone penetration test	BS 1377:part 9:1990, clause 3.1	ASTM D3441—86
Vane test	BS 1377:part 9:1990, clause 4.4	ASTM D2573—72 (re-approved 1978)
Plate loading tests	BS 1377:part 9:1990, clauses 4.1,4.2	ASTM D1194—72 (re-approved 1978) ASTM D4395—84
Pressuremeter test		ASTM D4719—87

9. *Journals*. The information required to form the driller's daily report must be recorded as drilling proceeds. At the end of each day's drilling, the drilling foreman of each rig must prepare a report incorporating the following information:

   (i) job name and location;
   (ii) contractor's name;
   (iii) exploratory hole reference number;
   (iv) depth of drilling at the start and end of the shift;
   (v) type of drilling rig;
   (vi) diameters and depths of all casing;
   (vii) depth of each stratum change;
   (viii) groundwater records;
   (ix) brief description of each soil type; and
   (x) type, diameter and upper and lower depths of each sample, drill run, or *in situ* test;

   for boreholes:

   (xi) locations where water was added to the boring;
   (xii) depths when chiselling was required; and
   (xiii) details of instruments installed;

   for drillholes:

   (xiv) orientation of the drillhole;
   (xv) type and diameter of barrel, and bit; and
   (xvi) flush type, and notes on flush return and loss of return.

These records, produced on standard sheets (Fig. 1.7), should be submitted to the site engineer without fail before the start of the next day's drilling.

Fig. 1.7 Layout for rotary drilling daily report (from Redford 1981).

NUTTALL GEOTECHNICAL SERVICES LTD. Old Bath Road, Colnbrook, Slough. SL30NJ Colnbrook 3565	ROTARY DRILLING - FOREMAN'S DAILY REPORT			
	Job Name		Date	Job No.
	Rig Type No.	Flush	Day	DH

DRILL RUN				CORE RE-COVERY		SIZE		CASING		FLUSH RETURN			FIELD CLASSIFICATION AND/OR REMARKS
No.	From	To	Length										
	m	m	m	m	%	⌀/hole	Core	Size	Depth	All	Some	Nil	

SITUATION AT END OF SHIFT:			BITS – Serial No.	Metres this shift
DEPTH m		FIELD LOG OF DRILLING		
From	To			

WATER STRIKES (Depths)			
R.E.			
WEATHER			
PROGRESS THIS SHIFT	At start	At end	At finish of DH (Time)
Depth of hole			
Depth of casing			
Depth of water			

POSITION	NAME	HOURS	TIME DISTRIBUTION THIS SHIFT	
			Drilling	Casing
			Moving	Stand by
			Other (Specify)	
			Breakdown	Sheet No. 3 of 6

10. *Laboratory testing*. BS 1377:1991 and ASTM Part D18 give detailed specifications for the testing of soils, and some specifications for the testing of rocks. In addition, ISRM (International Society for Rock Mechanics) gives recommendations for methods of testing rock (Table 1.10). Table 1.9 gives details of the Specifications available at the time of writing. As with *in situ* testing, individual clauses should be given in the Specification, and where appropriate details requiring special attention should be highlighted.

