Site Investigation

The general objective of a site investigation is to assess the suitability of a site for the proposed purpose. As such, it involves exploring the ground conditions at and below the surface (Anon, 1999). It is a prerequisite for the successful and economic design of engineering structures and earthworks. Accordingly, a site investigation also should attempt to foresee and provide against difficulties that may arise during construction because of ground and/or other local conditions. Indeed, investigation should not cease once construction begins. It is essential that the prediction of ground conditions that constitute the basic design assumption be checked as construction proceeds and designs modified accordingly if conditions are revealed to be different from those predicted. The investigation of a site for an important structure requires exploration and sampling of strata likely to be significantly affected by the structural load. Data appertaining to groundwater conditions, extent of weathering, and discontinuity pattern in rock masses are also important. In some areas there are special problems that need investigating, for example, potential subsidence in areas of shallow abandoned mine workings and contaminated ground. What is more, as Culshaw (2005) pointed out, the rapid development of information technology and the digitization of increasing amounts of geological data now means that it often is possible to produce three-dimensional (3D) special models of the shallow subsurface.

The complexity of a site investigation depends upon the nature of the ground conditions and the type of engineering structure. More complicated ground conditions and sensitive large engineering structures require more rigorous investigation of the ground conditions. Although a site investigation usually consists of three stages, namely a desk study, a preliminary reconnaissance and a site exploration, there must be a degree of flexibility in the procedure since no two sites are the same.

Desk Study and Preliminary Reconnaissance

A desk study is undertaken as the first stage of a site investigation in order to make an initial assessment of the ground conditions and to identify, if possible, any potential geotechnical problems (Herbert et al., 1987). In other words, the objective of a desk study is to examine available archival records, literature, maps, imagery and photographs relevant to the area or site concerned to ascertain a general picture of the existing geological conditions prior to a field investigation, that is, to begin the process of constructing what Fookes (1997) referred to as the geological model. The effort expended in any desk study depends on the complexity and size of the proposed project and on the nature of the ground conditions. Detailed searches for information, however, can be extremely time consuming and may not be justified for small schemes at sites where the ground conditions are relatively simple. In such cases, a study of the relevant topographical and geological maps and memoirs, and possibly aerial photographs, may suffice. On large projects, literature and map surveys may save time and thereby reduce the cost of the site investigation programme. The data obtained during such searches should help the planning of the subsequent site exploration and prevent duplication of effort. In some parts of the world, however, little or no literature or maps are available.

Topographical, geological and soil maps can provide valuable information that can be used during the planning stage of a construction operation. The former are particularly valuable when planning routeways. Geological maps afford a generalized picture of the geology of an area. Generally, the stratum boundaries and positions of the structural features, especially faults, are interpolated. As a consequence, their accuracy cannot always be trusted. Map memoirs may accompany maps, and these provide a detailed survey of the geology of the area in question.

From the engineer's point of view, one of the shortcomings of conventional geological maps is that the boundaries are stratigraphical and more than one type of rock may be included in a single mappable unit. What is more, the geological map is lacking in quantitative information that the engineer requires, concerning such facts as the physical properties of the rocks and soils, the amount and degree of weathering, the hydrogeological conditions, etc. However, information such as that relating to the distribution of superficial deposits, landslipped areas and potential sources of construction materials frequently can be obtained from geological maps. A geological map also can be used to indicate those rocks or soils that could be potential sources of groundwater. Now many geological surveys are producing hazard maps, environmental geology maps and engineering geology maps that provide data more relevant to engineers and planners. Such maps represent an attempt to make geological information more understandable by the non-geologist. Frequently, because it is impossible to represent all environmental or engineering data on one map, a series of thematic maps, each of a different topic, is incorporated into a report on a given area. Smith and Ellison (1999) have provided a review of applied geological maps for planning and development. Their review describes various ways by which geological data can be represented on maps.

A desk study for the planning stage of a project can encompass a range of appraisals from the preliminary rapid response to the comprehensive. Nonetheless, there are a number of common factors throughout this spectrum that need to be taken into account. These are summarised in Table 7.1, from which it can be concluded that an appraisal report typically includes a factual and interpretative description of the surface and geological conditions, information on previous site usage, a preliminary assessment of the suitability of the site for the planned development, an identification of potential constraints and provisional recommendations with regard to ground engineering aspects. A desk study also can reduce the risk of encountering unexpected ground conditions that could adversely affect the financial viability of a project. However, a desk study should not be regarded as an alternative to a ground exploration for a construction project.

The preliminary reconnaissance involves a walk over the site. The factors that should be taken into account depend on the nature of the site and the project but, where possible, note can be taken of the distribution of the soil and rock types present, the relief of the ground, the surface drainage and associated features, any actual or likely landslip areas, ground cover and obstructions, earlier uses of the site such as tipping or evidence of underground workings etc. The inspection should not be restricted to the site but should examine adjacent areas to see how they affect or will be affected by construction on the site in question.

The importance of the preliminary investigation is that it should assess the suitability of the site for the proposed works, and if it is suitable, it will form the basis upon which the site exploration is planned. The preliminary reconnaissance also allows a check to be made on any conclusions reached in the desk study.

Remote Sensing

Remote imagery and aerial photographs prove to be invaluable during the planning and reconnaissance stages of certain projects. The information they provide can be transposed to a base map, which is checked during fieldwork. The data also can be used in geographical information systems.

Remote sensing involves the identification and analysis of phenomena on the Earth's surface by using devices borne by aircraft or spacecraft. Most techniques used in remote sensing depend on recording energy from part of the electromagnetic spectrum, ranging from gamma rays through the visible spectrum to radio waves. The scanning equipment used measures both emitted and reflected radiation, and the employment of suitable detectors and filters permits the measurement of certain spectral bands. Two of the main systems of remote sensing are infrared linescan (IRLS) and side-looking airborne radar (SLAR). Signals from several bands of the spectrum can be recorded simultaneously by multi-spectral scanners. Lasers are used in remote sensing.

Table 7.1. Summary contents of engineering geological desk study appraisals (after Herbert et al., 1987). With kind permission of the Geological Society

Item	Content and main points of relevance
Introduction	Statement of terms of reference and objectives, with indication of any limitations. Brief description of nature of project and specific ground-orientated proposals. Statement of sources of information on which appraisal is based
Ground conditions	Description of relevant factual information. Identification of any major features that might influence scheme layout, planning or feasibility
Site description and topography	Descriptions of existing surface conditions from study of topographic maps and actual photographs, and also from site walkover inspection (if possible)
Engineering history	Review of information on previous surface conditions and usage (if different from present) based on study of old maps, photographs, archival records and related to any present features observed during site walkover. Identification of features such as landfill zones, mine workings, pits and quarries, sources of contamination, old water courses, etc.
Engineering geology	Description of subsurface conditions, including any information on groundwater, from study of geological maps and memoirs, previous site investigation reports and any features or outcrops observed during site walkover. Identification of possible geological hazards, e.g. buried channels in alluvium, solution holes in chalk and limestone, swelling/shrinkable clays
Provisional assessment of site suitability	Summary of main engineering elements of proposed scheme, as understood. Comments on suitability of site for proposed development, based on existing knowledge
Provisional land classification	Where there is significant variation in ground conditions or assessed level of risk, subdivision of the site into zones of high and low risk, and any intermediate zones. Comparison of various risk zones with regard to the likely order of cost and scope of subsequent site investigation requirements, engineering implications, etc.
Provisional engineering comments	Statement of provisional engineering comments on such aspects as foundation conditions and which methods appears most appropriate for structural foundations and ground slabs, road pavement subgrade conditions, drainage, excavatability of soils and rocks, suitability of local borrow materials for use in construction, slope stability considerations, nature and extent of any remedial works, temporary problems during construction
Recommendations for further work	Proposals for phased ground investigation, with objectives, requirements and estimated budget costs

Infrared linescanning is dependent upon the fact that all objects emit electromagnetic radiation generated by the thermal activity of their component atoms. Identification of grey tones is the most important aspect as far as the interpretation of thermal imagery is concerned, since these provide an indication of the radiant temperatures of a surface. Warm areas give rise to light, and cool areas to dark tones. The data can be processed in colour as well as black and white, colours substituting for grey tones. Relatively cool areas are depicted as purple and relatively warm areas as red on a positive print. Thermal inertia is important in this respect since rocks with high thermal inertia, such as dolostone or quartzite, are relatively cool during the day and warm at night. Rocks and soils with low thermal inertia, for example, shale, gravel or sand, are warm during the day and cool at night. The variation in temperature of materials with high thermal inertia during the daily cycle is much less than those with low thermal inertia. Because clay soils possess relatively high thermal inertia, they appear warm in pre-dawn imagery, whereas sandy soils, because of their relatively low thermal inertia, appear cool. The moisture content of a soil influences the image produced, that is, soils that possess high moisture content appear cool irrespective of their type. Consequently, high moisture content may mask differences in soil types. Fault zones often are picked out because of their higher moisture content. Similarly, the presence of old landslides frequently can be discerned because their moisture content differs from that of their surroundings.

Texture also can help interpretation. For instance, outcrops of rock may have a rough texture due to the presence of bedding or jointing, whereas soils usually give rise to a relatively smooth texture. However, where soil cover is less than 0.5 m, the rock structure usually is observable on the imagery since deeper, more moist soil occupying discontinuities gives a darker signature. Free-standing bodies of water usually are readily visible on thermal imagery, however, the thermal inertia of highly saturated organic deposits may approach that of water masses, the two therefore may prove difficult to distinguish at times.

In side-looking airborne radar, short pulses of energy, in a selected part of the radar waveband are transmitted sideways to the ground from antennae on both sides of an aircraft. The pulses strike the ground and are reflected back to the aircraft. The reflected pulses are transformed into black-and-white photographs. Mosaics of photographs are suitable for the identification of regional geological features and for preliminary identification of terrain units. Lateral overlap of radar cover can give a stereoscopic image, which offers a more reliable assessment of the terrain and can provide appreciable detail of landforms. The wavelengths used in SLAR are not affected by cloud cover. This is particularly important in equatorial regions, which are rarely free of cloud.

The large areas of the ground surface that satellite images can cover give a regional physiographic setting and permit the distinction of various landforms. Accordingly, such imagery can provide a geomorphological framework from which a study of the component landforms is possible. The character of the landforms may afford some indication of the type of material of which they are composed, and geomorphological data aid the selection of favourable sites for investigation on larger-scale aerial surveys.

The value of space imagery is important where existing map coverage is inadequate. For example, it can be of use for the preparation of maps of terrain classification, interpretation of geological structure, geomorphological studies, regional engineering soil maps, maps used for route selection, regional inventories of construction materials, groundwater studies, and inventories of drainage networks and catchment areas (Sabins, 1996). A major construction project is governed by the terrain. In order to assess the ground conditions, it is necessary to make a detailed study of all the photo-pattern elements that comprise the landforms on the satellite imagery. Important evidence relating to soil types, or surface or subsurface conditions may be provided by erosion patterns, drainage characteristics or vegetative cover. Engineering soil maps frequently are prepared on a regional basis for both planning and location purposes in order to minimize construction costs, the soils being delineated for the landforms within the regional physiographic setting.

Satellite imagery has improved in its resolution over time so that its use has extended from regional geological mapping and mineral exploration to larger-scale geomorphological mapping and geohazard identification. High-resolution airborne geophysical surveys involving magnetic, gamma spectrometry and very-low-frequency electromagnetic sensors are improving the ability to locate, for example, landfills with high ferrous contents, contaminated sites and abandoned mine sites. Such surveys provide rapid comprehensive data coverage, which permits focused confirmatory ground coverage. This is advantageous when investigating hazardous sites.

Later-generation LANDSAT satellites carry an improved imaging system called thematic mapper (TM) as well as a multi-spectral scanner (MSS). Thermal mapper images have a spatial resolution of 30 m and excellent spectral resolution. Generally, TM bands are processed as normal and infrared colour images. Data gathered by Landsat TM are available as CD-ROMS, which can be read and processed by computers. The weakest point in the system is the lack of adequate stereovision capability, however, a stereomate of a TM image can be produced with the help of a good digital elevation model.

Radar and laser sensors on airborne platforms are being used to produce high-resolution (centimetre to metre) digital terrain models. The light detecting and ranging (LIDAR) system sends a laser pulse from an airborne platform to the ground and measures the speed and intensity of the returning signal. From this, changes in ground elevation can be mapped. Radar systems use radars rather than lasers to achieve the same end. The satellite technique known as permanent scatterer interferometry (PSInSAR) uses radar data collected by satellites 800 km out in space. The PSInSAR method exploits a dense network of “natural” reflectors that can be any hard surface such as a rock outcrop, a building wall or roof or a road kerb. These reflectors are visible to the radar sensor over many years. Permanent scatterer interferometry produces maps showing rates of displacement, accurate to a few millimetres per year, over time periods, currently up to a decade long. The process provides millimetric displacement histories for each reflector point across the entire time period analysed, as calculated at every individual radar scene acquisition. Hence, small incremental ground movements can be detected.

Aerial Photographs

The amount of useful information that can be obtained from aerial photographs varies with the nature of the terrain and the type and quality of the photographs. A study of aerial photographs allows the area concerned to be divided into topographical and geological units, and enables the engineering geologist to plan fieldwork and to select locations for sampling. This should result in a shorter, more profitable period in the field.

Aerial photographs are being digitized and distributed on CD-ROMS that are compatible with desktop computers and image processing software. Orthophotographs are aerial photographs that have been scanned into digital format and computer processed so that radial distortion is removed. These photographs have a consistent scale and therefore may be used in the same ways as maps.

Examination of consecutive pairs of aerial photographs with a stereoscope allows observation of a 3D image of the ground surface. The 3D image means that heights can be determined and contours can be drawn, thereby producing a topographic map. However, the relief presented in this image is exaggerated, and therefore slopes appear steeper than they actually are. Nonetheless, this helps the detection of minor changes in slope and elevation. Unfortunately, exaggeration proves a definite disadvantage in mountainous areas, as it becomes difficult to distinguish between steep and very steep slopes. A camera with a longer focal lens reduces the amount of exaggeration, and therefore its use may prove preferable in such areas. Digital photogrammetric methods use digital images and a computer instead of a photogrammetric plotter to derive digital elevation models (DEMs) with the advantage that various aspects of the measurement process can be automated (Chandler, 2001).

There are four main types of film used in normal aerial photography, namely black and white, infrared monochrome, true colour and false colour. Black-and-white film is used for topographic survey work and for normal interpretation purposes. The other types of film are used for special purposes. For example, infrared monochrome film makes use of the fact that near-infrared radiation is strongly absorbed by water. Accordingly, it is of particular value when mapping shorelines, the depth of shallow underwater features and the presence of water on land, as for instance, in channels, at shallow depths underground or beneath vegetation. Furthermore, it is more able to penetrate haze than conventional photography. True colour photography generally offers much more refined imagery. As a consequence, colour photographs have an advantage over black and white ones as far as photogeological interpretation is concerned. False colour is the term frequently used for infrared colour photography. False colour provides a more sensitive means of identifying exposures of bare grey rocks than any other type of film. Lineaments, variations in water content in soils and rocks and changes in vegetation that may not be readily apparent on black-and-white photographs often are clearly depicted by false colour. A summary of the types of geological information that can be obtained from aerial photographs is given in Table 7.2.

Site Exploration – Direct Methods

The aim of a site exploration is to try to determine and thereby understand the nature of the ground conditions on site and those of its surroundings (Clayton et al., 1996). The extent to which this stage of a site investigation is carried depends, to some extent, upon the size and importance of the construction operation. The site exploration must be concluded by a report embodying the findings, which can be used for design purposes. This should contain geological plans of the site with accompanying sections, thereby conveying a 3D picture of the subsurface strata.

The scale of the mapping will depend on the engineering requirement, the complexity of the geology, and the staff and time available. Rock and soil types should be mapped according to their lithology and, if possible, presumed physical behaviour, that is, in terms of their engineering classification, rather than age. Geomorphological conditions, hydrogeological conditions, landslips, subsidences, borehole and field-test information all can be recorded on geotechnical maps. Particular attention should be given to the nature of the superficial deposits and, where present, made-over ground.

There are no given rules regarding the location of boreholes or drillholes, or the depth to which they should be sunk. This depends upon the geological conditions and the type of project concerned. The information provided by the desk study, the preliminary reconnaissance and from any trial trenches should provide a basis for the initial planning and layout of the borehole or drillhole programme. Holes should be located so as to detect the geological sequence and structure. Obviously, the more complex this is, the greater the number of holes needed. In some instances, it may be as well to start with a widely spaced network of holes. As information is obtained, further holes can be put down if and where necessary.

Table 7.2. Types of photogeological investigation

Structural geology	Mapping and analysis of folding. Mapping of regional fault systems and recording any evidence of recent fault movements. Determination of the number and geometry of joint systems
Rock types	Recognition of the main lithological types (crystalline and sedimentary rocks, unconsolidated deposits)
Soil surveys	Determining main soil type boundaries, relative permeabilities and periglacial studies
Topography	Determination of relief and landforms. Assessment of stability of slopes, detection of old landslides
Stability	Slope instability (especially useful in detecting old failures that are difficult to appreciate on the ground) and rock fall areas, quick clays, loess, peat, mobile sand, soft ground and features associated with old mine workings
Drainage	Outlining of catchment areas, steam divides, surface run-off characteristics, areas of subsurface drainage such as karstic areas, especially of cavernous limestone as illustrated by surface solution features; areas liable to flooding. Tracing swampy ground, perennial or intermittent streams, and dry valleys. Levees and meander migration. Flood control studies. Forecasting effect of proposed obstructions. Run-off characteristics. Shoals, shallow water, stream gradients and widths
Erosion	Areas of wind, sheet and gully erosion, excessive deforestation, stripping for opencast work, coastal erosion
Groundwater	Outcrops and structure of aquifers. Water bearing sands and gravels. Seepages and springs, possible productive fracture zones. Sources of pollution. Possible recharge sites
Reservoirs and dam sites	Geology of reservoir site, including surface permeability classification. Likely seepage problems. Limit of flooding and rough relative values of land to be submerged. Bedrock gullies, faults and local fracture pattern. Abutment characteristics. Possible diversion routes. Ground needing clearing. Suitable areas for irrigation
Materials	Location of sand and gravel, clay, rip-rap, borrow and quarry sites with access routes
Routes	Avoidance of major obstacles and expensive land. Best graded alternatives and ground conditions. Sites for bridges. Pipe and power line reconnaissance. Best routes through urban areas
Old mine workings	Detection of shafts and shallow abandoned workings, subsidence features

Exploration should be carried out to a depth that includes all strata likely to be significantly affected by structural loading. As far as soils are concerned, experience has shown that damaging settlement usually does not take place when the added stress in the soil due to the weight of a structure is less is less than 10% of the effective overburden stress. It therefore would seem logical to sink boreholes on compact sites to depths where the additional stress does not exceed 10% of the stress due to the weight of the overlying strata. It must be borne in mind that if a number of loaded areas are in close proximity the effect of each is additive. Under certain special conditions, holes may have to be sunk more deeply as, for example, when voids due to abandoned mining operations are suspected or when it is suspected that there are highly compressible layers, such as interbedded peats, at depth. If possible, boreholes should be taken through superficial deposits to rockhead. In such instances, adequate penetration of the rock should be specified to ensure that isolated boulders are not mistaken for the solid formation.

The results from a borehole or drillhole should be documented on a log (Fig. 7.1). Apart from the basic information such as number, location, elevation, date, client, contractor and engineer responsible, the fundamental requirement of a borehole log is to show how the sequence of strata changes with depth. Individual soil or rock types are presented in symbolic form on a log. The material recovered must be described adequately, and in the case of rocks frequently include an assessment of the degree of weathering, fracture index and relative strength. The type of boring or drilling equipment should be recorded, the rate of progress made being a significant factor. The water level in the hole and any water loss, when it is used as a flush during rotary drilling, should be noted, as these reflect the mass permeability of the ground. If any in situ testing is done during boring or drilling operations, then the type(s) of test and the depth at which it/they were carried out must be recorded. The depths from which samples are taken must be noted. A detailed account of the logging of cores for engineering purposes is provided by Anon (1970). Description and classification of soils, and of rocks and rock masses, can be found in Anon (1999), while a description and classification of weathered rocks is given in Anon (1995) and of discontinuities in Barton (1978).

Direct observation of strata down a hole, of discontinuities and cavities can be undertaken by cameras or closed-circuit television equipment, and drillholes can be viewed either radially or axially. The camera can be used in boreholes or drillholes down to a minimum diameter of 100 mm. Remote focusing for all heads and rotation of the radial head through 360° are controlled from the surface. The television heads have their own light source. Focussing, light intensity, rotation and digital depth control on the image are made by means of a surface control unit and the image is recorded on standard VHS format video tape. Colour changes in rocks can be detected as a result of the varying amount of light reflected from the drillhole walls. Discontinuities appear as dark areas because of the non-reflection of light. However, if the drillhole is deflected from the vertical, variations in the distribution of light may result in some lack of picture definition.

Subsurface Exploration in Soils

The simplest method whereby data relating to subsurface conditions in soils can be obtained is by hand augering. Soil samples that are obtained by augering are badly disturbed

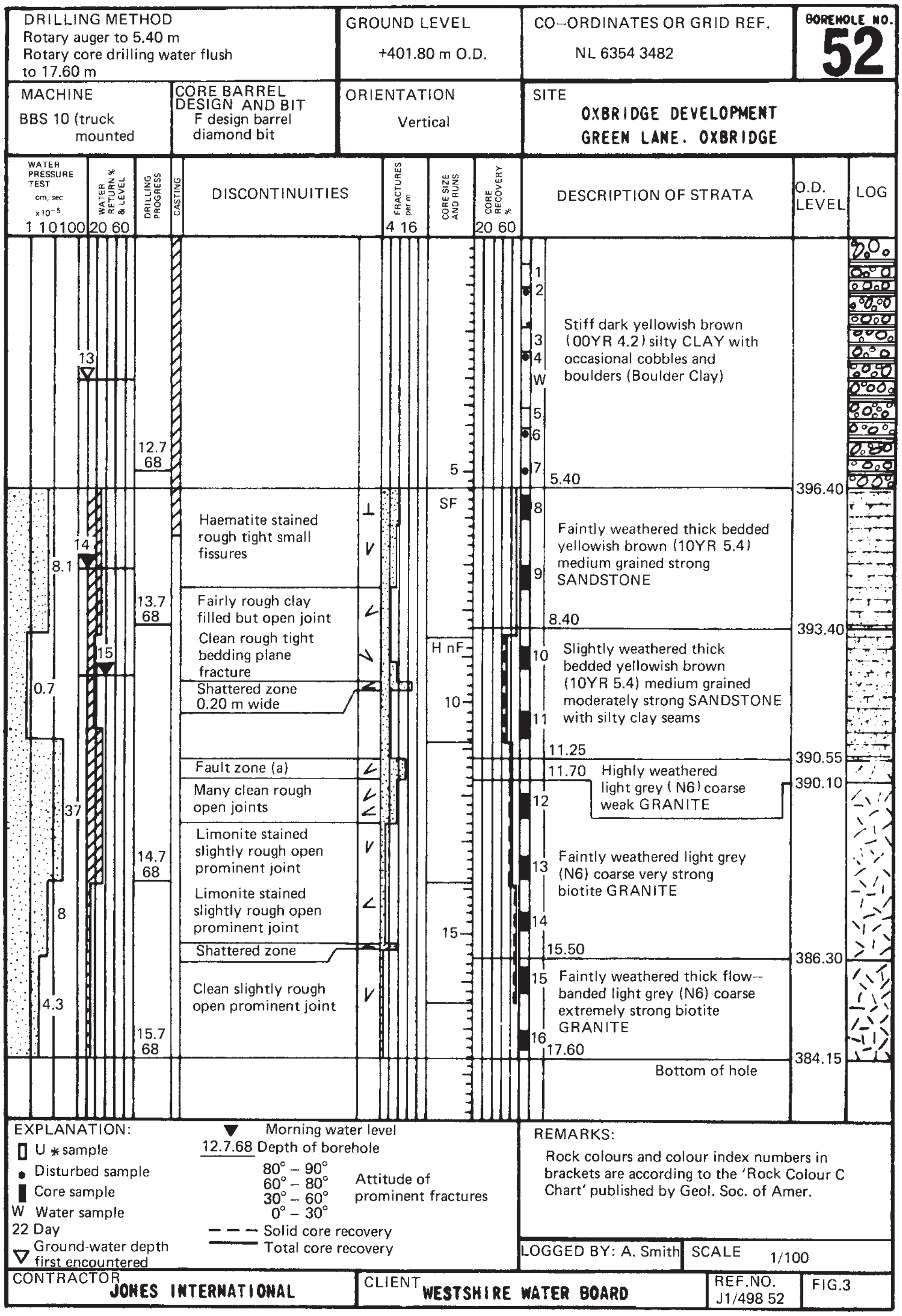

Figure 7.1

Drillhole log. With kind permission of the Geological Society.

and invariably some amount of mixing of soil types occurs. Critical changes in ground conditions therefore are unlikely to be located accurately. Even in very soft soils it may be very difficult to penetrate more than 7 m with hand augers.

Power augers are available as solid stem or hollow stem both having an external continuous helical flight. The later are used in those soils in which the borehole does not remain open. The hollow stem can be sealed at the lower end with a combined plug and cutting bit that is removed when a sample is required. Hollow-stem augers are useful for investigations where the requirement is to locate bedrock beneath overburden. Solid-stem augers are used in stiff clays that do not need casing, however, if an undisturbed sample is required, then they have to be removed. Disturbed samples taken from auger holes often are unreliable. In favourable ground conditions, such as firm and stiff homogeneous clays, auger rigs are capable of high output rates. The development of large earth augers and patent piling systems have made it is possible to sink 1 m diameter boreholes in soils more economically than previously. The ground conditions can be inspected directly from such holes. Depending on the ground conditions, the boreholes may be unlined, lined with steel mesh or cased with steel pipe. In the latter case, windows are provided at certain levels for inspection and sampling.

Pits and trenches allow the ground conditions in soils and highly weathered rocks to be examined directly, although they are limited as far as their depth is concerned. Trenches can provide a flexible, rapid and economic method of obtaining information. Groundwater conditions and stability of the sides obviously influence whether or not they can be excavated, and safety must at all times be observed, necessitating shoring the sides. Pits are expensive and should be considered only if the initial subsurface survey has revealed any areas of special difficulty. The soil conditions in pits and trenches can be mapped or photographed throughout. Undisturbed, as well as disturbed, samples can be collected where necessary.

The light cable and tool boring rig is used for investigating soils (Fig. 7.2). The hole is sunk by repeatedly dropping one of the tools into the ground. A power winch is used to lift the tool, suspended on a cable, and by releasing the clutch of the winch the tool drops and cuts into the soil. Once a hole is established, it is lined with casing, the drop tool operating within the casing. This type of rig usually is capable of penetrating about 60 m of soil, and in doing so the size of the casing in the lower end of the borehole is reduced. The basic tools are the shell and the clay cutter, which are essentially open-ended steel tubes to which cutting shoes are attached. The shell, which is used in granular soils, carries a flap valve at its lower end, which prevents the material from falling out on withdrawal from the borehole. The material is retained in the cutter by the adhesion of the clay.

For boring in stiff clays the weight of the clay cutter may be increased by adding a sinker bar. In very stiff clays, a little water often is added to assist boring progress. This must be done

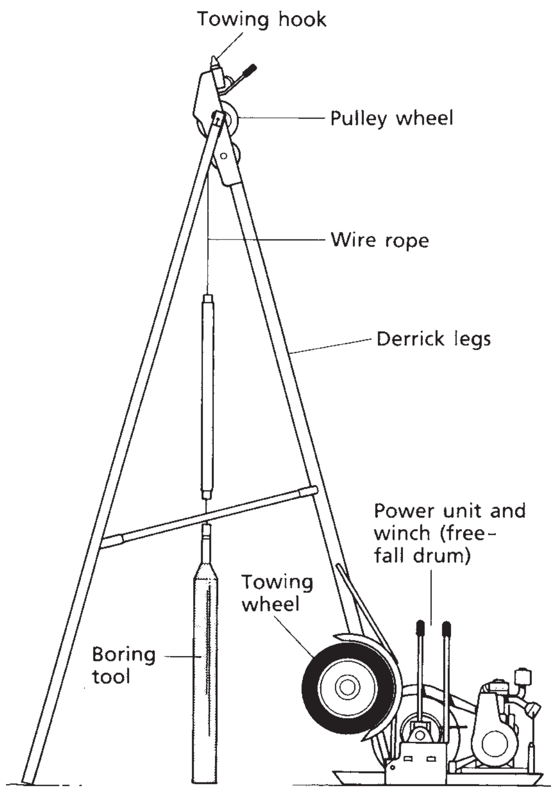

Figure 7.2

Light cable and tool percussion boring rig.

with caution so as to avoid possible changes in the properties of any soil about to be sampled. Furthermore, in such clays, the borehole often can be advanced without lining, except for a short length at the top to keep the hole stable. If cobbles or small boulders are encountered in clays, particularly tills, then these can be broken by using heavy chisels.

When boring in soft clays, although the hole may not collapse, it tends to squeeze inwards and to prevent the cutter operating; the hole therefore must be lined. The casing is driven in and winched out, however, in difficult conditions it may have to be jacked out. Casing tubes have internal diameters of 150, 200, 250 and 300 mm, the most commonly used sizes being 150 and 200 mm (the large sizes are used in coarse gravels).

The usual practice is to bore ahead of the casing for about 1.5 m (the standard length of a casing section) before adding a new section of casing and surging it down. The reason for surging the casing is to keep it “free” in the borehole so that it can be extracted more easily on completion. When the casing can no longer be advanced by surging, smaller diameter casing is introduced. If the hole is near its allotted depth the casing may be driven into the ground for quickness. Where clay occurs below coarse deposits, the casing used as a support in the coarse soils is driven a short distance into the clay to create a seal and the shell is used to remove any water that might enter the borehole.

Boreholes in sands or gravels almost invariably require lining. The casing should be advanced with the hole or overshelling is likely to occur, that is, the sides collapse and prevent further progress. Because of the mode of operation of the shell, the borehole should be kept full of water so that the shell may operate efficiently. Where coarse soils are water-bearing, all that is necessary is for the water in the borehole to be kept topped up. If flow of water occurs, then it should be from the borehole to the surrounding soil. However, if water is allowed to flow into the borehole, piping probably will occur. Piping usually can be avoided by keeping the head of water in the borehole above the natural head. To overcome artesian conditions, the casing should be extended above ground and kept filled with water. The shell generally cannot be used in highly permeable coarse gravels since it usually is impossible to maintain a head of water in the borehole. Fortunately, these conditions often occur at or near ground level, and the problem can sometimes be overcome by using an excavator to open a pit either to the water table or to a depth of 3 to 4 m. Casing can then be put in place, the pit backfilled and boring then can proceed. Another method of penetrating gravels and cobbles above the water table is to employ a special grab with a heavy tripod and winch and casing of 400 mm diameter or greater.

Rotary attachments are available that can be used with light cable and tool rigs. However, they are much less powerful than normal rotary rigs and tend to be used only for short runs as, for example, to prove rockhead at the base of a borehole.

In the wash boring method, the hole is advanced by a combination of chopping and jetting the soil or weak or weathered rock, the cuttings thereby produced being washed from the hole by the water used for jetting (Fig. 7.3). The method cannot be used for sampling, and therefore its primary purpose is to sink the hole between sampling positions. When a sample is required, the bit is replaced by a sampler. Nevertheless, some indication of the type of ground penetrated may be obtained from the cuttings carried to the surface by the wash water, from the rate of progress made by the bit or from the colour of the wash water. Several types of chopping bits are used. Straight and chisel bits are used in sands, silts, clays and very soft rocks, while cross bits are used in gravels and soft rocks. Bits are available with either the jetting points facing upwards or downwards. The former types are better at cleaning the base of the hole than are the latter. The wash boring method may be used in both cased and uncased holes. Casing obviously has to be used in coarse soils to avoid the sides of the hole from collapsing. Although this method of boring commonly is used in the

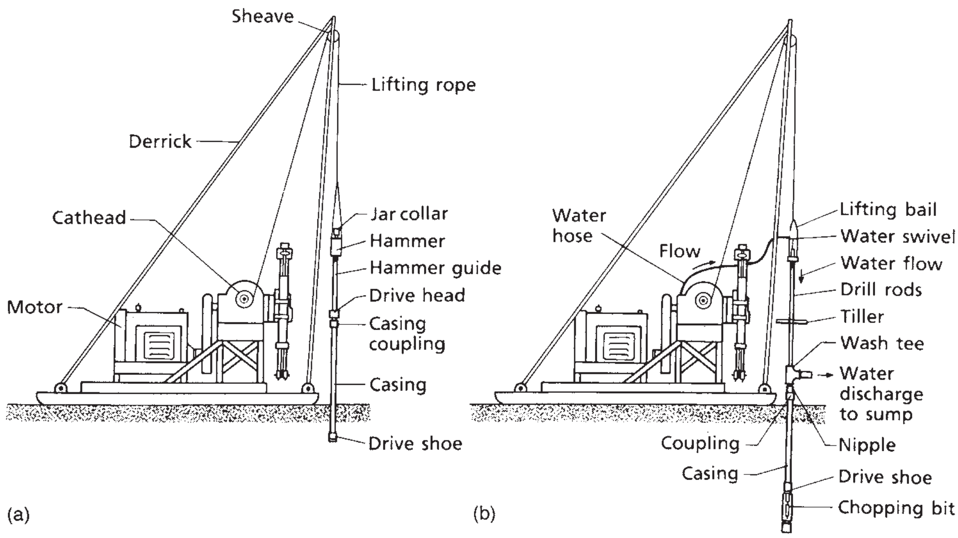

Figure 7.3

Wash-boring rig. (a) Driving the casing, (b) Advancing the hole.

United States, it rarely has been employed in Britain. This is mainly because wash boring does not lend itself to many of the ground conditions encountered and also to the difficulty of identifying strata with certainty.

Sampling in Soils

As far as soils are concerned, samples may be divided into two types, disturbed and undisturbed. Disturbed samples can be obtained by hand, by auger or from the clay cutter or shell of a boring rig. Samples of fine soils should be approximately 0.5 kg in weight, providing a sufficient size for index testing. The samples are sealed in jars. A larger sample is necessary if the particle size distribution of coarse soil is required, and this may be retained in a tough plastic sack. Care must be exercised when obtaining such samples to avoid loss of fines.

An undisturbed sample can be regarded as one that is removed from its natural condition without disturbing its structure, density, porosity, moisture content and stress condition. Although it must be admitted that no sample is ever totally undisturbed, every attempt must be made to preserve the original condition of such samples. Unfortunately, mechanical disturbances produced when a sampler is driven into the ground distort the soil structure. Furthermore, a change of stress condition occurs when a borehole is excavated.

Undisturbed samples may be obtained by hand from surface exposures, pits and trenches. Careful hand trimming is used to produce a regular block, normally a cube of about 250 mm dimensions. Block samples are covered with muslin and sealed with wax. Such samples are particularly useful when it is necessary to test specific horizons, such as shear zones.

As far as any undisturbed sampling tool is concerned, its fundamental requirement is that on being forced into the ground it should cause as little remoulding and displacement of the soil as possible. The amount of displacement is influenced by a number of factors. Firstly, there is the cutting shoe or edge of the sampler. A thin cutting shoe and sampling tube minimize displacement but they can be damaged easily, and they cannot be used in gravels and hard soils. Secondly, the internal diameter of the cutting shoe, D_i, should be slightly less than that of the sample tube, thereby providing inside clearance that reduces drag effects due to friction. Thirdly, the outside diameter of the cutting shoe, D_o, should be from 1 to 3% larger than that of the sampler, again to allow for clearance. The relative displacement of a sampler can be expressed by the area ratio, A_r:

$$A_r = \frac{D_i^2 - D_o^2}{D_o^2} \times \mathbf{100} \tag{7.1}$$

This ratio should be kept as low as possible, for example, displacement is minimized by keeping the area ratio below 15%. It should not exceed 25% (Hvorslev, 1949). Fourthly, friction also can be reduced if the tube has a smooth inner wall. A coating of light oil also may prove useful in this respect.

The standard sampling tube for obtaining samples from cohesive soils is referred to as the U100, having a diameter of 100 mm, a length of approximately 450 mm and walls 1.2 mm thick (Fig. 7.4). The cutting shoe should meet the requirements noted above. The upper end of the tube is fastened to a check valve that allows air or water to escape during driving and helps to hold the sample in place when it is being withdrawn. On withdrawal from the borehole, the sample is sealed in the tube with paraffin wax and the end caps screwed on. In soft materials, two or three tubes may be screwed together to reduce disturbance of the sample.

The standard type of sampler is suitable for clays with a shear strength exceeding 50 kPa. However, a thin-walled piston sampler should be used for obtaining clays with lower shear strength since soft clays tend to expand into the sample tube. Expansion is reduced by a piston in the sampler, the thin-walled tube being jacked down over a stationary internal piston, which, when sampling is complete, is locked in place and the whole assembly then is pulled (Fig. 7.5). Piston samplers range in diameter from 54 to 250 mm. A vacuum tends to be created between the piston and the soil sample, which thereby helps to hold it in place.

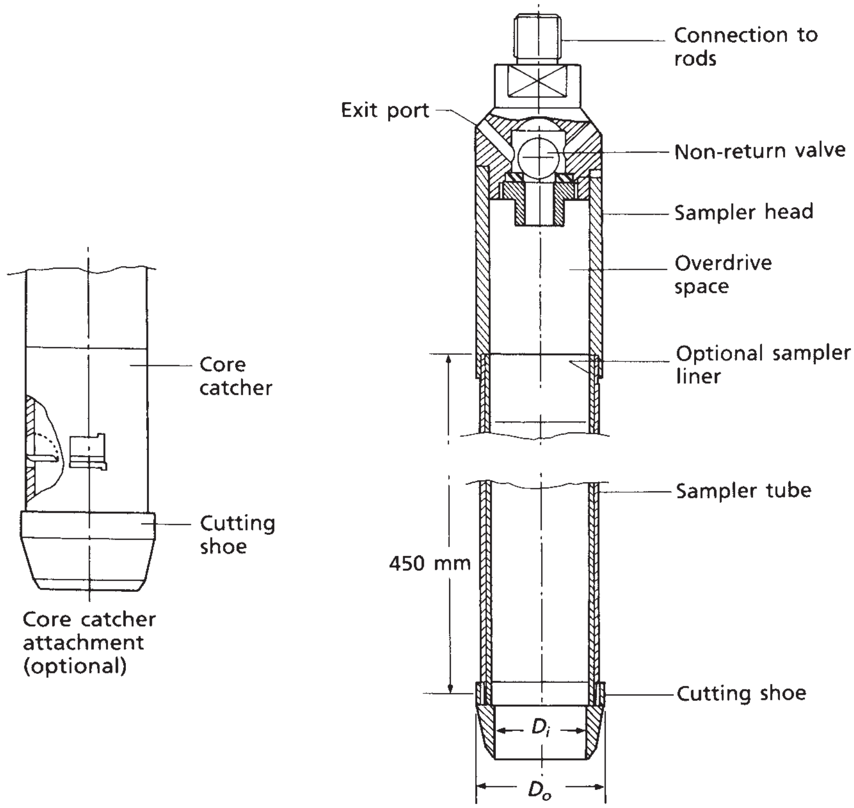

Figure 7.4

The general-purpose open-tube sampler, U100.

When continuous samples are required, particularly from rapidly varying or sensitive soils, a Delft sampler may be used (Fig. 7.6). This can obtain a continuous sample from ground level to depths of about 20 m. The core is retained in a self-vulcanising sleeve as the sampler is continuously advanced into the soil.