Table 1.9 Standards available for laboratory testing of soils

Test	British Standard	American Standard
Classification tests		
Moisture content	BS 1377:part 2:1990, clause 3	ASTM D2216—91 ASTM D4643—87
Atterberg limits	BS 1377:part 2:1990, clauses 4,5	ASTM D4318—84
Density	BS 1377:part 2:1990, clause 7	
Specific gravity	BS 1377:part 2:1990, clause 8	ASTM D854—92
Particle size distribution	BS 1377:part 2:1990, clause 9	ASTM D422—63 (re-approved 1972) ASTM D2217—85
Pinhole dispersion test		ASTM D4647—87
Chemical tests		
Organic matter content	BS 1377:part 3:1990, clause 3	
Loss on ignition	BS 1377:part 3:1990, clause 4	ASTM D2974—87
Sulphate content	BS 1377:part 3:1990, clause 5	
Carbonate content	BS 1377:part 3:1990, clause 6	ASTM D4373—84
Chloride content	BS 1377:part 3:1990, clause 7	
pH	BS 1377:part 3:1990, clause 9	ASTM G51—77 (re-approved 1984)
Resistivity	BS 1377:part 3:1990, clause 10	
Redox potential	BS 1377:part 3:1990, clause 11	
Compaction tests		
Proctor/2.5kg rammer	BS 1377:part 4:1990, clause 3.3	ASTM D698—91
Heavy/4.5kg rammer	BS 1377:part 4:1990, clause 3.5	ASTM D1557—91
Vibrating hammer	BS 1377:part 4:1990, clause 3.7	
Strength tests		
California bearing ratio	BS 1377:part 4:1990, clause 7	ASTM D1883—92
Undrained triaxial shear strength	BS 1377:part 7: 1990, clauses 8,9	ASTM D2850—87
Effective strength from the consolidated-undrained triaxial compression test with pore pressure measurement	BS 1377:part 8:1990, clause 7	
Effective strength from the consolidated-drained triaxial compression test with volume change measurement	BS 1377:part 8:1990, clause 8	
Residual strength by direct shear testing in the shear box	BS 1377:part 7:1990, clause 5	ASTM D3080—90
Residual strength using the Bromhead ring shear apparatus	BS 1377:part 7:1990, clause 6	
Compressibility tests		
One-dimensional compressibility in the oedometer	BS 1377:part 5:1990, clauses 3,4	ASTM D2435—90
Isotropic consolidation in the triaxial apparatus	BS 1377:part 8:1990, clause 6	
Permeability tests		
In the constant-head apparatus	BS 1377:part 5:1990, clause 5	ASTM D2434—68 (re-approved 1974)

Table 1.10 Suggested methods for laboratory testing of rocks;
ISRM Commission on Testing Methods (formerly The Commission for the Standardization of Laboratory and Field Tests)

Test	Reference in International Journal of Rock Mechanics Mining Science and Geomechanics Abstracts
Description	
Petrographic description	1978, **15**, (2), 41—46
Description of discontinuities	1978, **15**, (6), 319—368
Index tests	
Water content, porosity, density, absorption-related properties, swelling and slake durability	1979, **16**, (2), 141—156
Point load strength	1985, **22**, (2). 51—60
Hardness and abrasiveness	1978, **15**, (3), 89—98
Sound velocity	1978, **15**, (2), 53—58
Mechanical properties	
Uniaxial compressive strength and deformability	1979, **16**, (2), 135— 140
Strength in triaxial compression	1978, **15**, (2), 47—52 revised 1983, **20**, (6), 283—290
Tensile strength	1978, **15**, (3), 99—104
Fracture toughness	1988, **25**, (2), 71—96
Laboratory testing of argillaceous swelling rocks	1989, **26**, (5), 415—426
Large-scale sampling and triaxial testing of jointed rock	1989, **26**, (5), 427—434

Cost considerations

Most published and unpublished opinions on the methods of control and finance of site investigations in the UK express the need for more time and money (Williams and Mettam 1971; Rowe 1972), flexibility of procedure (Green 1968), and adequate liaison between geotechnical and structural design teams (Bridge and Elliott 1967).

Site investigation in the UK traditionally has been carried out by specialist geotechnical contractors. These contractors vary considerably. They may be very experienced organizations controlled by qualified engineers and geologists, and supported by extensive facilities for air photograph interpretation, geotechnical laboratory testing, and computer studies: often, however, they may be organizations with limited assets, limited plant, limited engineering knowledge — and limited liability!

In recent years, the financial restrictions on site investigation seem to have become tighter, but in 1972 Rowe delivered the following arguments in favour of spending more on site investigation.

1. It is known that more claims by piling contractors arise due to poorly or inaccurately known ground conditions than to any other cause (Tomlinson and Meigh 1971).
2. Site investigation costs are very low compared with the cost of earthworks or foundation construction, and even smaller as a proportion of the total capital cost of the works, can be seen in Table 1.11.

These figures represent a decline in expenditure since the 1940s since Harding (1949) reckoned the cost of site investigations for 'fair-sized works' to be usually about 1 to 2% of the cost of the main work.

The influence of incorrect site investigation data on the final cost of a project is difficult to assess but can be very large. Rowe cites examples of a case where the omission or inclusion of sand drains could make a difference of 2 to 5% of total project cost, and where unnecessary foundation treatment added 5% to the cost of the works. These figures are certainly not representative of the upper end of the spectrum, as claims for unforeseen ground conditions can easily amount to 10% of contract value.