Sub-surface Exploration in Rocks and Sampling

Rotary drills are either skid-mounted, trailer mounted or, in the case of larger types, mounted on lorries (Fig. 7.7). They are used for drilling through rock, although they can penetrate and take samples from soil.

Rotary percussion drills are designed for rapid drilling in rock (Fig. 7.8). The rock is subjected to rapid high-speed impacts while the bit rotates, which brings about compression and shear

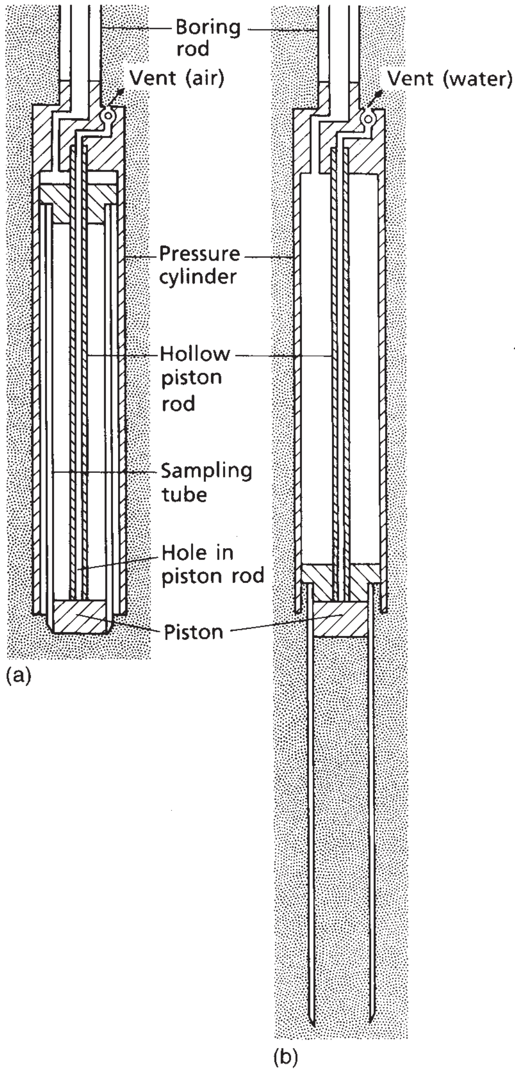

Figure 7.5

Piston sampler of hydraulically operated type. (a) Lowered to bottom of borehole, boring rod clamped in fixed position at the ground surface, (b) Sampling tube after being forced into the soil through water supplied through boring rod.

in the rock. Full-face bits, which produce an open hole, are used. These are usually of the studded, cruciform or tricone roller bit type (Fig. 7.9). The technique is most effective in brittle materials since it relies on chipping the rock. The rate at which drilling proceeds depends upon the type of rock, particularly on its strength, hardness and fracture index; the type of drill and drill bit; the flushing medium and the pressures used; as well as the experience of the drilling crew. Compressed air, water or mud may be used as the flush. If the drilling operation is standardized,

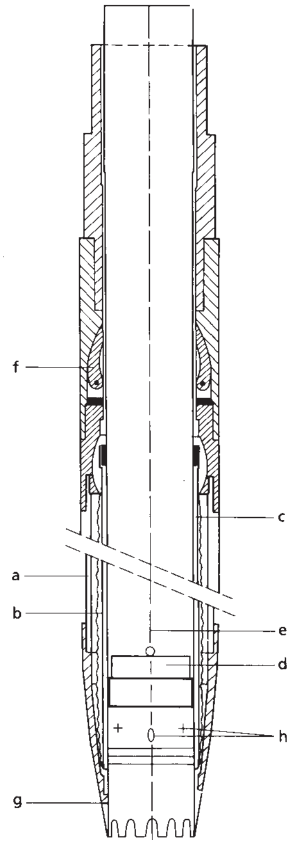

Figure 7.6

Section through a 66-mm continuous sampling apparatus. (a) Outer tube, (b) stocking tube over which pre-coated nylon stocking is slid, (c) plastic inner tube, (d) cap at top of sample, (e) steel wire to fixed point at the ground surface (tension cable), (f) sample-retaining clamps, (g) cutting shoe, (h) holes for entry of lubricating fluid.

then differences in the rate of penetration reflect differences in rock types. Drill flushings should be sampled at regular intervals, at changes in the physical appearance of the flushings and at significant changes in penetration rates. Interpretation of rotary percussion drillholes should be related to a cored drillhole near by. Rotary percussion drilling sometimes is used as a means of advancing a hole at low cost and high speed between intervals where core drilling is required.

For many engineering purposes, a solid, and as near as possible continuous rock core, is required for examination. The core is cut with a bit and housed in a core barrel (Fig. 7.10). The bit is set with diamonds or tungsten carbide inserts. In set bits, diamonds are set on the face of the matrix. The coarser surface set diamond and tungsten carbide tipped bits are used in softer formations. These bits generally are used with air rather than with water flush. Impregnated bits possess a matrix impregnated with diamond dust, and their grinding action

Figure 7.7

Medium-size, skid-mounted rotary drill.

is suitable for hard and broken formations. In fact, most core drilling is carried out using diamond bits, the type of bit used being governed by the rock type to be drilled. In other words, the harder the rock, the smaller the size and the higher the quality of the diamonds that are required in the bit. Tungsten bits are not suitable for drilling in very hard rocks. Thick-walled bits are more robust but penetrate more slowly than thin-walled bits. The latter produce a larger core for a given hole size. This is important where several reductions in size have to be made. Core bits vary in size, and accordingly core sticks range between 17.5 and 165 mm diameter. Other factors apart, generally the larger the bit, the better is the core recovery.

A variety of core barrels is available for rock sampling. The simplest type of core barrel is the single tube, but because it is suitable only for hard massive rocks, it rarely is used. In the single-tube barrel, the barrel rotates the bit and the flush washes over the core. In double-tube barrels, the flush passes between the inner and outer tubes. Double tubes may be of the rigid or swivel type. The disadvantage of the rigid barrel is that both the inner and outer tubes rotate together, and in soft rock this can break the core as it enters the inner tube.

Figure 7.8

Rotary percussion drilling rig.

It therefore is only suitable for hard rock formations. In the double-tube swivel-core barrel, the outer tube rotates while the inner tube remains stationary (Fig. 7.11). It is suitable for use in medium and hard rocks, and gives improved core recovery in soft friable rocks. The face-ejection barrel is a variety of the double-tube swivel-type in which the flushing fluid does not affect the end of the core. This type of barrel is a minimum requirement for coring badly shattered, weathered and soft rock formations. Triple-tube barrels are used for obtaining cores from very soft rocks and

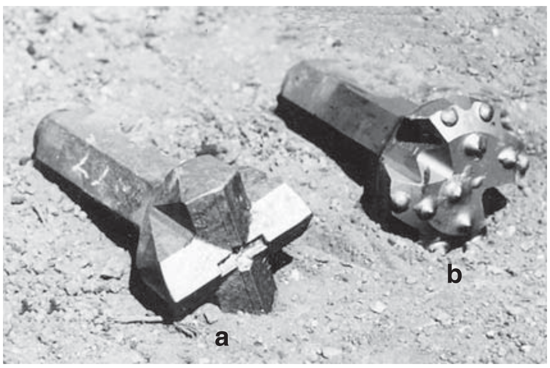

Figure 7.9

Full-face bits for rotary percussion, (a) cross-chisel or cruciform bit, (b) studded bit.

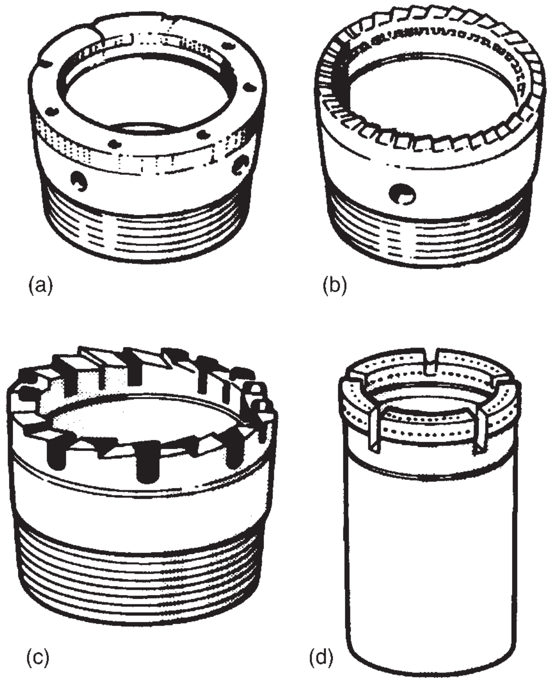

Figure 7.10

Some common types of coring bits, (a) surface-set diamond bit (bottom discharge), (b) stepped saw-tooth bit, (c) tungsten carbide bit, (d) impregnated diamond bit.

from highly jointed and cleaved rocks. This type of core barrel has an inner triple tube that is split into two halves longitudinally. Hence, when withdrawn from the outer casing of the core barrel the core can be observed and described without the risk of disturbance.

Both the bit and core barrel are attached by rods to the drill by which they are rotated. Either water or air is used as a flush. This is pumped through the drill rods and discharged at the bit. The flushing agent serves to cool the bit and to remove the cuttings from the drillhole. Bentonite is sometimes added to the water flush. It eases the running and pulling of casing by lubrication, it holds chippings in suspension and promotes drillhole stability by increasing flush returns through the formation of a filter skin on the walls of the hole.

Disturbance of the core is likely to occur when it is removed from the core barrel. Most rock cores should be removed by hydraulic extruders while the tube is held horizontal. To reduce disturbance during extrusion the inner tube of double-core barrels can be lined with a plastic sleeve before drilling commences. On completion of the core run, the plastic sleeve containing the core is withdrawn from the barrel.

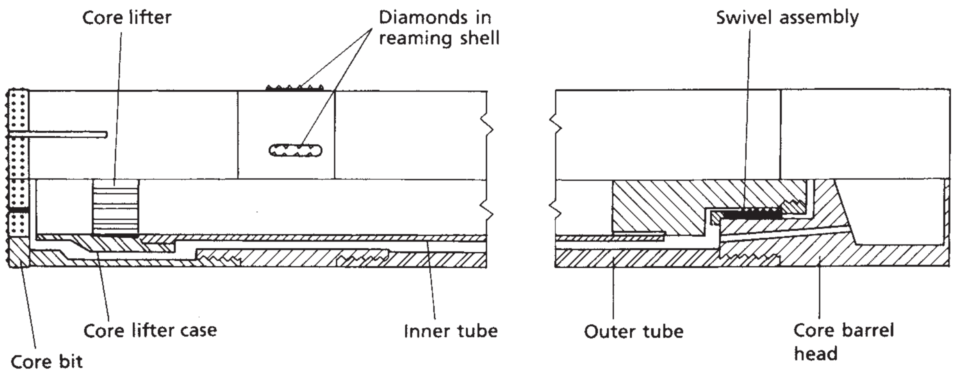

Figure 7.11

Double-tube swivel-type core barrel.

If casing is used for drilling operations, then it is drilled into the ground using a tungsten-carbide- or diamond-tipped casing shoe with air, water or mud flush. The casing may be inserted down a hole drilled to a larger diameter to act as conductor casing when reducing and drilling ahead in a smaller diameter, or it may be drilled or reamed in a larger diameter than the initial hole to allow continued drilling in the same diameter.

Many machines will core drill at any angle between vertical and horizontal. Unfortunately, inclined drillholes tend to go off line, the problem being magnified in highly jointed formations. In deeper drilling, the sag of the rods causes the hole to deviate. Drillhole deviation can be measured by an inclinometer.

The weakest strata generally are of the greatest interest, but these are the materials that are most difficult to obtain and most likely to deteriorate after extraction. Shales and mudstones are particularly prone to deterioration, and some may disintegrate completely if allowed to dry. Deterioration of suspect rock may be reduced by wrapping core material with aluminium foil or plastic sheeting. Core material may be photographed before it is removed from site. Zones of core loss or no recovery must be recorded as these could represent problem zones. Hawkins (1986) introduced the concept of lithology quality designation, LQD, which he defined as the percentage of solid core present greater than 100 mm in length within any lithological unit. He also recommended that the total core recovery, TCR, and the maximum intact core length, MICL, should be recorded.

A simple but nonetheless important factor is labelling of core material. This must record the site, the drillhole number and the position in the drillhole from which material was obtained. The labels themselves must be durable and properly secured. When rock samples are stored in a core box, the depth of the top and bottom of the core contained and of the separate core runs should be noted both outside and inside the box. Zones of core loss should be identified.

In Situ Testing

There are two categories of penetrometer tests, the dynamic and the static. Both methods measure the resistance to penetration of a conical point offered by the soil at any particular depth. Penetration of the cone creates a complex shear failure and thus provides an indirect measure of the in situ shear strength of the soil.

The most widely used dynamic method is the standard penetration test. This empirical test, which was designed initially for use in sands, consists of driving a split-spoon sampler, with an outside diameter of 50 mm, into the soil at the base of a borehole. If the test is carried out in gravelly soils, then the cutting shoe is replaced by a 60° cone. Drivage is accomplished by a trip hammer, weighing 65 kg, falling freely through a distance of 760 mm onto the drive head, which is fitted at the top of the rods (Fig. 7.12). First, the split-spoon is driven 150 mm into the soil at the bottom of the borehole. It then is driven a further 300 mm, and the number of blows required to drive this distance is recorded. The blow count is referred to as the N value from which the relative density of coarse soil can be assessed (Table 7.3). Refusal is regarded as 50 blows. In deep boreholes, the standard penetration test suffers the disadvantage that the load is applied at the top of the rods so that some of the energy from the blow is dissipated in the rods. Hence, with increasing depth the test results become more suspect.

The results obtained from the standard penetration test provide an evaluation of the degree of compaction of sands, and the *N* values may be related to the values of the angle of internal friction, ϕ, and the allowable bearing capacity. The lowest values of the angle of internal friction given in Table 7.3 are conservative estimates for uniform clean sand, and they should be reduced by at least 5° for clayey sand. The upper values apply to well graded sand and may be increased by 5° for gravelly sand. Terzaghi and Peck (1968) suggested that the relative density for very fine or silty submerged sand with a standard penetration value *N*' greater than 15 would be nearly equal to that of a dry sand with a standard penetration value, *N*, where:

$$N = \mathbf{15} + \frac{\mathbf{1}}{\mathbf{2}}(N' - \mathbf{15}) \qquad (7.2)$$

If this correction was not made, Terzaghi and Peck suggested that the relative density of even moderately dense very fine or silty submerged sand might be overestimated by the results of standard penetration tests. In gravel deposits, care must be taken to determine whether a large gravel size may have influenced the results. Usually, in the case of

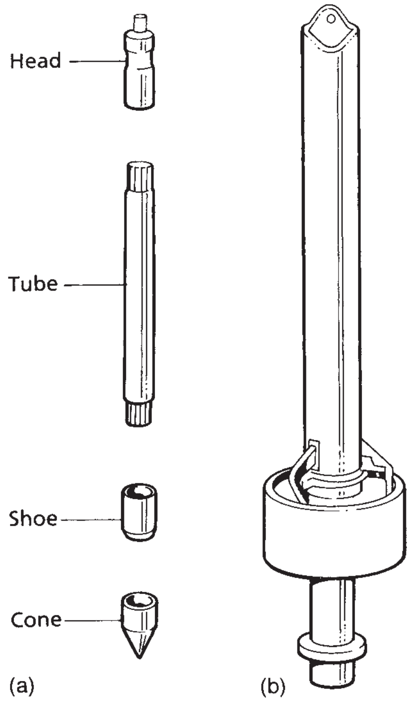

Figure 7.12

Standard penetration test equipment, (a) split spoon sampler with shoe or cone end caps, (B) trip hammer.

gravel, only the lowest values of *N* are taken into account. The standard penetration test also can be employed in stiff clays, weak rocks and in the weathered zones of harder rocks (Table 7.3).

The most widely used static method employs the Dutch cone penetrometer (Fig. 7.13). It is particularly useful in soft clays and loose sands, where boring operations tend to disturb in situ values. In this technique, a tube and inner rod with a conical point at the base are hydraulically advanced into the ground, the reaction being obtained from pickets screwed into the ground. The cone has a cross-sectional area of 1000 mm^2 with an angle of 60°. At approximately every 300 mm depth, the cone is advanced ahead of the tube a distance of 50 mm and the maximum resistance noted. The tube then is advanced to join the cone after each measurement and the process repeated. The resistances are plotted against their corresponding depths so as to give a profile of the variation in consistency (Fig. 7.14). One type of Dutch cone penetrometer has a sleeve behind the cone that can measure side friction. The ratio of sleeve resistance to that of cone resistance is higher in fine than in coarse soils, thus affording a tentative estimate of the type of soil involved.

Table 7.3. Relative density and consistency of soil

(a) Relative density of sand and SPT values, and relationship to angle of friction

SPT(N)	Relative density (D_r)	Description of compactness	Angle of internal friction (φ)
4	0.2	Very loose	Under 30°
4–10	0.2–0.4	Loose	30–35°
10–30	0.4–0.6	Medium dense	35–40°
30–50	0.6–0.8	Dense	40–45°
Over 50	0.8–1.0	Very dense	Over 45°

(b) N values, consistency and unconfined compressive strength of cohesive soils

N	Consistency	Unconfined compressive strength (kPa)
Under 2	Very soft	Under 20
2–4	Soft	20–40
5–8	Firm	40–75
9–15	Stiff	75–150
16–30	Very stiff	150–300
Over 30	Hard	Over 300

In the piezocone, a cone penetrometer is combined with a piezometer, the latter being located between the cone and the friction sleeve. The pore water pressure is measured by the piezometer at the same time as the cone resistance, and sleeve friction is recorded. Because of the limited thickness of the piezometer (the filter is around 5 mm), much thinner layers can be determined with greater accuracy than with a conventional cone penetrometer. If the piezocone is kept at a given depth so that the pore water pressure can dissipate with time, then this allows assessment of the in situ permeability and consolidation characteristics of the soil to be made (Sills and Hird, 2005).