Table 1.11 Site investigation costs (from Rowe (1972))

Type of work	% of capital cost of works	% of earthworks and foundation cost
Earth dams	0.89—3.30	1.14—5.20
Embankments	0.12—0.19	0.16—0.20
Docks	0.23—0.50	0.42—1.67
Bridges	0.12—0.50	0.26—1.30
Buildings	0.05—0.22	0.50—2.00
Roads	0.20—1.55	(1.60)?—5.67
Railways	0.60—2.00	3.5
Overall mean	0.7	1.5

As noted earlier, Tyrrell *et al.* (1983) found, in an analysis of ten selected highway contracts, that additional expenditure rose to an average of 35% of the tender value. Of this about one-half could be attributed to geotechnical matters. On this basis it is easy to argue for an increase in expenditure on site investigation. But it has proved difficult to establish that increased expenditure on site investigation leads to reductions in construction cost over-runs. What is required is that all expenditure on ground investigation sitework and testing, which typically amounts to 60—70% of the total cost of a site investigation, should be carefully targeted at giving information required for particular and well-defined geotechnical problems. This will lead to reductions in expenditure in some cases, and increases in others.

PROCUREMENT

In the UK it has been widely considered that procurement, in its broadest sense, is the key to obtaining a good site investigation at a reasonable price. Investigations carried out for the Construction Industry Research and Information Association (CIRIA) have been reported by Uff and Clayton (1986, 1991). Many of their more general recommendations are incorporated into the earlier parts of this chapter; only those dealing with the detailed mechanisms of procurement are considered below.

The way in which ground investigation work is organized has been described briefly above, under ‘Implementation’ and ‘Planning’. A number of different organizational models are used worldwide, as can be seen from the examples given in Fig. 1.8. In essence, a good system of procurement will ensure that key elements of work are carried out properly, by competent personnel. In Fig. 1.8, examples A, B and C are satisfactory; D and E omit significant parts of the investigation process, and are bad. It is essential that:

1. desk study, air photo interpretation and a walk-over survey are carried out;
2. the ground investigation is properly designed, taking into account the probable ground conditions and the proposed construction;
3. the required type and standards of ground investigation field and laboratory work are properly defined;
4. during the ground investigation, standards are enforced by competent supervision; and
5. as ground investigation proceeds, the ground conditions are reassessed in the light of information emerging from the work, and that work is rescheduled if necessary.

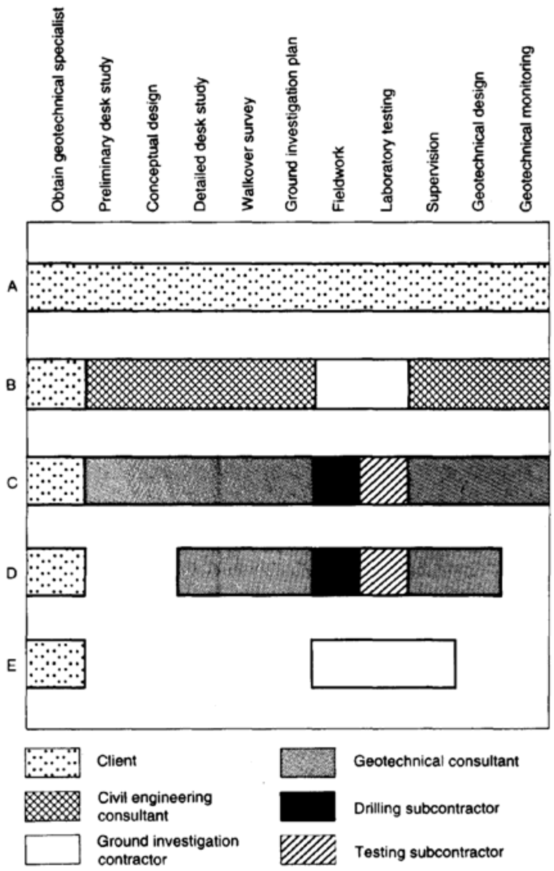

Fig. 1.8 Examples of division of site investigation work.