Because soft clays may suffer disturbance when sampled and therefore give unreliable results when tested for strength in the laboratory, a vane test may be used to measure the in situ undrained shear strength. Vane tests can be used in clays that have a consistency varying from very soft to firm. In its simplest form, the shear vane apparatus consists of four blades arranged in cruciform fashion and attached to the end of a rod (Fig. 7.15). To eliminate the effects of friction of the soil on the vane rods during the test, all rotating parts, other than the vane, are enclosed in guide tubes. The vane normally is housed in a protective shoe. The vane and rods are pushed into the soil from the surface or the base of a borehole to a point 0.5 m above the required depth of testing. Then, the vane is pushed out of the protective shoe and advanced to the test position. It then is rotated at a rate of 6 to 12° per minute. The torque is applied to the vane rods by means of a torque-measuring instrument mounted at ground

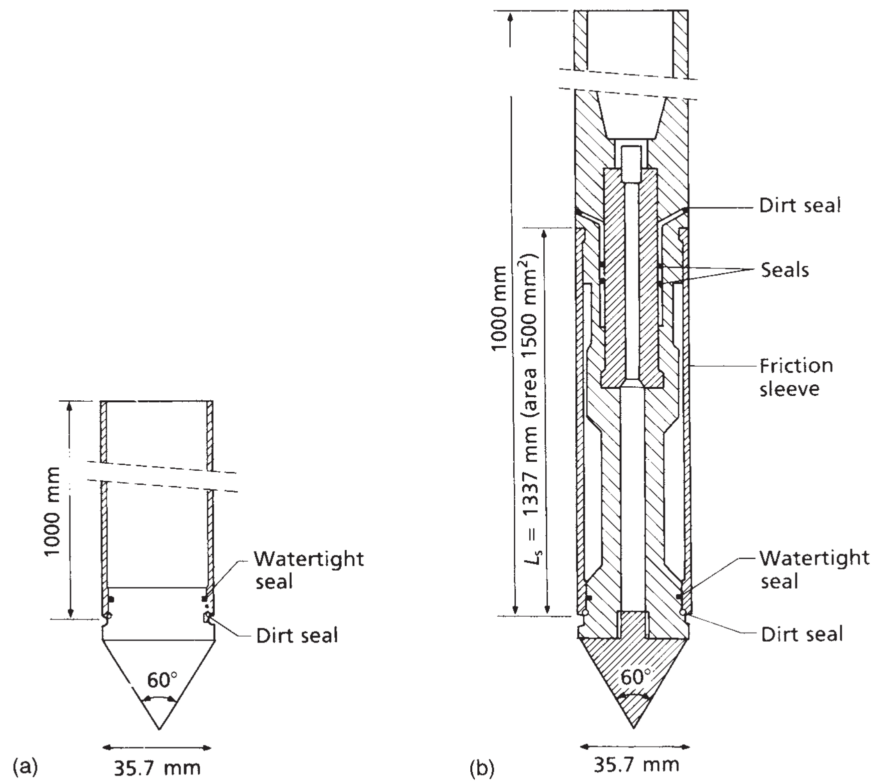

Figure 7.13

An electric penetrometer tip. (a) without friction sleeve, (b) with friction sleeve.

level and clamped to the borehole casing or rigidly fixed to the ground. The maximum torque required for rotation is recorded. When the vane is rotated, the soil fails along a cylindrical surface defined by the edges of the vane as well as along the horizontal surfaces at the top and bottom of the blades. The shearing resistance is obtained from the following expression:

$$\tau = \frac{M}{\pi\left(\frac{D^2H}{2} + \frac{D^3}{6}\right)} \tag{7.3}$$

where τ is the shearing resistance, D and H are the diameter and height of the vane, respectively, and M is the torque. Tests in clays with high organic contents or with pockets of sand or silt are likely to produce erratic results. The results therefore should be related to borehole evidence.

Loading tests can be carried out on loading plates in soils or rocks (Fig. 7.16a). However, just because the ground immediately beneath a plate is capable of carrying a heavy load without excessive settlement, this does not necessarily mean that the ground will carry the proposed

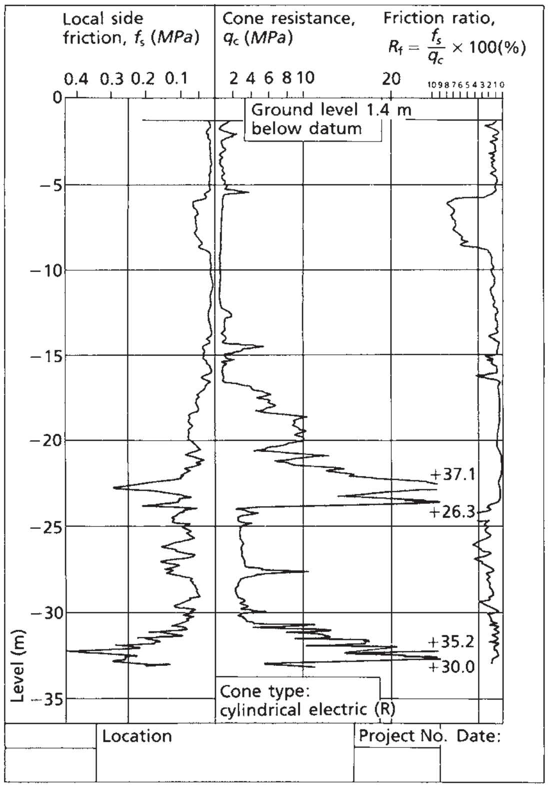

Figure 7.14

Typical record of cone penetrometer test.

structural load. This is especially the case where a weaker horizon occurs at depth but is still within the influence of the bulb of pressure that will be generated by the structure (Fig. 7.16b). The plate-loading test provides information by which the bearing capacity and settlement characteristics of a foundation can be assessed (Matthews and Clayton, 2004). Such a test may be carried out in a trial pit, usually at excavation base level. Plates vary in size from 0.15 to 1.0 m in diameter. Tomlinson (2001) recommended that a 300 mm plate was the minimum size that should be used in stiff fissured clays in order to obtain their undrained shear strength. If the deformation modulus is required for such soils, then Tomlinson recommended a plate size of 750 mm. The plate should be bedded properly and the test carried out on undisturbed material so that reliable results may be obtained. The load is applied by a hydraulic jack bearing against beams supporting kentledge, or reaction may be provided by ground anchors or tension piles installed on either side of the load position. The load may be applied in increments, either of one-fifth of the proposed bearing pressure or in steps of 25 to 50 kPa (these are smaller in soft soils, i.e. where the settlement under the first increment of 25 kPa is greater than 0.002D, D being the diameter of the plate). Successive increments

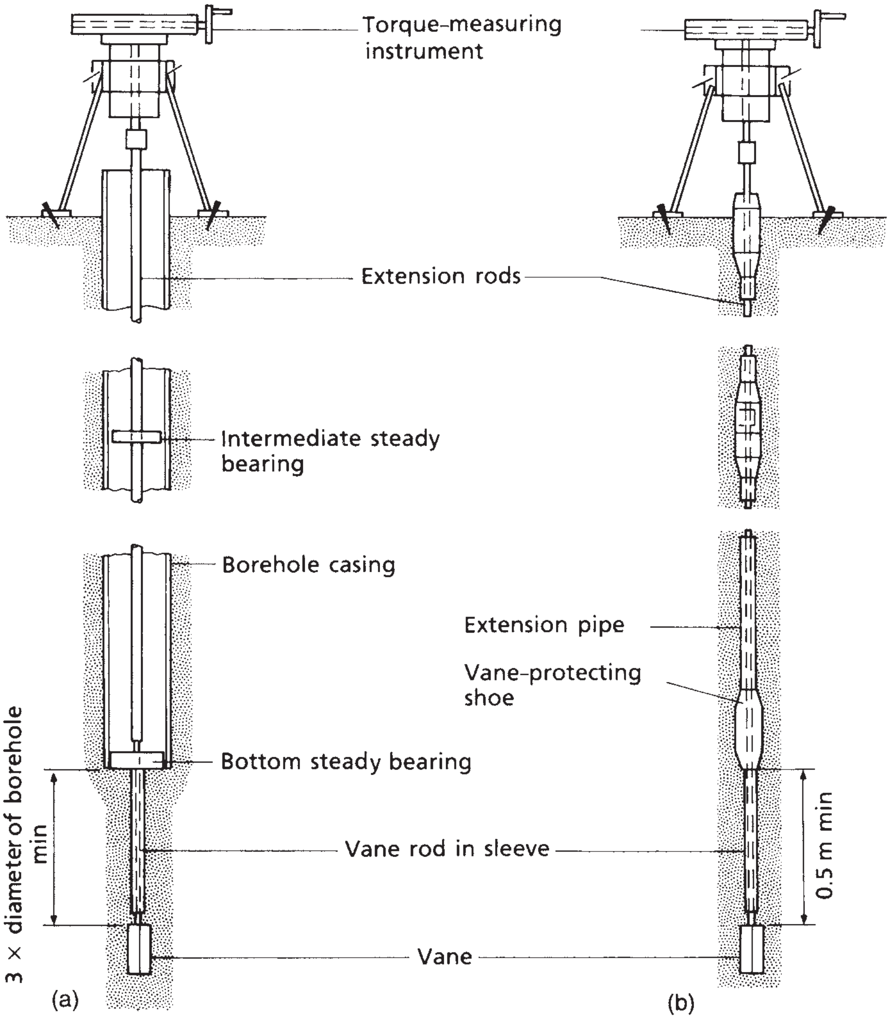

Figure 7.15

Shear vane tests, (a) borehole vane test, (b) penetration vane test.

should be made after settlement has ceased. The test generally is continued up to two or three times the proposed loading or in clays until settlement equal to 10 to 20% of the plate dimension is reached or the rate of increase of settlement becomes excessive. When the final increment is applied in clays, the load should be maintained until the rate of settlement becomes less than 0.1 mm in 2 h. This can be regarded as the completion of the primary consolidation stage. Settlement curves can be drawn with this information from which the ultimate loading can be determined and an evaluation of Young's modulus made. At the end of the consolidation stage, the plate can be unloaded in the same incremental steps in order to obtain an unloading curve.

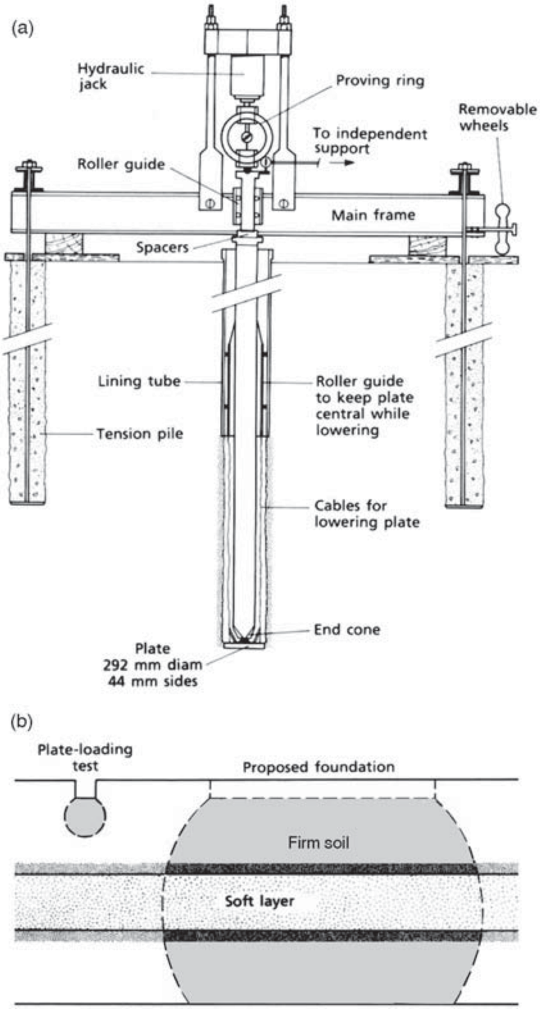

Figure 7.16

(a) Plate load test. With the permission of the Director of the Building Research Establishment. (b) Bulb of pressure developed beneath a foundation compared with one developed beneath a plate load test.

The screw plate is a variant of the plate load test in which a helical screw is rotated into the ground to the depths at which the test is to be conducted. The test has the advantage that no excavation or drilling are needed, and it can be performed beneath the water table. Unfortunately, however, screwing the plate into the soil may cause disturbance around the plate.

Large-plate-bearing tests frequently are used to determine the value of Young's modulus of the foundation rock at large civil engineering sites, such as at dam sites. Loading of the order of several mega-newtons is required to obtain measurable deformation of representative areas. The area of rock load is usually 1 m^2. Tests may be carried out in specially excavated galleries in order to provide a sufficiently strong reaction point for the loading jacks to bear against. The test programme normally includes cycles of loading and unloading. Such tests show that during loading a noticeable increase in rigidity normally occurs in the rock mass and that during unloading a very small deformation occurs for the high stresses applied, with very large recuperation of deformation being observed for stresses near zero. This is due to joint closure. Once the joints are closed, the adhesion between the faces prevents their opening until a certain unloading is reached. However, when brittle rocks such as granite, basalt and limestone have been tested, they generally have given linear stress–strain curves and have not exhibited hysteresis.

Variations of the plate-load test include the freyssinet jack test. This is placed in a narrow slit in a rock mass and then grouted into position so that each face is in uniform contact with the rock. Pressure then is applied to the jack. Unless careful excavation, particularly if blasting, takes place in

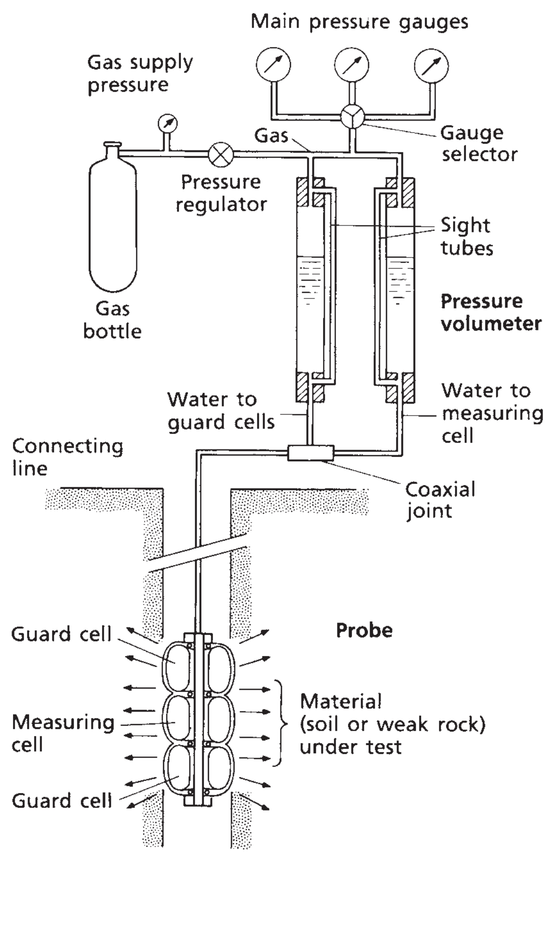

Figure 7.17

The Menard pressuremeter.

the testing area, the results of a test may be worthless. All loose rock must be removed before cutting the slot. Freyssinet jacks can be used to measure residual stress as well as Young's modulus.

The Menard pressuremeter is used to determine the in situ strength of the ground (Fig. 7.17). It is particularly useful in those soils from which undisturbed samples cannot be obtained readily. This pressuremeter consists essentially of a probe that is placed in a borehole at the appropriate depth and then expanded. Where possible the test is carried out in an unlined hole but if necessary a special slotted casing is used to provide support. The probe consists of a cylindrical metal body over which are fitted three cylinders. A rubber membrane covers the cylinders and is clamped between them to give three independent cells. The cells are inflated with water and a common gas pressure is applied by a volumeter located at the surface, thus a radial stress is applied to the soil. The deformations produced by the central cell are indicated on the volumeter. A simple pressuremeter test consists of 10 or more equal pressure increments with corresponding volume change readings, taken to the ultimate failure strength of the soil concerned. Four volume readings are made at each pressure step at time intervals of 15, 30, 60 and 120 s after the pressure has stabilized. It is customary to unload the soil at the end of the elastic phase of expansion and to repeat the test before proceeding to the ultimate failure pressure. This test thus provides the ultimate bearing capacity of soils as well as their deformation modulus. The test can be applied to any type of soil, and takes into account the influence of discontinuities. It also can be used in weathered zones of rock masses and in weak rocks such as some shales and marls. It provides an almost continuous method of in situ testing.

The major advantage of a self-boring pressuremeter is that a borehole is unnecessary. Consequently, the interaction between the probe and the soil is improved. Self-boring is brought about either by jetting or using a chopping tool (Fig. 7.18). For example, the camkometer has a special cutting head so that it penetrates soft ground to form a cylindrical cavity of its exact dimensions and thereby creates a minimum of disturbance (Fig. 7.18b). The camkometer measures the lateral stress, undrained stress–strain properties and the peak stress of soft clays and sands in situ. Clarke (1990) described the use of the self-boring pressuremeter test to determine the in situ consolidation characteristics of clay soils.

A dilatometer can be used in a drillhole to obtain data relating to the deformability of a rock mass (Fig. 7.19). These instruments range up to about 300 mm in diameter and over 1 m in length and can exert pressures of up to 20 MPa on the drillhole walls. Diamentral strains can be measured either directly along two perpendicular diameters or by measuring the amount of liquid pumped into the instrument. The last method is less accurate and is only used when the rock is very deformable.

In an in situ shear test, a block of rock is sheared from a rock surface while a horizontal jack exerts a vertical load. It is advantageous to make the tests inside galleries, where

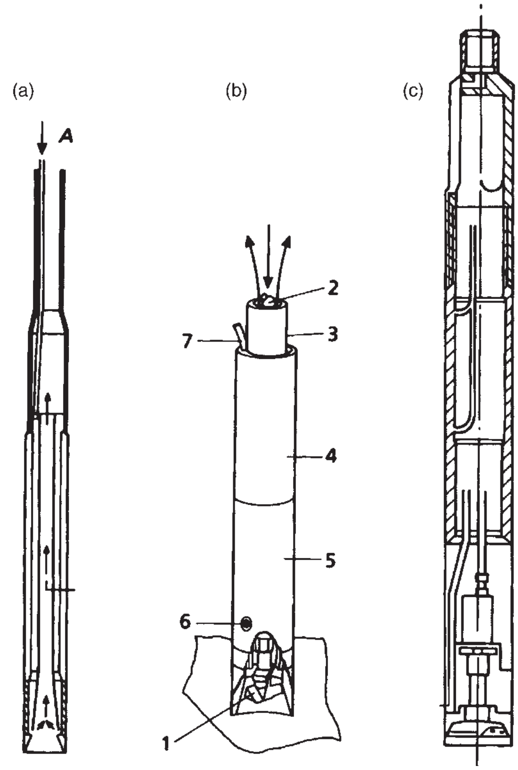

Figure 7.18

(a) Schematic diagram of self-boring pressuremeter. This pressuremeter is available in three diameters (65, 100 and 132 mm). The injection fluid flow that can be applied is limited by the section of flexible pipe (A). Consequently, this pressuremeter can be used only in fine sands or soft cohesive soils. (b) The Camkometer breaks up the soil with a chopping tool rotated by a drill string driven from the surface. The chopping tool (1) is driven by a hollow middle rod (2) through which water is driven under pressure. This rod turns freely within a tube (3) used for removing sediment to the surface. There also is a tube (4) that carries the pressiometric cell (5) that may be equipped with a pore pressure tap (6). The pressiometeric cell supply and measurement lines (7) run through the annulus between the two tubes. (c) Self-boring pressuremeter probe with built in motor.

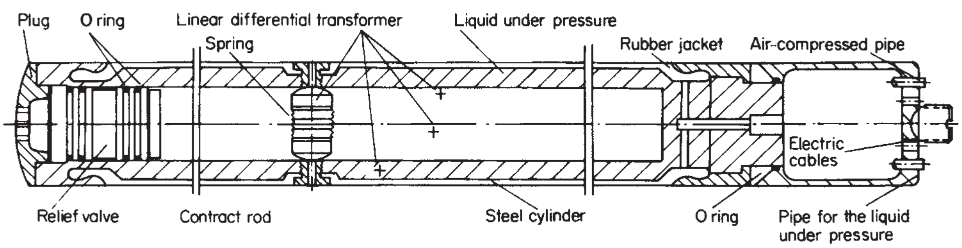

Figure 7.19

A dilatometer.

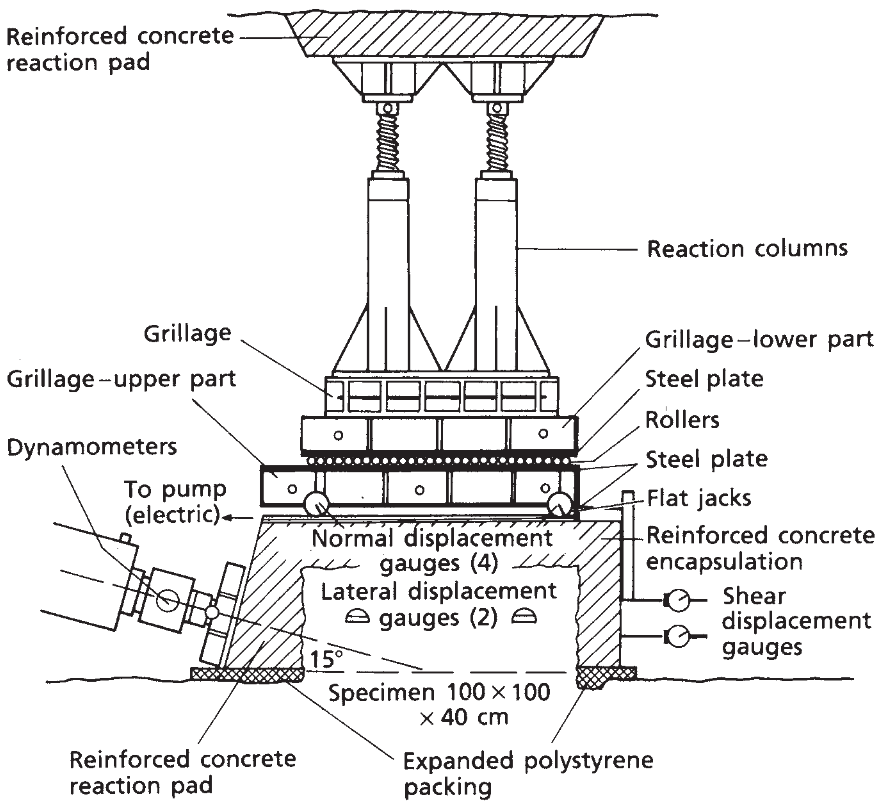

Figure 7.20

The in situ shear test apparatus.

reactions for the jacks are readily available (Fig. 7.20). The tests are performed at various normal loads and give an estimate of the angle of shearing resistance and cohesion of the rock. The value of this test in very jointed and heterogeneous rocks is severely limited both because of the difficulty in isolating undisturbed test blocks and because the results cannot be translated to the scale of conditions of the actual structure and its foundation. In situ shear tests usually are performed on blocks, 700 × 700 mm^2, cut in the rock. These tests can be made on the same rock where it shows different degrees of alteration and can be used to derive the shear strength parameters along discontinuities.

Field Instrumentation

When some degree of risk is involved in construction, some type of field instrumentation may be required in order to provide a continual check on the stability of the structure during its life span. Furthermore, field observations of both the magnitude and rate of subsurface ground movements are needed in connection with deep excavations, slope stability and earth and rockfill dam construction. Such instrumentation needs to assess the pore water pressure, deformation and stress and strain in the ground. However, an instrumentation programme does not usually constitute part of a site investigation.

Surface deformation either in the form of settlements or horizontal movements can be monitored by precise surveying methods, the use of electronic distance measurement, EDM, or laser equipment providing particularly accurate results. Settlement, for example, can be recorded by positioning reference marks on the structures concerned and readings being taken by precise surveying methods. The observations are related to nearby bench marks. Vertical movements also can be determined by settlement tubes or by water-level or mercury-filled gauges.

Borehole extensometers are used to measure the vertical displacement of the ground at different depths. A single-rod extensometer is anchored in a borehole, and movement between the anchor and the reference tube is monitored. Multiple-rod installations monitor displacements at various depths using rods of various lengths. Each rod is isolated by a close-fitting plastic sleeve and the complete assembly is grouted into place, fixing the anchors to the ground while allowing free movement of each rod within its sleeve (Fig. 7.21a). A precise borehole extensometer consists of circular magnets embedded in the ground, which act as markers, and reed switch sensors move in a central access tube to locate the positions of the magnets (Fig. 7.21b).

An inclinometer is used to measure horizontal movements below ground and relies on the measurement of the angle a pendulum makes with the vertical at given positions in a specially cased borehole (Fig. 7.22). The gravity-operated pendulum transmits electrical signals to a recorder, and a vertical profile thereby is obtained. Sets of readings over a period of time enable both the magnitude and rate of horizontal movement to be determined.

The measurement of stress, contact pressures and stress change may be made in two ways. Strain may be measured and then converted to stress, or stress may be measured directly by an earth pressure cell such as the Glotzl cell. This is a hydraulic (flat diaphragm) cell that has a high stiffness at constant temperature and is used for measuring contact pressures. An earth cell must be placed in position in such a way as to minimize disturbance of the stress and strain distribution. Ideally, an earth pressure cell should have the same elastic properties as the surrounding soil. This, of course, cannot be attained, and in order to minimize the magnitude of error (i.e. the cell action factor), the ratio of the thickness to the diameter of the cell should not exceed 0.2 and the ratio of the diameter to the deflection of the diaphragm must be 2000 or greater. Most strain measurements in soils and soft rocks are deformation measurements that are interpreted in terms of strain. A strain cell is required to move with the soil without causing it to be reinforced. In order to record strain, it is necessary to monitor the relative movements of two fixed points at either end of a gauge length. Strain cells with a

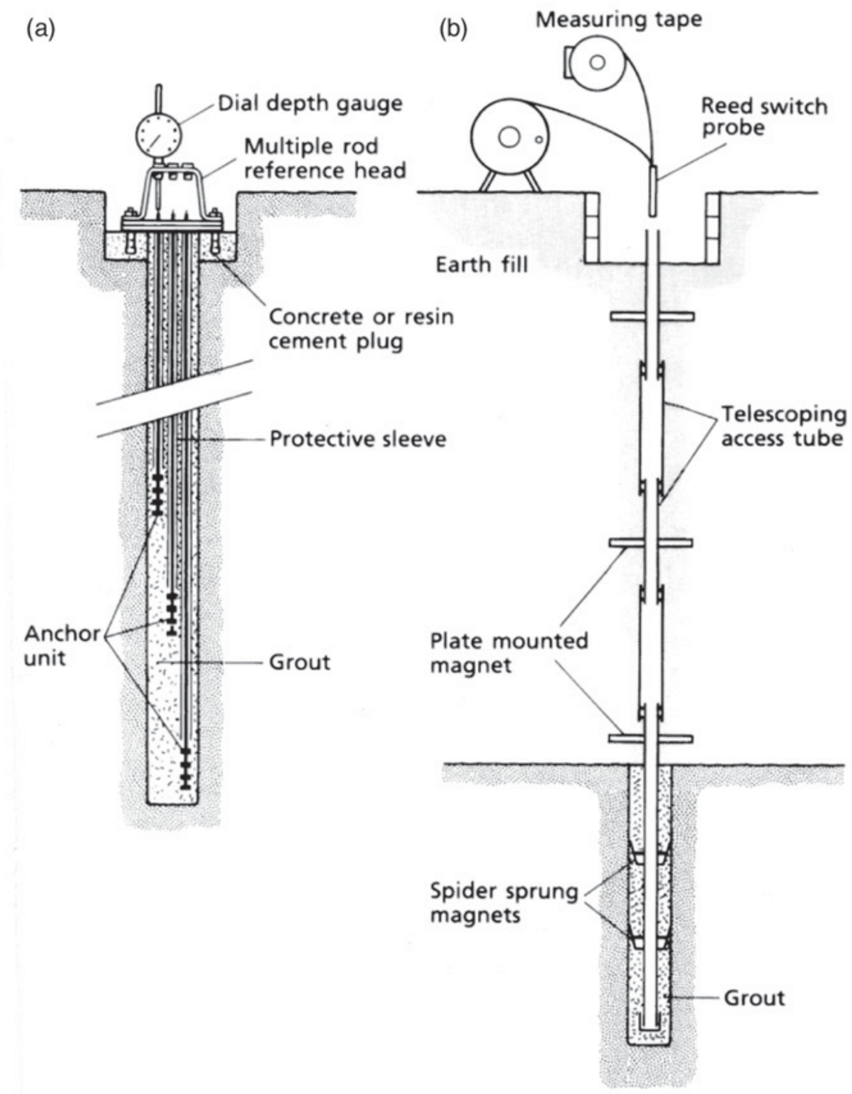

Figure 7.21

(a) Multiple rod extensometer. (b) Magnetic probe extensometer.

positive connection between their end plates have difficulty in measuring small strains. This can be overcome by substituting separated strain cells at either end of the gauge length.

Geophysical Methods: Indirect Site Exploration

A geophysical exploration may be included in a site investigation for an important engineering project in order to provide subsurface information over a large area at reasonable cost.

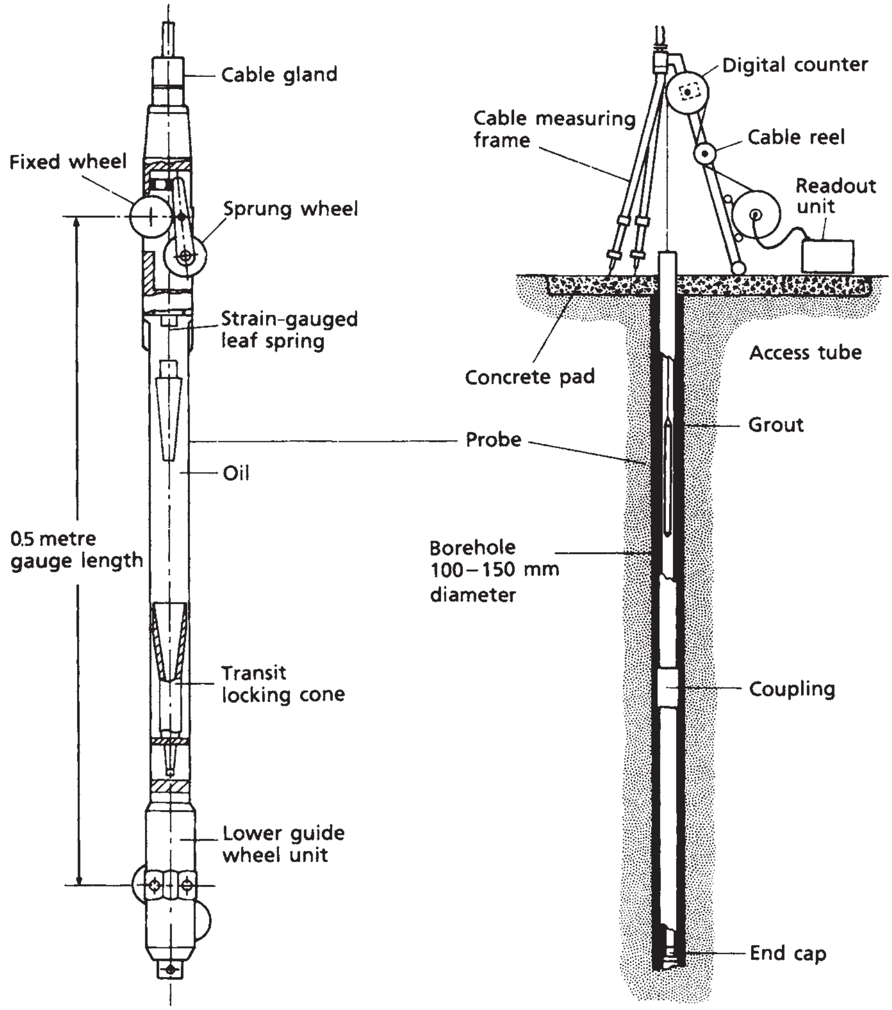

Figure 7.22

Borehole inclinometer.

The information obtained may help eliminate less favourable alternative sites, may aid the location of test holes in critical areas and may prevent unnecessary repetitive boring or drilling in fairly uniform ground. A geophysical survey not only helps to locate the position of boreholes or drillholes but also detects variations in subsurface conditions between them. Boreholes and drillholes provide information about the strata where they are sunk but provide no information about the ground in between. Nonetheless, boreholes or drillholes to aid interpretation and correlation of the geophysical measurements are an essential part of any geophysical survey. Therefore, an appropriate combination of direct and indirect methods often can yield a high standard of results.

Geophysical methods are used to determine the geological sequence and structure of subsurface rocks by the measurement of certain physical properties or forces. The properties that are made most use of in geophysical exploration are density, elasticity, electrical conductivity, magnetic susceptibility and gravitational attraction. In other words, seismic and resistivity methods record the artificial fields of force applied to the area under investigation, while magnetic and gravitational methods measure natural fields of force. The former techniques have the advantage over the latter in that the depth to which the forces are applied can be controlled. By contrast, the natural fields of force are fixed and can only be observed and not controlled. Seismic and resistivity methods are more applicable to the determination of horizontal or near horizontal changes or contacts, whereas magnetic and gravimetric methods generally are used to delineate lateral changes or vertical structures.

In a geophysical survey, measurements of the variations in certain physical properties usually are taken in a traverse across the surface, although they may be made in order to log a borehole. Generally speaking, observations should be close enough for correlation between them to be obvious, so enabling interpolation to be carried out without ambiguity (McDowell et al., 2002). Anomalies in the physical properties measured generally reflect anomalies in the geological conditions. The ease of recognizing and interpreting these anomalies depends on the contrast in physical properties that, in turn, influence the choice of method employed.

The actual choice of method to be used for a particular survey may not be difficult to make. The character and situation of the site also have to be taken into account, especially in built-up areas, which may be unsuitable for one or other of the geophysical methods either because of the presence of old buildings or services on the site, interference from some source or lack of space for carrying out the survey. When dealing with layered rocks, provided their geological structure is not too complex, seismic methods have a distinct advantage in that they give more detailed, precise and unambiguous information than any other method. On the other hand, electrical methods may be preferred for small-scale work, where the structures are simple. On occasions more than one method may be used to resolve the same problem. However, as McCann et al. (1997) pointed out, if there is any doubt about the feasibility of a geophysical survey, then a trial survey should be undertaken to determine the most suitable method. McCann et al. also noted that modern geophysical equipment allows downloading of the results to a suitable portable PC so that a preliminary interpretation can be carried out daily. In this way data can be checked, plotted and evaluated, and then can be compared with data gathered by other means. As a result, any errors can be recognized and, if necessary, traverses re-run to gather better information. Indeed, the survey programme can be modified in the light of any new information obtained.

Seismic Methods

The sudden release of energy from the detonation of an explosive charge in the ground or the mechanical pounding of the surface generates shock waves that radiate out in a hemispherical wave front from the point of release. The waves generated are compressional, P, dilational shear, S, and surface waves. The velocities of the shock waves generally increase with depth below the surface since the elastic moduli increase with depth. The compressional waves travel faster, and are generated and recorded more easily than shear waves. They are therefore used almost exclusively in seismic exploration. The shock wave velocity depends on many variables, including rock fabric, mineralogy and pore water. In general, velocities in crystalline rocks are high to very high (Table 7.4). Velocities in sedimentary rocks increase with amount of consolidation and decrease in pore fluids and with increase in the degree of cementation and diagenesis. Unconsolidated sedimentary deposits have maximum velocities varying as a function of the volume of voids, either air filled or water filled, mineralogy and grain size.

When seismic waves pass from one layer to another in the ground, some energy is reflected back towards the surface while the remainder is refracted. Thus, two methods of seismic surveying can be distinguished, that is, seismic reflection and seismic refraction. Measurement of the time taken from the generation of the shock waves until they are recorded by detector arrays forms the basis of the two methods.

The seismic reflection method is the most extensively used of all geophysical techniques, its principal employment being in the oil industry. In this technique, the depth of investigation is large compared with the distance from the shot to detector array. This is to exclude refraction waves. Indeed, the method is able to record information from a large number of horizons down to depths of several thousands of metres.

In seismic refraction, one ray approaches the interface between two rock types at a critical angle that means that, if the ray is passing from a low, V_o, to a high velocity V_1 layer, it will be refracted along the upper boundary of the latter layer (Fig. 7.23). After refraction, the pulse travels along the interface with velocity V_1. The material at the boundary is subjected to

Table 7.4. Velocities of compressional waves of some common rocks

	V_p (km s^{-1})		V_p (km s^{-1})
Igneous rocks		*Sedimentary rocks*	
Basalt	5.2–6.4	Gypsum	2.0–3.5
Dolerite	5.8–6.6	Limestone	2.8–7.0
Gabbro	6.5–6.7	Sandstone	1.4–4.4
Granite	5.5–6.1	Shale	2.1–4.4
Metamorphic rocks		*Unconsolidated deposits*	
Gneiss	3.7–7.0	Alluvium	0.3–0.6
Marble	3.7–6.9	Sands and gravels	0.3–1.8
Quartzite	5.6–6.1	Clay (wet)	1.5–2.0
Schist	3.5–5.7	Clay (sandy)	2.0–2.4

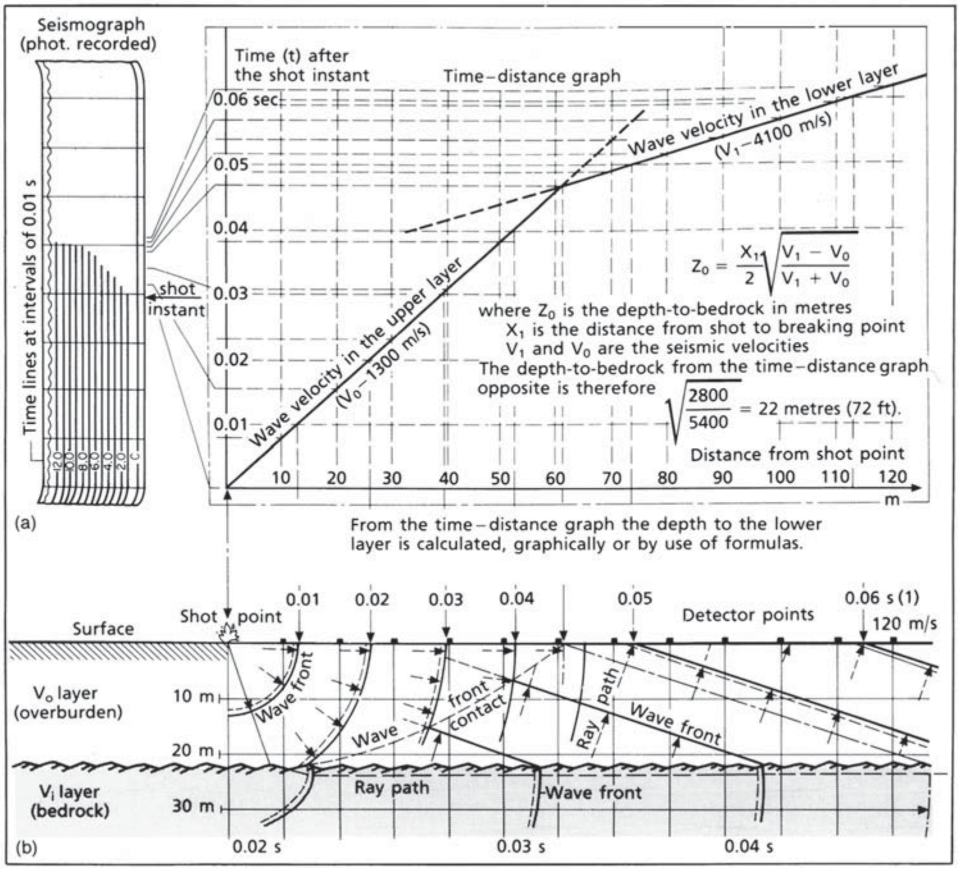

Figure 7.23

Time–distance graphs for a theoretical single-layer problem, with parallel interface. With non-parallel interfaces, both forward and reverse profiles must be surveyed.

oscillating stress from below. This generates new disturbances along the boundary that travel upwards through the low velocity rock and eventually reach the surface.

At short distances from the point where the shock waves are generated, the geophones record direct waves, while at a critical distance, both the direct and refracted waves arrive at the same time. Beyond this, because the rays refracted along the high velocity layer travel faster than those through the low velocity layer above, they reach the geophones first. In refraction work the object is to develop a time–distance graph that involves plotting arrival times against geophone spacing (Fig. 7.23). Hence, the distance between geophones, together with the total length and arrangement of the array, has to be chosen carefully to suit each particular problem.

The most common arrangement in refraction work is profile shooting. Here, the explosive shot or impact points and geophones are laid out in long lines, with geophones receiving refracted waves from the impacts or shots fired. The process is repeated at uniform intervals. In many surveys for civil engineering purposes where it is required to determine depth to bedrock, it may be sufficient to record from two shotpoint distances at each end of the receiving spread. By traversing in both directions in simple geological conditions, the angle of dip can be determined.