Procurement methods will often concentrate upon obtaining minimum prices, without considering how well the required quality of ground investigation work can be defined. This is a serious mistake, since many of the activities involved cannot very readily be checked. For example, a good quality standard penetration test requires attention not only to the test equipment and the method used for the test itself, but also to the method of boring, and the water levels within the borehole, both before and during the test. The end product is a series of numbers, the validity of which can be known only if all these matters have been observed, reported, and considered.

Therefore, it is suggested that the procurement system should aim:

1. to ensure that a competent geotechnical adviser is retained by the promoter/ developer at an early stage during the conceptualization of the project, in order to guide the project;
2. as far as possible, to give overall responsibility for all geotechnical matters to a single individual or company; and
3. to select geotechnical advisers and contractors on the basis of their resources (staff, equipment, etc.), and experience with similar forms of construction and ground conditions, and not primarily on the basis of their fee level or unit rates.

In the UK, two systems of procurement of site investigation are in common use, as detailed in *CIRIA Special Publication* SP45 (Uff and Clayton 1986).

System 1: Use of a geotechnical adviser with the separate employment of a contractor for physical work, testing, and reporting as required

In this system the desk study, the planning and supervision of any fieldwork (such as boring, drilling, trial pitting or *in situ* testing) and laboratory testing work that may be necessary is carried out by the geotechnical adviser. He will often be a member of a firm of civil engineering consultants but may also be a specialist geotechnical consultant.

This system is widely used on large civil engineering projects. The geotechnical adviser will normally be employed by the developer under the Association of Consulting Engineers Conditions of Engagement, while the specialist ground investigation contractor will be chosen by competitive tender and will work under ICE Conditions of Contract. Two versions of ICE contract are in use; the *ICE 5th Edition* and the *ICE Conditions of Contract for Ground Investigation*. When using this system it is important that the developer or his advisers should check that the chosen geotechnical adviser has sufficient geotechnical skill to carry out the desk study, plan and supervise the ground investigation and interpret its results. It is possible to make use of the contractor's engineering skills only after the tendering process. Therefore the skills of the geotechnical adviser are extremely important.

The geotechnical adviser is expected to carry out a thorough desk study and plan an investigation appropriate to the needs of the developer. This is then used to prepare a specification and bill of quantities which, together with the conditions of contract, form the basis of the tender for the field and laboratory work to be carried out by a specialist contractor. Generally between three and four companies should be selected by the geotechnical adviser to tender for the field and laboratory work, on the basis of their previous experience of this type of work, the skills of their staff and the amount and quality of their equipment. The lowest submitted tender price is generally accepted but the contract is subject to remeasurement as the work proceeds. The final cost to the developer of the entire ground investigation will be the sum of the final contract price after measurement and the professional fees paid to the consulting engineer.

This system has been found to work well provided that:

1. an adviser with a sufficient number of skilled geotechnical staff is engaged;
2. a thorough desk study, made by the geotechnical adviser, is used as the basis for the planning of any programme of drilling and testing;
3. not more than four specialist contractors arc asked to tender and the selection of these companies is rationally and thoroughly carried out; and
4. proper levels of supervision are provided by the geotechnical adviser in the control of field and laboratory work. Supervision is the key to the successful use of System 1.

In certain cases it may be advantageous for parts of the work to be done by the contractor on a dayworks basis. Under System 1, the work to be carried out by the contractor must be closely defined before the contract is let and must be paid for at fixed rates independent of the time taken to carry it out. If the work is particularly important to the success of the investigation, if it is very complex, or if the geotechnical adviser needs to be able to vary the work as it proceeds, dayworks payments may be helpful. For example, dayworks could be used to pay for plate loading tests, for drilling and boring in key zones, or for time spent in investigating groundwater conditions. It is also possible to pay a specialist contractor to carry out the reporting of an investigation; this is better done on an hourly basis rather than by lump sums.

System 1 has the advantage of using forms of contract that are well known in the civil engineering construction field and it can be used to demonstrate cost-accountability through the tendering process. This is the most commonly used form of procurement for larger ground investigations and is therefore well understood. Its difficulties lie in the complexity of its contractual arrangements, the need to ensure that sufficient expertise and supervision are provided by the geotechnical adviser and the division of responsibility for the satisfactory outcome of the investigation between the geotechnical adviser and the contractor. It has frequently been said that the method of competitive tendering commonly associated with this system, and the consequent low prices paid to contractors for investigation work, is a major cause of low-quality investigation. This problem, however, is a consequence of too large tender lists prepared without detailed selection of tenderers. It is not necessarily a result of using the system.

System 2: Package deal contract, with desk study, planning and execution of field and laboratory work, and reporting, being carried out by one company or a consortium

No formal conditions of contract exist for this system, although draft documents have been proposed in *CIRIA Special Publication 45*. Despite the lack of published conditions of contract, versions of this system are in common use to obtain ground investigations for low-rise building development. The system is also used for large site investigation contracts carried out abroad, for example in the Middle East.

In this system the developer selects up to three specialist ground investigation companies on the basis of past experience, reputation, and published information relating to specialists in the field. Information on companies and individuals is available from:

- the British Geotechnical Society;
- the Association of Ground Investigation Specialists;
- the Institution of Civil Engineers; and
- the Geological Society.

The companies selected may be either ‘contractors’ or ‘consultants’ according to the British Geotechnical Society’s Directory, but they should have sufficient qualified and experienced staff to be able to carry out the proposed size of investigation. On the basis of a preliminary desk study, the companies offer to carry out a complete site investigation, including desk study, air photograph interpretation, design and execution of ground investigation and reporting, either for a lump sum or on the basis of measurement of work agreed as the investigation progresses. The specialist company that carries out the work is expected to supervise its own drilling and testing and will be liable under the 1982 Supply of Goods and Services Act both for the quality of work and for any recommendations that are made in the report of the investigation.

The advantages of System 2 to a developer are that a lump sum contract can be negotiated; this is obviously important when carrying out financial forecasting. A further advantage is that the responsibility for ground investigation is not divided between two parties, as in System 1. Because of the cost to the tenderers of preliminary desk studies, it is unlikely that lump sum contracts can be used for very large civil engineering projects, but this type of procurement will certainly be more suited than System 1 to many low-rise building developments, because of its relatively simple contract documentation and its flexibility.

An advantage of this system is that the leading design professional (who might typically be an architect in the case of a low-rise building development) is not necessarily required to have geotechnical skill and experience of ground investigation techniques. If he does not possess such skill, however, it becomes extremely important that care is taken in the selection of ground investigation specialists who are suitable for the complexity of work to be carried out. A possible disadvantage of System 2 is the lack of well-tried and proven contract documentation. However, this does not appear to have prevented the successful use of this method of procurement in recent years. To overcome this it is suggested that the contract documents used are those given in the appendices to *CIRIA Special Publication 45*.

EXECUTION

Supervision

A good site investigation is made in the field. Engineering excellence, sophisticated laboratory techniques and the use of powerful computational methods cannot ever be expected to make any contribution to a site investigation performed by bad drillers without engineering supervision. Since this often occurs, it is hardly surprising that the value of site investigation is sometimes questioned by engineers not familiar with its techniques.

Supervision of any site investigation requires an engineer who is familiar with:

1. the techniques of investigation; and
2. the objectives of the particular investigation.

This engineer is the key person in ensuring that the best use is made of the expenditure on site investigation, and to this end he must spend a very large part of his time on site during the investigation. While on site, the supervising engineer should:

1. closely watch the drilling and sampling techniques, to ensure that disturbance of soil is minimized; and the techniques and equipment comply with the specification;
2. frequently check the records of borings provided by the drillers for authenticity and accuracy;
3. carry out sample description and prepare engineering logs, except on small investigations where it will be more economical to transport samples to a laboratory for description;
4. liaise with the structural design engineer, so that the investigation can be modified as a result of its initial findings;
5. ensure that driller’s and engineer’s borehole records, and the samples are despatched to the soil laboratory at frequent intervals;
6. provide conditions of storage for the samples on site which ‘will not lead to their deterioration; and
7. check the adequacy of sample sealing by the rig foremen.

Quite clearly, it will be difficult for one man to supervise more than one drilling rig satisfactorily, and for this reason drilling technicians have sometimes been used. A drilling technician will be assigned to one rig, and will be responsible for all the technical aspects of that rig’s work. He would normally, for example, prepare the records of drilling, instruct the driller at which level to take samples, and carry out *in situ* testing and the installation of instrumentation.