In the simple case of refraction by a single high velocity layer at depth, the travel time for the seismic wave that proceeds directly from the impact point to the detectors and the travel time for the critical refracted wave to arrive at the geophones are plotted graphically against geophone spacing (Fig. 7.23). The depth, Z, to the high velocity layer then can be obtained from the graph by using the expression:

$$Z = \frac{X}{2}\left(\frac{V_1 - V_0}{V_1 + V_0}\right) \tag{7.4}$$

where V_o is the speed in the low velocity layer, V_1 the speed in the high velocity layer and X is the critical distance. The method also works for multi-layered rock sequences if each layer is thick enough and transmits seismic waves at higher speeds than the one above it. However, in the refraction method, a low velocity layer underlying a high velocity layer usually cannot be detected as in such an inversion the pulse is refracted into the low velocity layer. Also, a layer of intermediate velocity between an underlying refractor and overlying layers can be masked as a first arrival on the travel-time curve. The latter is known as a blind zone. The position of faults also can be estimated from the time–distance graphs.

As noted in the preceding text, the velocity of shock waves is related to the elastic moduli and can therefore provide data relating to the engineering performance of the ground. Young's modulus, E, and Poisson's ratio, υ, can be derived by using the following expressions if the density, ρ, and compressional, V_p, and shear, V_s, wave velocities are known:

$$E = \rho V_p^2 \frac{(1+\upsilon)(1-2\upsilon)}{(1-\upsilon)} \tag{7.5}$$

or

$$E = 2V_s^2\rho(1+\upsilon) \tag{7.6}$$

or

$$E = \frac{V_S^2}{g}\rho\left[\frac{3(V_p/V_s)^2-4}{(V_p/V_s)^2-1}\right] \tag{7.7}$$

or

$$\upsilon = \frac{0.5\,(V_P/V_S)^2-1}{(V_P/V_S)^2-1} \tag{7.8}$$

where g is the acceleration due to gravity.

These dynamic moduli correspond to the initial tangent moduli of the stress–strain curve for an instantaneously applied load and are usually higher than those obtained in static tests. The frequency and nature of discontinuities within a rock mass affect its deformability. In other words, a highly discontinuous rock mass exhibits a lower compressional wave velocity than a massive rock mass of the same type. The influence of discontinuities on the deformability of a rock mass can be estimated from a comparison of its in situ compressional velocity, V_{pf}, and the laboratory sonic velocity, V_{pl}, determined from an intact specimen taken from the rock mass. The velocity ratio, V_{pf}/V_{pl}, reflects the deformability and so can be used as a quality index. A comparison of the velocity ratio with other rock quality indices is given in Table 2.7.

Resistivity Methods

The resistivity of rocks and soils varies within a wide range. Since most of the principal rock forming minerals are practically insulators, the resistivity of rocks and soils is determined by the amount of conducting mineral constituents and the content of mineralized water in the pores. The latter condition is by far the dominant factor, and in fact, most rocks and soils conduct an electric current only because they contain water. The widely differing resistivity values of the various types of impregnating water can cause variations in the resistivity of rocks ranging from a few tenths of an ohm-metre to hundreds of ohm-metres (Ω m) as can be seen from Table 7.5.

In the resistivity method, an electric current is introduced into the ground by means of two current electrodes and the potential difference between two potential electrodes is measured. It is preferable to measure the potential drop or apparent resistance directly in ohms rather than observe both current and voltage. The ohms value is converted to apparent resistivity by use of a factor that depends on the particular electrode configuration in use (see below).

Table 7.5. Resistivity of some types of natural water

Type of water	Resistivity in Ωm
Meteoric water, derived from precipitation	30 to 1000
Surface waters, in districts of igneous rocks	30 to 500
Surface waters, in districts of sedimentary rocks	10 to 100
Groundwater, in areas of igneous rocks	30 to 150
Groundwater, in areas of sedimentary rocks	Larger than 1
Sea water	About 0.2

The relation between the depth of penetration and the electrode spacing is given in Figure 7.24, from which it can be seen that 50% of the total current passes above a depth equal to about half the electrode separation and 70% flows within a depth equal to the electrode separation. Analysis of the variation in the value of apparent resistivity with respect to electrode separation enables inferences about the subsurface formations to be drawn.

The resistivity method is based on the fact that any subsurface variation in conductivity alters the pattern of current flow in the ground and therefore changes the distribution of electric potential at the surface. Since the electrical resistivity of such factors as superficial deposits and bedrock differ from each other, the resistivity method may be used in their detection and to give their approximate thicknesses, relative positions and depths (Table 7.6). The first step in any resistivity survey should be to conduct a resistivity depth sounding at the site of a borehole in order to establish a correlation between resistivity and lithological layers. If a correlation cannot be established, then an alternative method is required.

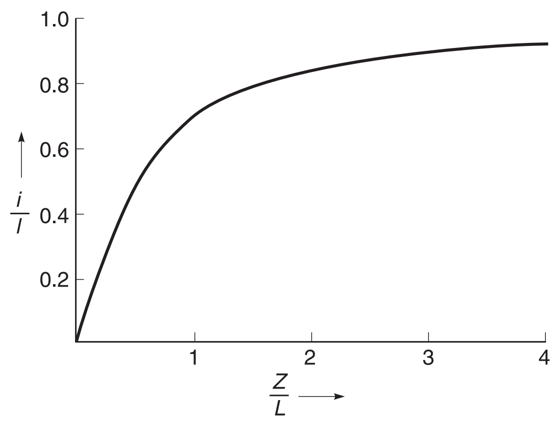

Figure 7.24

Fraction of total current, I, which passes above a horizontal plane at depth, Z, as a function of the distance, L, between two current electrodes.

Table 7.6. Resistivity values of some common rock types

Rock type	Resistivity (Ωm)
Topsoil	5–50
Peat and clay	8–50
Clay, sand and gravel mixtures	40–250
Saturated sand and gravel	40–100
Moist to dry sand and gravel	100–3000
Mudstones, marls and shales	8–100
Sandstones and limestones	100–1000
Crystalline rocks	200–10 000

The electrodes normally are arranged along a straight line, the potential electrodes being placed inside the current electrodes and all four are disposed symmetrically with respect to the centre of the configuration. The configurations of the symmetric type that are used most frequently are those introduced by Wenner and Schlumberger. Other configurations include the dipole–dipole and the pole–dipole arrays. In the Wenner configuration, the distances between all four electrodes are equal, whereas the distances between the potential electrodes and the centre of the array in the Schlumberger configuration are less than those between the current and potential electrodes (Fig. 7.25). The expressions used to compute the apparent resistivity, ρ_a, for the Wenner and Schlumberger configurations are as follows:

Wenner:

$$\rho_a = 2\pi aR \tag{7.9}$$

Schlumberger:

$$\rho_a = \frac{\pi(L^2 - l^2)}{2l} \times R \tag{7.10}$$

where a, L and l are explained in Figure 7.25 and R is the resistance reading.

Horizontal profiling is used to determine variations in apparent resistivity in a horizontal direction at a pre-selected depth. For this purpose, an electrode configuration, with fixed inter-electrode distances, is moved along a straight traverse, resistivity determinations being made at stations located at regular intervals. The length of the electrode configuration must be carefully chosen because it is the dominating factor in depth penetration. The data of a constant-separation survey consisting of a series of traverses arranged in a grid pattern, may

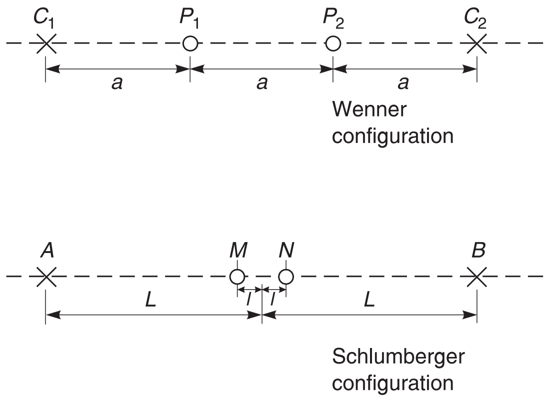

Figure 7.25

Wenner and Schlumberger configurations.

be used to construct a contour map of lines of equal resistivity. These maps often are useful in locating areas of anomalous resistivity such as gravel pockets in clay soils and the trend of buried channels. Even so, interpretation of resistivity maps as far as the delineation of lateral variations is concerned is mainly qualitative.

Electrical sounding furnishes information concerning the vertical succession of different conducting zones and their individual thicknesses and resistivities. For this reason, the method is particularly valuable for investigations on horizontally stratified ground. In electrical sounding, the mid-point of the electrode configuration is fixed at the observation station while the length of the configuration is increased gradually, that is, in the Wenner configuration, the distances between all four electrodes is increased progressively. Only the current electrodes are moved outwards about a station after each reading in the case of the Schlumberger configuration. As a result the current penetrates deeper and deeper, the apparent resistivity being measured each time the current electrodes are moved outwards. The readings, therefore, become increasingly affected by the resistivity conditions at advancing depths. The Schlumberger configuration is preferable to the Wenner configuration for depth sounding. The data obtained usually is plotted as a graph of apparent resistivity against electrode separation in the case of the Wenner array, or half the current electrode separation for the Schlumberger array. The electrode separation at which inflection points occur in the graph provide an idea of the depth of interfaces. The apparent resistivities of the different parts of the curve provide some idea of the relative resistivities of the layers concerned.

If the ground approximates to an ideal condition, then a quantitative solution, involving a curve-fitting exercise, should be possible. The technique requires a comparison of the observed curve with a series of master curves prepared for various theoretical models.

Generally, it is not possible to determine the depths to more than three or four layers. If a second layer is relatively thin and its resistivity much larger or smaller than that of the first layer, the interpretation of its lower contact will be inaccurate. For all depth determinations from resistivity soundings, it is assumed that there is no change in resistivity laterally. This is not the case in practice. Indeed, sometimes the lateral change is greater than that occurring with increasing depth, and so corrections have to be applied for the lateral effects when depth determinations are made.

Electromagnetic Methods

A wide variety of electromagnetic survey methods are available, each involving the measurement of one or more electric or magnetic field components induced in the ground by a primary field. A primary field is produced by a natural (transient) current source or an alternating current artificial source, and this field spreads out in space above and below the ground, inducing currents in subsurface conductors. Secondary electromagnetic fields are produced by these currents that distort the primary field. The resultant field differs from the primary field in intensity, phase and direction, and so can be detected by a suitable receiving coil. The secondary field induced in the subsurface conductor fades gradually when a transient primary field is switched off, fading being slower in media of higher conductivity. Hence, measurement of the rate at which the secondary currents fade and their field offers a means of detecting anomalously conducting bodies.

The terrain conductivity meter represents a means of measuring the conductivity of the ground. Electromagnetic energy is introduced into the ground by inductive coupling produced by passing an alternating current through a coil. The receiver also detects its signal by induction. The conductivity meter is carried along traverse lines across a site and can provide a direct continuous readout. Hence, surveys can be carried out quickly. Conductivity values are taken at positions set out on a grid pattern. Corrected values of conductivity can be plotted as contoured maps of conductivity. Where the thickness of overburden varies within fairly narrow limits and the conductivities of the overburden and bedrock do not change appreciably, the depth to bedrock can be estimated from standard curves. As these depth values are approximate, they need to be checked against borehole evidence or data obtained from more quantitative geophysical methods.

The very-low-frequency, VLF, method is the most widely used fixed-source method operating on a single frequency, making use of powerful radio transmitters. A disadvantage is that wave penetration is limited. The method also is affected by topography. The interpretation of VLF data generally is qualitative, and it frequently is used for reconnaissance work. The method is well suited to detecting near-vertical contacts and fracture zones.

As a consequence, the method has found particular application in site investigations for the delineation of faults.

The ground probing radar method is based upon the transmission of pulsed electromagnetic waves in the frequency range 1 to 1000 MHz. In this method, the travel times of the waves reflected from subsurface interfaces are recorded as they arrive at the surface, and the depth, Z, to an interface is derived from:

$$Z = VT/2 \tag{7.11}$$

where V is the velocity of the radar pulse and T is its travel time. The conductivity of the ground imposes the greatest limitation on the use of radar probing, that is, the depth to which radar energy can penetrate depends upon the effective conductivity of the strata being probed. This, in turn, is governed chiefly by the water content and its salinity. Furthermore, the value of effective conductivity is also a function of temperature and density, as well as the frequency of the electromagnetic waves being propagated. The least penetration occurs in saturated clayey materials or where the moisture content is saline. For example, attenuation of electromagnetic energy in wet clay and silt mean that depth of penetration frequently is less than 1 m. The technique appears to be reasonably successful in sandy soils and rocks in which the moisture content is non-saline. Rocks such as limestone and granite can be penetrated for distances of tens of metres and in dry conditions the penetration may reach 100 m. Ground probing radars have been used for a variety of purposes in geotechnical engineering, for example, the detection of fractures and faults in rock masses, the location of subsurface voids and the delineation of contaminated plumes.

Magnetic Methods

All rocks, mineral and ore deposits are magnetized to a lesser or greater extent by the Earth's magnetic field. As a consequence, in magnetic surveying, accurate measurements are made of the anomalies produced in the local geomagnetic field by this magnetization. The intensity of magnetization and hence the amount by which the Earth's magnetic field is changed locally depend on the magnetic susceptibility of the material concerned. In addition to the magnetism induced by the Earth's field, rocks possess a permanent magnetism that depends on their history.

Rocks have different magnetic susceptibilities related to their mineral content. Some minerals, for example, quartz and calcite are magnetized reversely to the field direction, and therefore have negative susceptibility and are described as diamagnetic. Paramagnetic minerals, which are the majority, are magnetized along the direction of magnetic field so that their susceptibility is positive. The susceptibility of the ferromagnetic minerals, such as magnetite, ilmenite, pyrrhotite and hematite, is a very complicated function of the field intensity. However, since the magnitudes of their susceptibility amount to 10 to 10^5 times the order of susceptibility of the paramagnetic and diamagnetic minerals, the ferromagnetic minerals can be found by magnetic field measurements.

If the magnetic field ceases to act on a rock, then the magnetization of paramagnetic and diamagnetic minerals disappears. However, in ferromagnetic minerals the induced magnetization is diminished only to a certain value. This residuum is called remanent magnetization and is of great importance in rocks. All igneous rocks have a very high remanent magnetization acquired as they cooled down in the Earth's magnetic field. In the geological past, during sedimentation in water, grains of magnetic materials were orientated by ancient geomagnetic fields so that some sedimentary rocks show stable remanent magnetization.

The strength of the magnetic field is measured in nanoteslas (nT), and the average strength of the Earth's magnetic field is about 50,000 nT. Obviously, the variations associated with magnetized rock formations are very much smaller than this. The intensity of magnetization and consequently the amount by which the Earth's magnetic field changes locally depends on magnetic susceptibility of the rocks concerned.

Aeromagnetic surveying has almost completely supplanted ground surveys for regional reconnaissance purposes. Accurate identification of the plan position of the aircraft for the whole duration of the magnetometer record is essential. The object is to produce an aeromagnetic map, the base map with transcribed magnetic values being contoured.

The aim of most ground surveys is to produce isomagnetic contour maps of anomalies to enable the form of the causative magnetized body to be estimated (Fig. 7.26). Profiles are surveyed across the trend of linear anomalies with stations, if necessary, at intervals of as little as 1 m. A base station is set up beyond the anomaly where the geomagnetic field is uniform. The reading at the base station is taken as zero, and all subsequent readings are expressed as plus-or-minus differences. Corrections need to be made for the temperature of the instrument as the magnets lose their effectiveness with increasing temperature. A planetary correction also is required that eliminates the normal variation of the Earth's magnetic field with latitude. Large metallic objects such as pylons are a serious handicap to magnetic investigation and must be kept at a sufficient distance as it is difficult to correct for them.

A magnetometer also may be used for mapping geological structures. For example, in some thick sedimentary sequences, it is sometimes possible to delineate the major structural features because the succession includes magnetic horizons. These may be ferruginous sandstones or shales, tuffs or basic lava flows. In such circumstances, anticlines produce positive and

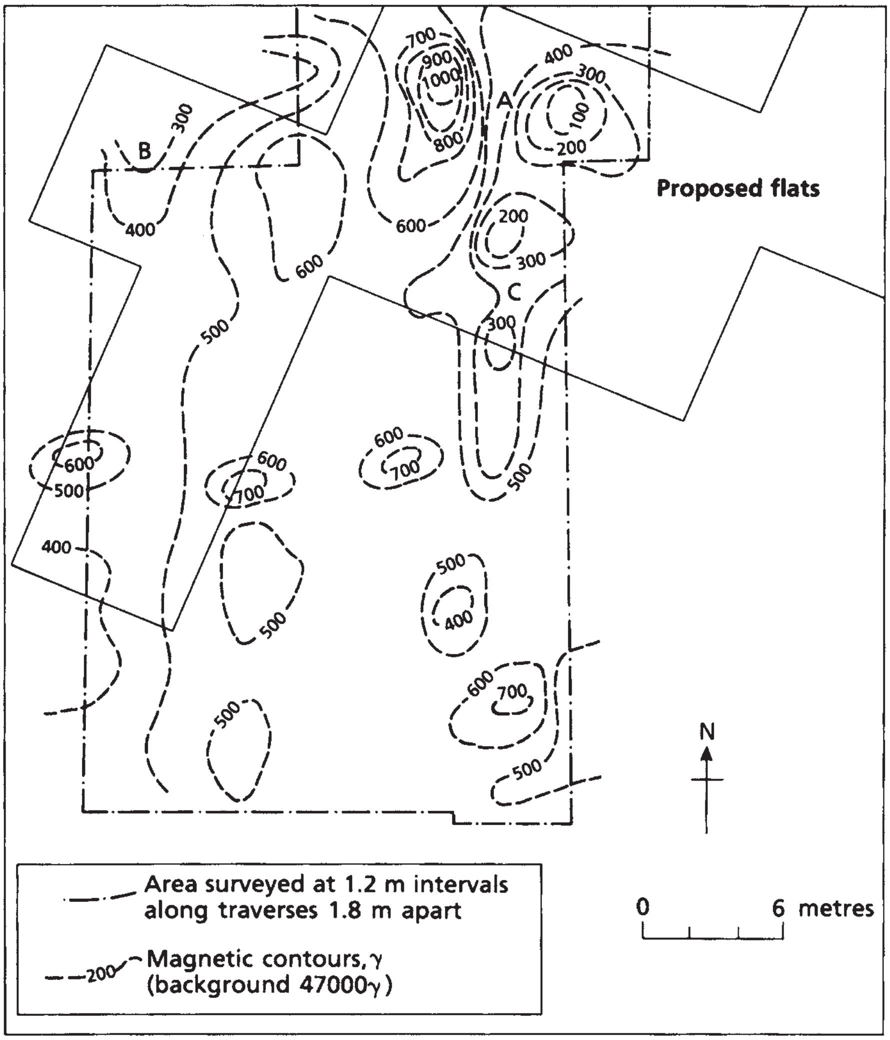

Figure 7.26

Magnetometer survey of a site for proposed flats in which mine shafts occurred at A, B and C (after Cripps et al., 1998).

synclines negative anomalies. Faults and dykes are indicated on isomagnetic maps by linear belts of somewhat sharp gradient or by sudden swings in the trend of the contours. However, in many areas the igneous and metamorphic basement rocks, which underlie the sedimentary sequence, are the predominant influence controlling the pattern of anomalies since they usually are far more magnetic than the sediments above. Where the basement rocks are brought near the surface in structural highs, the magnetic anomalies are large and characterised by strong relief. Conversely, deep sedimentary basins usually produce contours with low values and gentle gradients on isomagnetic maps.

Magnetic surveying has been used to detect abandoned mine shafts, a proton precession magnetometer normally being used (Bell, 1988c). A good subsurface magnetic contrast may be obtained if the shaft is lined with iron tubbing or with bricks or if the shaft is filled and the filling consists of burnt shale or ash or contains scrap iron. On the other hand, if a shaft is unfilled and unlined or lined with timber, then it may not give rise to a measurable anomaly.