In the majority of cases, both in the UK and overseas, drilling technicians are not used. Site investigations are usually carried out by drillers who do not understand the mechanisms of disturbance of soil samples, who are not informed of the objectives of the individual investigation, and who are often motivated solely by productivity bonuses. Under these conditions, the supervising engineer is the only force available in the struggle to produce a sound investigation. To be effective, the supervising engineer must understand the practical aspects of drilling.

The key points in checking the effectiveness of a site investigation are as follows.

1. *Avoid excessive disturbance*. Look for damaged cutting shoes, rusty, rough or dirty sample barrels, or badly designed samplers. Check the depth of casings to ensure that these never penetrate beneath the bottom of the borehole. Try to assess the amount of displacement occurring beneath power augers, and prevent their use if necessary.
2. *Check for water*. Ensure that adequate water levels are maintained when drilling in granular soils or soft alluvium beneath the water table. The addition of water in small quantities should be kept to a minimum, since this allows swelling without going any way towards replacing total stress levels. Make sure the driller stops drilling when groundwater is met.
3. *Check depths*. The depths of samples can be found approximately by noting the number of rods placed on the sampling tool as it is lowered down the hole, and the amount of ‘stick-up’ of the last rod at the top of the hole. This type of approach is often used by drillers, but is not always satisfactory. Immediately before any sample is taken or *in situ* test performed the depth

of the bottom of the hole should be measured, using a weighted tape. If this depth is different from the last depth of the drilling tools then either the sides of the hole are collapsing, or soil is piping or heaving into the base. Open-drive sampling should not then be used.

4. *Look for faulty equipment*. On-site maintenance may lead to SPT hammers becoming non-standard, for example owing to threading snapping and the central stem being shortened, giving a short drop. When working overseas with subcontract rigs the weight of the SPT hammer should also be measured. Other problems which often occur are: (i) the blocking of vents in sampler heads; and (ii) the jamming of inner barrels in double tube swivel-type corebarrels.
5. *Examine driller's records regularly*. The driller should be aware that the engineer is seeking high quality workmanship. One of the easiest ways of improving site investigation is to demand that up to the moment records are kept by the driller as drilling proceeds. These should then be checked several times a day when the engineer visits the borehole. Any problems encountered by the driller can then be discussed, and decisions taken.

Safety

Safety should be of major concern during the fieldwork and laboratory testing phases of ground investigation. Potential hazards include:

1. incapacity as a result of prolonged exposure to bad working conditions (for example, deafness as a result of exposure to high levels of noise);
2. injury or death as a result of misuse of plant and equipment (for example, using frayed winch ropes, not setting up drilling equipment in a stable configuration, etc.);
3. injury or death as a result of contact with overhead electricity cables (particularly by contact with drilling rig masts, but also with cranes during transporting);
4. injury or death as a result of excavation through services (electricity, gas, water, etc.), during boring, drilling or pitting;
5. injury or death as a result of explosions of gases emanating from the ground (for example methane from landfill);
6. injury or death as a result of collapse of trenches on to personnel carrying out logging or sampling;
7. damage to health as a result of contact with contaminated ground, or in the laboratory, working with contaminated samples;
8. poisoning, as a result of inhaling or ingesting toxic gases or substances such as asbestos, cyanides, etc;
9. damage to health, or death, as a result of radiation; and
10. damage to health, or death, as a result of contact with animal carcases or sewage (leading, for example, to anthrax or Weil's disease).

Whilst many of these risks are associated with the investigation of contaminated land, a very large proportion may be present during any site investigation. Under the UK 'Health and Safety at Work etc.' Act, all persons involved with an investigation have a responsibility to see that safe working practices are adopted. This includes the promoter of the development, who may have knowledge of previous site use, the consulting engineer, who must ensure that sufficient resources are devoted to a safety assessment before field and testing work is specified, and the specialist ground investigation contractor, who must enforce safe working practices during the ground investigation.

Engineers and geologists will be particularly responsible, since they will be directly in control of those most exposed to risk. The construction industry has a poor safety record, and there is always the temptation to reduce costs by taking short cuts with safety. This must be prevented. To help in the drive for greater safety in ground investigation the British Drilling Association have recently published two reports:

Code of Safe Drilling Practice, British Drilling Association, Brentwood, Essex, UK (March 1992).

Guidance Notes for the Safe Drilling of Landfills and Contaminated Land, British Drilling Association, Brentwood, Essex, UK (March 1992).

It is recommended that all professionals involved in ground investigation should study both these and the literature to which they refer, before carrying out fieldwork.

Quality assurance

Quality assurance is 'All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements of quality'. In other words, quality assurance concerns the management of an organization to meet agreed quality objectives. In itself it does not guarantee that a service is of the necessary quality for a given job, but attempts to meet predetermined standards by approaching the work in a systematic manner. In this sense it simply represents good management practice.

In the UK, quality systems are now being implemented in the ground investigation industry. They are standardized internationally (ISO 9001—1987), in Europe by CEN (EN 29001—1987), and in the UK (BS 5750:1987) under identical documents.

Quality systems comprise several levels of activity (Fig. 1.9):

1. *Quality policy*. The overall quality intentions and direction of an organization as regards quality, as formally expressed by top management.
2. *Quality management*. That aspect of the overall management function that determines and implements the quality policy.
3. *Quality system*. The organizational structure, responsibilities, procedures, processes and resources for implementing quality management.
4. *Quality control*. The operational techniques and activities that are used to fulfil requirements for quality.

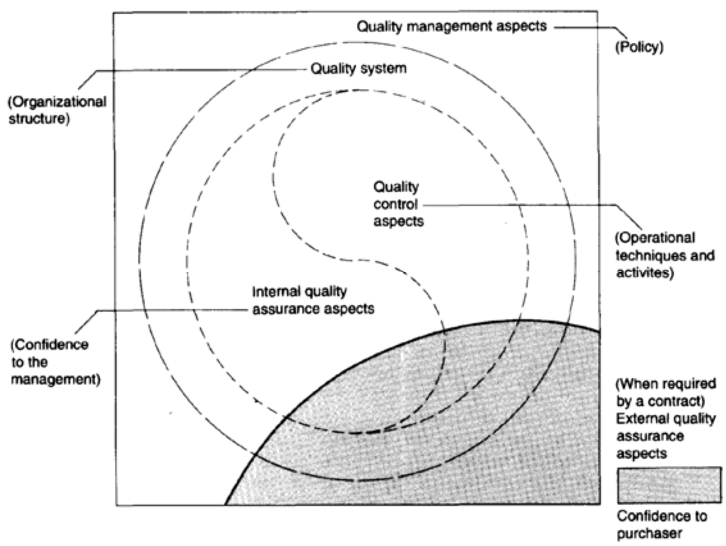

Fig. 1.9 Relationships of quality concepts (BS 5750: part 0: section 0.1: 1987).

In the UK, ground investigation industry quality assurance is being applied at two levels. First, 'internal quality assurance', which aims to provide the management of an organization with the confidence that the intended quality is being achieved, is being implemented. Under BS 5750, quality systems can be audited by a third party ‘certification’ body, such as Lloyds or the British Standards Institution. Since ground investigation generally has a rather short duration, it is sensible that at the outset it is the supplier who leads the quality process — it has been found that attempts to impose ‘external quality assurance’, i.e. activities which aim to provide confidence that the supplier’s quality system will provide a product that will satisfy the client’s stated quality requirements, are difficult to set up in the absence of legislation, for such small and diverse projects.

Secondly, laboratory testing services are becoming subject to third-party accreditation by the National Measurement Accreditation Service (NAMAS). This represents less of a problem, in theory, because British Standards provide tight specifications for most aspects of the more commonly used tests. At the time of writing (1992) the UK’s Department of Transport has stated that all work carried out on UK highway investigation after April 1993 must be carried out in NAMAS accredited laboratories. Presently there is only one major geotechnical laboratory accredited for a wide range of soil tests, although it is expected that several will be able to offer an accredited service by the end of 1992.

In procuring the services of geotechnical specialists, whether consultants, contractors, or specialist sub-contractors, it is recommended that, other things being equal, those who offer a certified quality management system, or an accredited laboratory or field testing service should be favoured.