Gravity Methods

The Earth's gravity field varies according to the density of the subsurface rocks, but at any particular locality, its magnitude also is influenced by latitude, elevation, neighbouring topographical features and the tidal deformation of the Earth's crust. The effects of these latter factors have to be eliminated in any gravity survey, where the object is to measure the variations in acceleration due to gravity precisely. This information then can be used to construct a contoured gravity map. In survey work, modern practice is to measure anomalies in gravity units (g.u. = 10^{-6} m s^{-2}). Modern gravity meters used in exploration measure not the absolute value of the acceleration due to gravity but the small differences in this value between one place and the next.

Gravity methods are used mainly in regional reconnaissance surveys to reveal anomalies that may be investigated subsequently by other methods. Since the gravitational effects of geological bodies are proportional to the contrast in density between them and their surroundings, gravity methods are particularly suitable for the location of structures in stratified formations. Gravity effects due to local structures in near surface strata may be partly obscured or distorted by regional gravity effects caused by large-scale basement structures. However, regional deep-seated gravity effects can be removed or minimized in order to produce a residual gravity map showing the effects of shallow structures that may be of interest.

A gravity survey is conducted from a local base station at which the value of the acceleration due to gravity is known with reference to a fundamental base where the acceleration due to gravity has been accurately measured. The way in which a gravity survey is carried out largely depends on the objective in view. Large-scale surveys covering hundreds of square kilometres, carried out in order to reveal major geological structures, are done by vehicle or helicopter with a density of only a few stations per square kilometre. For more detailed work such as the delineation of basic minor intrusions or the location of faults, spacing between stations may be as small as 20 m. Because gravity differences large enough to be of geological significance are produced by changes in elevation of several millimetres and of only 30 m in north-south distance, the location and elevation of stations must be established with very high precision.

Micro-gravity meters have been used to detect subsurface voids such as caverns in limestone, or abandoned mine shafts or shallow workings (Styles and Thomas, 2001). Gravity "lows" are recorded over voids, and they are more notable over air-filled than water- or sediment-filled voids.

Drillhole Logging Techniques

Drillhole logging techniques can be used to identify some of the physical properties of rocks. For example, the electrical resistivity method makes use of various electrode configurations down-the-hole. As the instrument is raised from the bottom to the top of the hole, it provides a continuous record of the variations in resistivity of the wall rock. In the normal or standard resistivity configuration, there are two potential electrodes and one current electrode in the sonde. The depth of penetration of the electric current from the drillhole is influenced by the electrode spacing. In a short normal resistivity survey, spacing is about 400 mm, whereas in a long normal survey, spacing generally is between 1.5 and 1.75 m. Unfortunately, in such a survey, because of the influence of thicker adjacent beds, thin resistive beds yield resistivity values that are much too low, while thin conductive beds produce values that are too high. The microlog technique may be used in such situations. In this technique the electrodes are very closely spaced (25–50 mm) and are in contact with the wall of the drillhole. This allows the detection of small lithological changes so that much finer detail is obtained than with the normal electric log (Fig. 7.30). A microlog is particularly useful in recording the position of permeable beds. If, for some reason, the current tends to flow between the electrodes on the sonde instead of into the rocks, then the laterolog or guard electrode is used. The laterolog 7 has seven electrodes in an array that focuses the current into the strata of the drillhole wall. The microlaterolog, a focused micro-device, is used in such a situation instead of the microlog.

A dipmeter generally is a four-arm side-wall micro-resistivity device. It measures small variations in the resistivity of a formation that allows the relative vertical shift of characteristic pattern variation produced by bedding planes, discontinuities or lithological changes to be used to determine, by aid of computer analysis, the attitude of a plane intersecting a drillhole. In this way, a fracture log can be produced.

Induction logging may be used when an electrical log cannot be obtained. In this technique, the sonde sends electrical energy into the strata horizontally and therefore only measures the resistivity immediately opposite the sonde, unlike in normal electrical logging where the current flows between electrodes. As a consequence, the resistivity is measured directly in

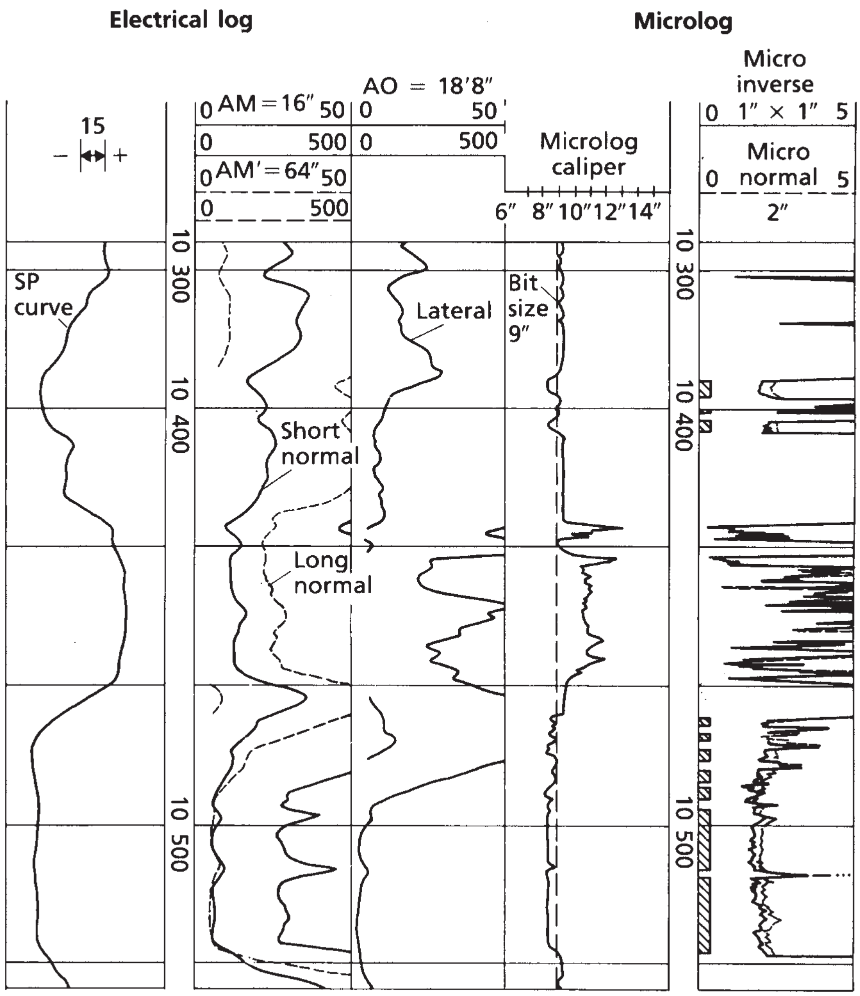

Figure 7.27

Drillhole logging curves. Microresistivity curves are shown on the right. Permeable portions of the penetrated section are indicated (cross-hatched bars) by extensions of the 50-mm micronormal curve beyond the microinverse. Note that the diameter of the bore, as recorded by the microlog calliper, is smaller than bit size where a mud filter cake is formed at the position of permeable beds. Standard electrical logs of the same stratigraphic interval are shown on the left for comparison.

an induction log, whereas in a normal electrical log, since the current flows across the stratal boundaries, it is measured indirectly from the electrical log curves. A gamma ray log usually is run with an induction log in order to reveal the boundaries of stratal units.

A spontaneous potential, SP, log is obtained by lowering a sonde down a drillhole that generates a small electric voltage at the boundaries of permeable rock units and especially between such strata and less permeable beds. For example, permeable sandstones show large SPs, whereas shales typically are represented by low values. If sandstone and shale are interbedded, then the SP curve has numerous troughs separated by sharp or rounded peaks, the widths of which vary in proportion to the thicknesses of the sandstones. Spontaneous potential logs frequently are recorded at the same time as resistivity logs. Interpretation of both sets of curves yields precise data on the depth, thickness and position in the sequence of the beds penetrated by the drillhole. The curves also enable a semi-quantitative assessment of lithological and hydrogeological characteristics to be made.

The sonic logging device consists of a transmitter–receiver system, transmitters and receivers being located at given positions on the sonde. The transmitters emit short, high-frequency pulses several times a second, and differences in travel times between receivers are recorded in order to obtain the velocities of the refracted waves. The velocity of sonic waves propagated in sedimentary rocks is largely a function of the character of the matrix. Normally, beds with high porosities have low velocities and dense rocks are typified by high velocities. Hence, the porosity of strata can be assessed. In the 3D sonic log, one transmitter and one receiver are used at a time. This allows both compressional and shear waves to be recorded, from which, if density values are available, the dynamic elastic moduli of the beds concerned can be determined. As velocity values vary independently of resistivity or radioactivity, the sonic log permits differentiation amongst strata that may be less evident on the other types of log.

Radioactive logs include gamma ray or natural gamma, gamma–gamma or formation density, and neutron logs. They have the advantage of being obtainable through the casing in a drillhole. On the other hand, the various electric and sonic logs can only be used in uncased holes. The natural-gamma log provides a record of the natural radioactivity or gamma radiation from elements such as potassium 40, and uranium and thorium isotopes, in the rocks. This radioactivity varies widely among sedimentary rocks, being generally high for clays and shales and lower for sandstones and limestones. Evaporites give very low readings. The gamma–gamma log uses a source of gamma rays that are sent into the wall of the drillhole. There they collide with electrons in the rocks and thereby lose energy. The returning gamma ray intensity is recorded, a high value indicating low electron density and hence low formation density. The neutron curve is a recording of the effects caused by bombardment of the strata with neutrons. As the neutrons are absorbed by atoms of hydrogen, which then emit gamma rays, the log provides an indication of the quantity of hydrogen in the strata around the sonde. The amount of hydrogen is related to the water (or hydrocarbon) content and therefore provides another method of estimating porosity. Since carbon is a good moderator of neutrons, carbonaceous rocks are liable to yield spurious indications as far as porosity is concerned.

The caliper log measures the diameter of a drillhole. Different sedimentary rocks show a greater or lesser ability to stand without collapsing from the walls of the drillhole. For instance, limestones may present a relatively smooth face slightly larger than the drilling bit whereas soft shale may cave to produce a much larger diameter. A caliper log is obtained along with other logs to help interpret the characteristics of the rocks in the drillhole.

Cross-Hole Methods

The cross-hole seismic method is based on the transmission of seismic energy between drillholes. In its simplest form, cross-hole seismic measurements are made between a seismic source in one drillhole (i.e. a small explosive charge, an air gun, a drillhole hammer, or an electrical sparker) and a receiver at the same depth in an adjacent drillhole. The receiver can either be a three-component geophone array clamped to the drillhole wall or a hydrophone in a liquid-filled drillhole to receive signals from an electric sparker in another drillhole similarly filled with liquid. The choice of source and receiver is a function of the distance between the drillholes, the required resolution and the properties of the rock mass. The best results are obtained with a high-frequency repetitive source. Generally, the source and receiver in the two drillholes are moved up and down together. Drillholes must be spaced closely enough to achieve the required resolution of detail and be within the range of the equipment. This is up to 400 m in clay, 160 m in chalk, and 80 m in sands and gravels. By contrast, because soft organic clay is highly attenuating, transmission is possible only over a few metres. These distances are for saturated material and the effective transmission is reduced considerably in dry superficial layers.

Such simple cross-hole seismic surveys are limited in the amount of data they produce. Hence, a system has been developed that uses a multitude of wave paths, thereby enabling the location, shape and velocity contrast relating to an anomaly or target in the rock mass between drillholes to be delineated in an unambiguous fashion. This is referred to as seismic tomography (tomography means a technique used to obtain an image of a selected plane section of a solid object). The method utilizes two or more drillholes, and possibly the ground surface, for the location of sources and detectors, the object being to derive one or more two-dimensional images of seismic properties within the rock mass (Jackson and McCann, 1997). Cross-hole seismic measurements provide a means by which the engineering properties of the rock mass between drillholes can be assessed. For example, the dynamic elastic properties can be obtained from the values of the compressional and shear wave velocities and the formation density (see the preceding text). Other applications include assessment of the continuity of lithological units between drillholes, identification of fault zones, assessment of the degree of fracturing and the detection of subsurface voids.

Electromagnetic and electrical resistivity techniques also have been used to produce tomographic imagery. For example, Corin et al. (1997) used drillhole radar tomography to assess the foundation conditions for a long viaduct to be constructed in limestone that was regarded as highly karstified. They concluded that cross-hole methods are probably the best tools available at present to provide the required detailed information, particularly in regions of karstic limestone, for good foundation design. Electrical resistance tomography is a relatively new geophysical imaging technique that uses a number of electrodes in drillholes, and sometimes at the ground surface, to image the resistivity of the subsurface.

Maps for Engineering Purposes

One of the important ways by which the geologist can be of service is by producing maps to aid the engineer, planner and others who are concerned with the development of land. A variety of maps can be produced from engineering geomorphological, environmental geological and engineering geological to geotechnical maps (Anon,1972). The distinction between these different types of maps is not always clear cut. Be that as it may, maps represent a means of storing and transmitting information, in particular, of conveying specific information about the spatial distribution of given factors or conditions. In addition, a map represents a simplified model of the facts, and the complexity of various geological factors can never be portrayed in its entirety. The amount of simplification required is governed principally by the purpose and scale of the map, the relative importance of particular geological factors or relationships, the accuracy of the data and on the techniques of representation employed.

The purpose of engineering geomorphological maps is to portray the surface form and the nature and properties of the materials of which the surface is composed, and to indicate the type and magnitude of the processes in operation. Surface form and pattern of geomorphological processes often influence the choice of a site. Hence, geomorphological maps give a rapid appreciation of the nature of the ground and thereby help the design of more detailed investigations, as well as focusing attention on problem areas. Such maps recognize landforms along with their delimitation in terms of size and shape (Fig. 7.28). Engineering geomorphological maps therefore should show how surface expression will influence an engineering project and should provide an indication of the general environmental relationship of the site concerned. If engineers are to obtain maximum advantage from a geomorphological survey, then derivative maps should be compiled from the geomorphological sheets. Such derivative maps generally are concerned with some aspect of ground conditions, such as landslip areas or areas prone to flooding or over which sand dunes migrate (Fig. 7.29).

The principal object during an engineering geomorphological survey is the classification of every component of the land surface in relation to its origin, present evolution and likely material properties. In other words, a survey should identify the general characteristics of the terrain of an area, thereby providing a basis for evaluation of alternative locations and avoidance of the

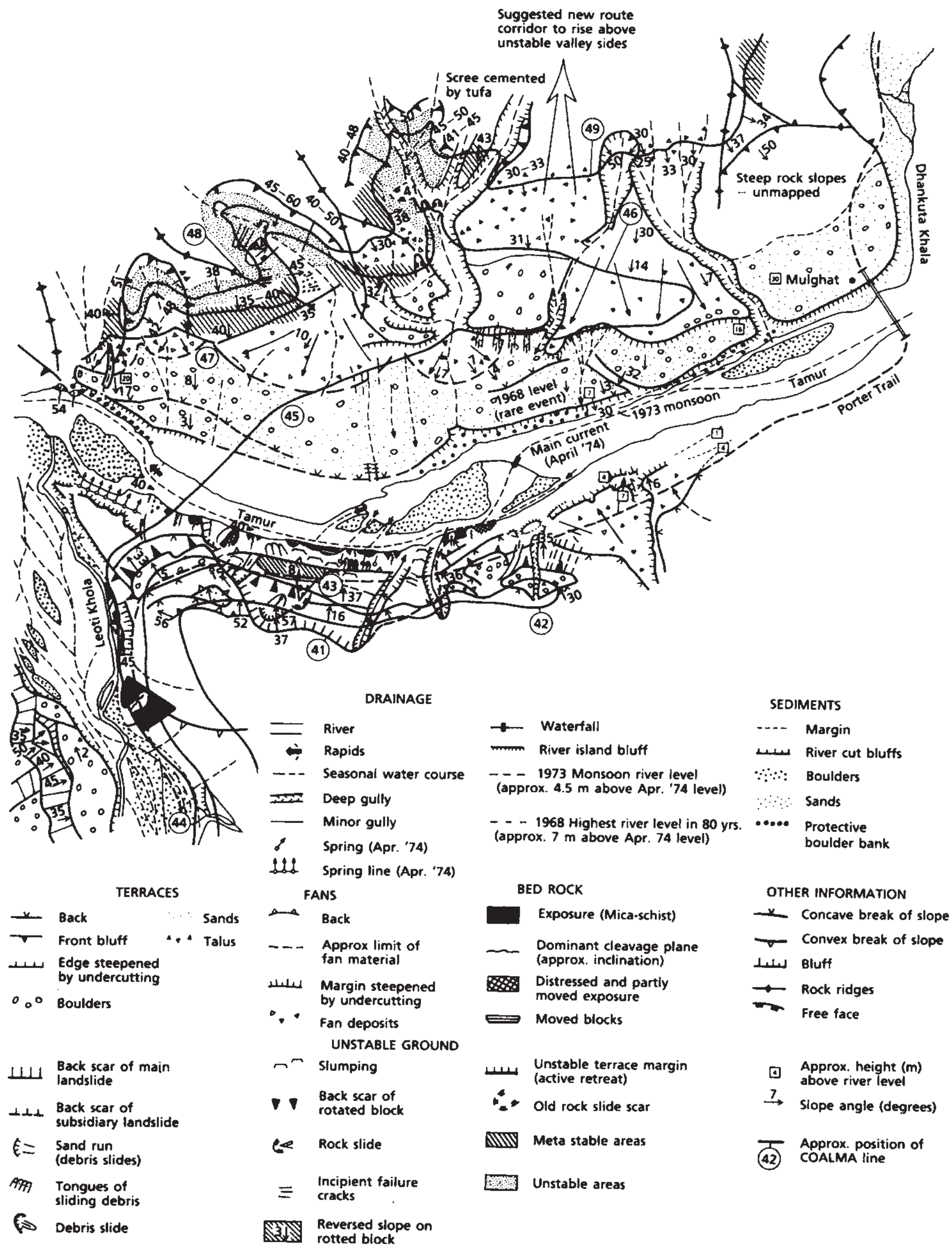

Figure 7.28

Engineering geomorphology map of the site and situation of a proposed bridge crossing on the Tamur River, eastern Nepal (after Brunsden et al., 1975). With kind permission of the Geological Society.

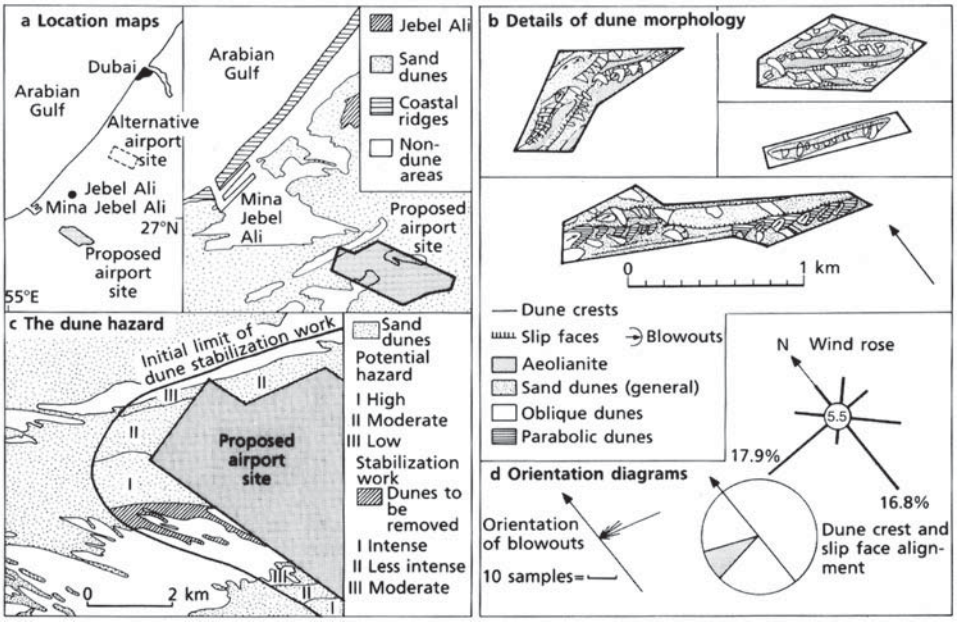

Figure 7.29

Geomorphological analysis of a proposed airport site in Dubai wih respect to the threat from mobile sand dunes (after Cooke et al., 1978). With kind permission of the Geological Society.

worst hazard areas. What is more, an understanding of the past and present development of an area is likely to aid prediction of its behaviour during and after construction operations. In addition, factors outside the site that may influence it, such as mass movement, should be identified and a synopsis of geomorphological development should be provided. Obtaining such information should facilitate the planning of a subsequent site investigation. For instance, it should aid the location of boreholes, and these hopefully will confirm what has been discovered by the geomorphological survey.

Environmental geology maps have been produced to meet the needs of planners (Forster et al., 2004). It is important that geological information should be understood readily by the planner and those involved in development. Unfortunately, conventional geological maps often are inadequate for the needs of such individuals (Section 7.1). Consequently, maps incorporating geological data are now being produced for planning and land-use purposes. Such maps are essentially simple and provide some indication of those areas where there are least geological constraints on development, and so they can be used by the planner or engineer at the feasibility stage of a project. The location of exploitable mineral resources also is of interest to planners. The obvious reason for presenting geological data in a way that can be understood by planners, administrators and engineers is that they then can seek appropriate professional advice and, in this way, bring about safer and more cost effective development and design of land, especially in relation to urban growth and redevelopment. In fact, two versions of environmental geology maps may be produced, one for the specialist and the other for the non-specialist.

Topics that are included on environmental geology maps vary, but may include solid geology, unconsolidated deposits, landslides, hydrogeology, mineral resources, contamination, shallow undermining and opencast workings, floodplain hazards, etc. (Fig. 7.30). Each aspect of geology can be presented as a separate theme on a basic or element map. Environmental potential maps are compiled from basic data maps. They present, in general terms, the constraints on development. They also can present those resources with respect to mineral, groundwater, or agricultural potential that might be used in development or that should not be sterilized by building over.

Engineering geological maps and plans provide engineers and planners with information that will assist them in the planning of land use and in the location and construction of engineering structures of all types. Such maps usually are produced on the scale of 1:10,000 or smaller, whereas engineering geological plans, being produced for a particular engineering

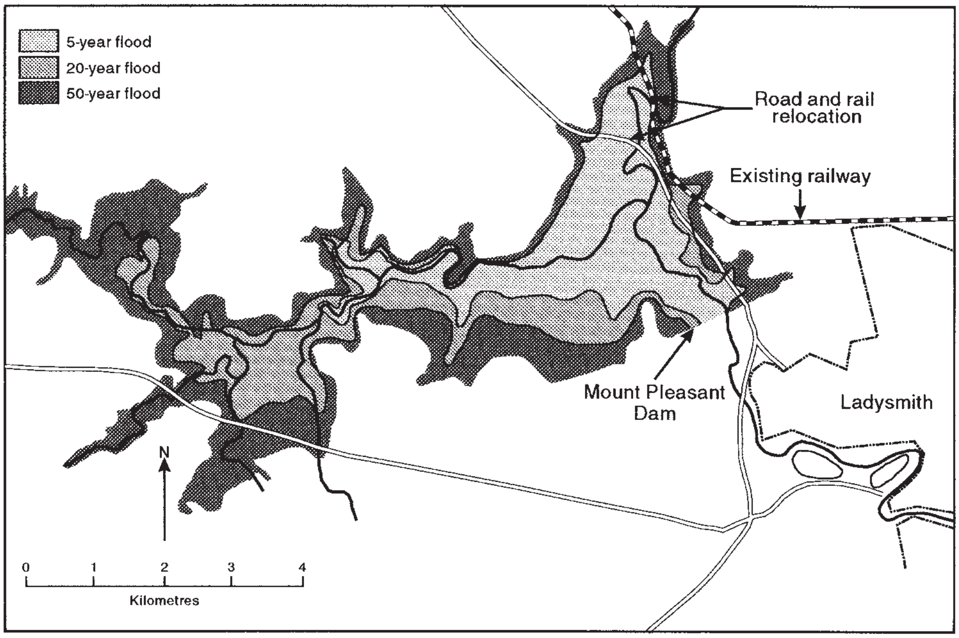

Figure 7.30

Proposed location of Mount Pleasant Dam to help protect Ladysmith from flooding, showing the 5-, 20- and 50- year flood boundaries, Natal, South Africa (after Bell and Mason, 1997).

purpose, have a larger scale. Engineering geological maps may serve a special purpose or a multipurpose (Anon, 1976). Special-purpose maps provide information on one specific aspect of engineering geology, for example, the engineering geological conditions at a dam site or along a routeway or for zoning for land use in urban development. Multipurpose maps cover various aspects of engineering geology.

Engineering geological maps should be accompanied by cross sections, and explanatory texts and legends. Detailed engineering geological information can be given, in tabular form, on the reverse side of the map (Fig. 7.31; Tables 7.7a and b). For example, a table of rock and soil characteristics summarizing the various rock and soil groups, listing their mode of occurrence, their thickness, their structure and their hydrogeological and geotechnical properties, may be provided. More than one map of an area may be required to record all the information that has been collected during a survey. In such instances a series of overlays or an atlas of maps can be produced. Preparation of a series of engineering geological maps can reduce the amount of effort involved in the preliminary stages of a site investigation, and may indeed allow site investigations to be designed for the most economical confirmation of the ground conditions.

Geotechnical maps and plans indicate the distribution of units, defined in terms of engineering properties. For instance, they can be produced in terms of index properties, rock quality or grade of weathering. A plan for a foundation could be made in terms of design parameters. The unit boundaries then are drawn for changes in the particular property. Frequently, the boundaries of such units coincide with stratigraphical boundaries. In other instances, as for example, where rocks are deeply weathered, they may bear no relation to geological boundaries. Unfortunately, one of the fundamental difficulties in preparing geotechnical maps arises from the fact that changes in physical properties of rocks and soils frequently are gradational. As a consequence, regular checking of visual observations by in situ testing or sampling is essential to produce a map based on engineering properties.

Geographical Information Systems

One means by which the power, potential and flexibility of mapping may be increased is by developing a geographical information system. Geographical information systems (GIS) represent a form of technology that is capable of capturing, storing, retrieving, editing, analyzing, comparing and displaying spatial information. For instance, Star and Estes (1990) indicated that a geographical information system consists of four fundamental components, namely, data acquisition and verification, data storage and manipulation, data transformation and analysis, and data output and presentation. The GIS software is designed to manipulate spatial data in order to produce maps, tabular reports or data files for interfacing with numerical models.

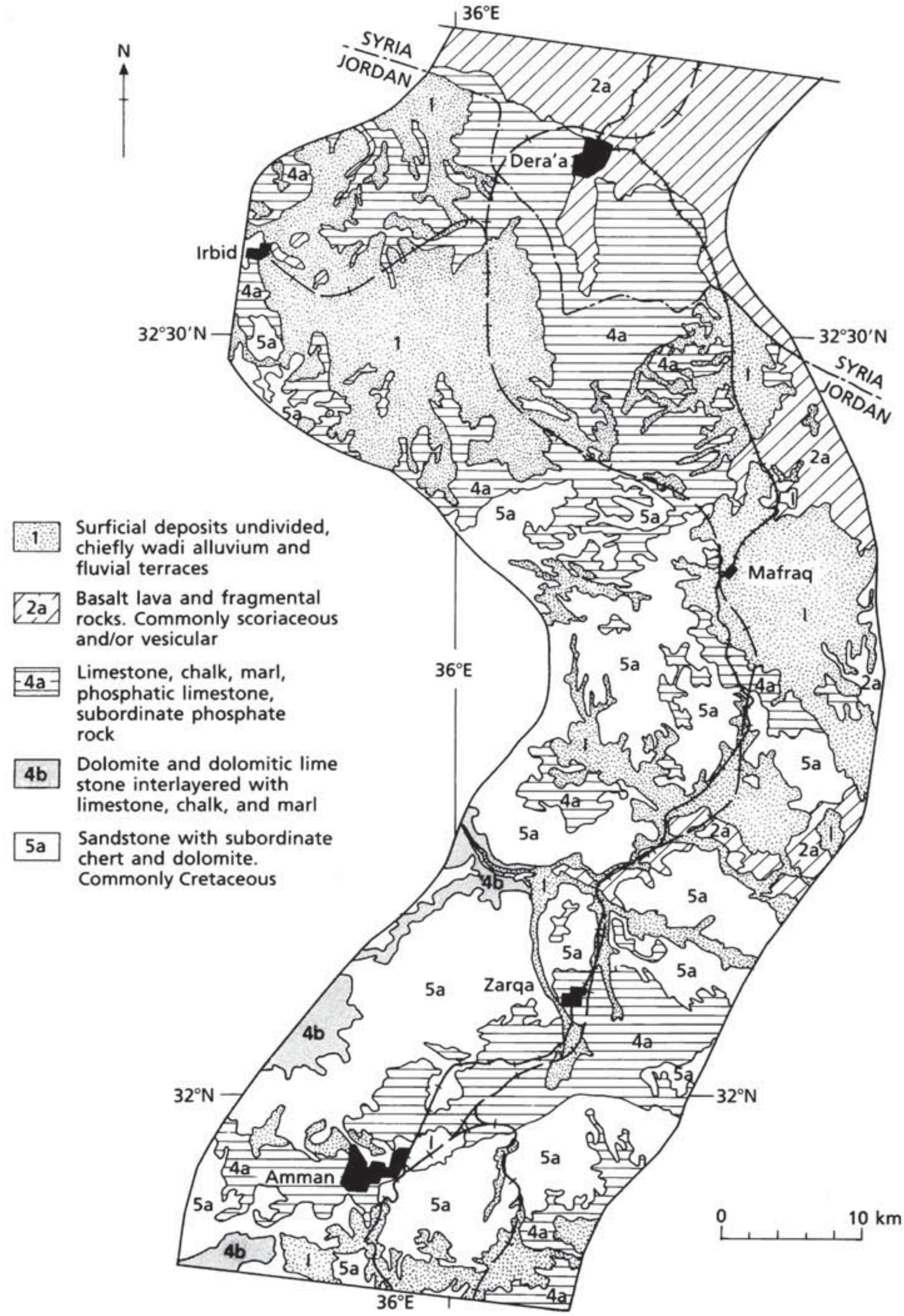

Figure 7.31

Segment for the engineering geological map for the Hijaz Railway in Jordan (after Briggs, 1987). Engineering geology and characteristics shown in Table 7.7a and b. With kind permission of the Association of Engineering Geologists.

Table 7.7a. Excerpts from the engineering geology table illustrating the variety of materials in the study area for the Hijaz Railway. Symbols 1, 2a, 4a, 4b and 5a are shown in Figure 7.31 (after Briggs, 1987)

Map symbol	Geological description	Distribution	Map segments	Engineering characteristics	Suitability as source of material for:	Moderate water supply favourability in shallow aquifers	Topographic expression
1	Surficial deposits undivided, chiefly wadi alluvium and fluvial and marine terraces	Most common in Saudi Arabia and southern Jordan	Present on most map segments	Excavation: easy Stability: poor Strength: fair Tunnel support: maximum	Ballast – 0 Coarse aggregate – + Sand – +++ Embankments – 0 Riprap –0	Fair to good with seasonal fluctuations. Coastal areas poor	Generally flat, locally steeply dissected
2a	Basalt lava and fragmental rocks. Commonly scoriaceous and/or vesicular	Widespread in southern Syria. Locally elsewhere	01, 02, 13, 19, 20 and 28	Excavation: difficult Stability: good Strengh: good Tunnel support: moderate	Ballast – + Coarse aggregate – + Sand – + Embankments – ++ Riprap – +	Generally poor. Locally fair to good, depending on interlayering	Flat to mountainous. Surfaces commonly bouldery
3c	Sandstone and conglomerate with limestone and marl. Loosely cemented.Locally hard	Along coastal plain between A1 Wajh and Yanbu, Saudi Arabia	26, 27, 28 and 30	Excavation: intermediate Stability: fair Strength: fair Tunnel support: moderate to maximum	Ballast – 0 Coarse aggregate – 0 Sand – + Embankments – ++ Riprap – 0	Poor	Flat to rolling, locally hilly and dissected
4a	Limestone, chalk, marl, phosphatic limestone, subordinate phosphate rock	Widespread in Jordan	02–05 and 29	Excavation: difficult Stability: fair to good Strength: fair to good	Ballast – 0 Coarse aggregate – + Sand – 0 Embankments – + Riprap – +	Generally poor	Hilly, locally rolling or mountainous

Continued

Table 7.7a. Excerpts from the engineering geology table illustrating the variety of materials in the study area for the Hijaz Railway. Symbols 1, 2a, 4a, 4b and 5a are shown in Figure 7.31 (after Briggs, 1987)—cont'd

Map symbol	Geological description	Distribution	Map segments	Engineering characteristics	Suitability as source of material for:	Moderate water-supply favourability in shallow aquifers	Topographic expression
				Tunnel support: moderate to minimum			
4b	Dolomite and dolomitic limestone interlayered with limestone, chalk, and marl	Central Jordan	02 and 03	Excavation: moderately difficult Stability: fair to good Strength: fair to good Tunnel support: moderate to minimum	Ballast – + Coarse aggregate – + Sand – 0 Embankments – ++ Riprap – +	Generally poor	Hilly, locally mountainous
5a	Sandstone with subordinate chert and dolomite. Commonly calcareous	Widespread in Jordan	02–05 and 29	Excavation: moderately difficult Stability: fair to good Strength: good Tunnel support: moderate to minimum	Ballast – 0 Coarse aggregate – 0 Sand – + Embankments – ++ Riprap – 0	Poor to fair	Hilly to mountainous

6b	Chiefly andesite lava and fragmental rocks. Common medium-grade metamorphism, greenstone	Widespread in Hijaz Mountains	10–13, 18–25, 27, 30 and 31	Excavation: difficult Stability: good Strength: good Tunnel support: minimum	Ballast – +++ Coarse aggregate – +++ Sand – 0 Embankments – ++ Riprap – +++	Poor	Core of Hijiz Mountains. Relief locally greater than 2000m
7b	Early and altered granites, granodiorite, quartz monzonite. Includes some gneiss	Common in the Hijaz Mountains and southern Jordan	10–13 and 19–31	Excavation: difficult Stability: good Strength: good Tunnel support: minimum to moderate	Ballast – + Coarse aggregate – + Sand – + Embankments – ++ Riprap – ++	Poor	Chiefly mountainous. Mostly more resistant than other intrusive rocks

Table 7.7b. Key to the engineering characteristics column (after Briggs, 1987)

Excavation facility	Stability of cut slopes	Foundation strength	Tunnel support requirements
Easy – can be excavated by hand tools or light power equipment. Some large boulders may require drilling and blasting for their removal. Dewatering and bracing of deep excavation walls may be required	Good – these rocks have been observed to stand on essentially vertical cuts where jointing and fracturing are at a minimum. However, moderately close jointing or fracturing is common, so slopes not steeper than 4:1 (vertical: horizontal) are recommended. In deep cuts, debris-catching benches are recommended	Good – bearing capacity is sufficient for the heaviest classes of construction, except where located on intensely fractured or jointed zones striking parallel to and near moderate to steep slopes	Minimum – support probably required for less than 10% of length of bore, except where extensively fractured
Moderately easy – probably rippable by heavy power equipment at least to weathered rock – fresh rock interface and locally to greater depth	Fair – cut slopes ranging from 2:1 to 1:1 are recommended; flatter where rocks are intensely jointed or fractured. Rockfall may be frequent if steeper cuts are made. Locally, lenses of harder rock may permit steeper cuts	Fair – choice of foundation styles is largely dependent on packing of fragments, clay content, and relation to the water table. If content of saturated clay is high, appreciable lateral movement of clay may be expected under heavy loads. If packing is poor, settling may occur	Moderate – support may be required for as much as 50% of length of bore, more where extensively fractured
Intermediate – probably rippable by heavy power equipment to depths chiefly limited by the manoeuverability of the equipment. Hard rock layers or zones of hard rock may require drilling and blasting	Poor – flatter slopes are recommended. Some deposits commonly exhibit a deceptive temporary stability, sometimes standing on vertical or near-vertical cuts for periods ranging from hours to more than a year	Poor – foundations set in underlying bedrock are recommended for heavy construction, with precautions taken to guard against failure due to lateral stress	Maximum – support probably required for entire length of bore
Moderately difficult – probably require drilling and blasting for most deep excavations, but locally may be ripped to depths of several metres			
Difficult – probably require drilling and blasting in most excavations except where extensively fractured or altered			

Table 7.8. Advantages and disadvantages of GIS

Advantages	Disadvantages
1. A much larger variety of analysis and techniques are available. Because of the speed of calculation, complex techniques requiring a large number of map overlays and table calculations become feasible.	1. A large amount of time is needed for data entry. Digitizing is especially time consuming.
2. It is possible to improve models by evaluating their results and adjusting the input variables. Users can achieve the optimum results by a process of trial and error, running the models several times, whereas it is difficult to use these models even once in the conventional manner. Therefore, more accurate results can be expected.	2. There is a danger in placing too much emphasis on data analysis as such at the expense of data collection and manipulation based on professional experience. A large number of different techniques of analysis are theoretically possible, but often the necessary data are missing. In other words, the tools are available but cannot be used because of the lack of certainty of input data.
3. In the course of a hazard assessment project, the input maps derived from field observations can be updated rapidly when new data are collected. Also, after completion of the project, the data can be used by others in an effective manner.	

An important feature of a GIS is the ability to generate new information by the integration of existing diverse data sets sharing a compatible referencing system. Data can be obtained from remote sensing imagery, aerial photographs, aeromagnetometry, gravimetry, and various types of maps. This data is recorded in a systematic manner in a computer database. Each type of data input refers to the characteristics of recognizable point, linear or spacial geographical features. Details of the features usually are stored in either vector (points, lines and polygons) or raster (grid cell) formats. The manipulation and analysis of data allows it to be combined in various ways to evaluate what will happen in certain situations.

Currently, there are many different geographical information systems available, ranging from public domain software for PCs to very expensive systems for mainframe computers. Since most data sets required in environmental or engineering geology data processing are still relatively small, they can be accommodated readily by inexpensive PC based GIS applications. The advantages of using GIS compared with conventional spatial analysis techniques have been reviewed by Burrough (1986) and are summarised in Table 7.8.

An ideal GIS for many engineering geological situations combines conventional GIS procedures with image processing capabilities and a relational database. Because frequent map overlaying, modelling and integration with scanned aerial photographs and satellite images are required, a raster system is preferred. The system should be able to perform spatial analysis on multiple-input maps and connected attribute data tables. Necessary GIS functions include map overlay, reclassification and a variety of other spatial functions incorporating logical, arithmetic, conditional and neighbourhood operations. In many cases, modelling requires the iterative application of similar analyses using different parameters. Consequently, the GIS should allow for the use of batch files and macros to assist in performing these iterations.

Mejía-Navarro and Gracia (1996) referred to several attempts to use GIS for geological hazard and vulnerability assessment. These were especially in relation to the assessment of landslide, seismic and fluvial hazards. They then went on to describe a decision support system for planning purposes that evaluates a number of variables by use of GIS. This integrated computer support system, termed Integrated Planning Decision Support System (IPDSS) was designed to assist urban planning by organizing, analyzing, and evaluating existing or needed spatial data for land-use planning. The system incorporates GIS software that allows comprehensive modelling capabilities for geological hazards, vulnerability and risk assessment. The IPDSS uses data on topography, aspect, solid and superficial geology, structural geology, geomorphology, soil, land cover and use, hydrology and floods, and historical data on hazards. As a consequence, it has been able to delineate areas of high risk from those where future urban development could take place safely and is capable of producing hazards susceptibility maps.