UNIVERSITY OF
NEWCASTLE

Feb 25, 1397

Malik Salman Ahsan
2016-MS-CEG-03

DEPARTMENT OF CIVIL ENGINEERING

GROUND EXPLORATION

by

B G Clarke

Department of Civil Engineering, University of Newcastle upon Tyne,
Newcastle upon Tyne NE1 7RU, UK

GROUND INVESTIGATION

by

B G Clarke
University of Newcastle upon Tyne, UK

1.1. WHAT IS GROUND INVESTIGATION

SITE INVESTIGATION A comprehensive study of the site including past use and environmental constraints. This includes a ground investigation.

GROUND INVESTIGATION An exploratory and geotechnical investigation of ground conditions required to determine the geological structure, characteristics of the superficial and solid deposits and existence of ground water. The extent of the ground investigation is based on the information obtained from the site investigation.

⇒ Planning stage :- ⇒ Surface investigation i.e topography, Existing structure ground levels, already present on scale - In both horizontal and vertical plane. Contouring

If there are slopes or cut/fills

⇒ Superficial material / Surface material that is soil.

⇒ Why we need G.I :-

It is prerequite for economical & safe Design of structure.

Since more chance our Design without investigation will be an uneconomical.

⇒ Feasibilities Studies requires G.I. large projects.

⇒ Without G.I our Design would be conservative and uneconomical.

⇒ For inappropriate G.I will cause delays since our assumptions may be wrong and then have to redesign or cater that situation.

Significance

1.2. REASONS FOR GROUND INVESTIGATION

1. More tests are carried out on man made construction materials than on natural materials despite the fact that we know more about the man made materials. like concrete (cube).

   e.g. A concrete structure contains many cubic metres of concrete. Concrete is man made and controlled with tests being carried out frequently to test the quality.

   Structures are founded on soil or rock. The amount of ground affected by a structure is many times greater than the volume of concrete in a structure. Ground is natural or man made, variable and expensive to control yet few tests are carried out to identify the strata and produce characteristic properties of the ground.

2. 37% of all delays in building construction are due to unforeseen ground problems.

3. 50% of insurance claims on properties are due to geotechnical problems.

4. The final costs of an highway project are 17% greater because of inadequate planning of SI or poor interpretation of results.

5. 85% of tunnelling contracts are based on inadequate SI.

6. The cost of SI is under 0.1% to 0.3% of the cost of a structure, that is less than the cost of bathroom fittings!

7. SI, properly carried out under qualified supervision, can reduce construction costs, maintenance and produce safer structures no matter how large or small the project.

8. SI data is only as good as the design and operation of the SI. improper investigation.

GARBAGE IN = GARBAGE OUT

Proper design and planning, execuation & Interpertation of Geotechnical Investigation.

1.3. THE OBJECTIVES

MAIN OBJECTIVES

1. To explore surface and sub surface features
2. To determine the geological features
3. To produce characteristic ground properties for design
4. To identify possible hazards to construction, changes in ground conditions that could affect the serviceability of the structure

GEOLOGICAL FEATURES

The ground investigation should identify the depth and extent of the main strata, any sub surface features and ground water conditions.

Geological descriptions of the main strata should be produced so that typical design parameters can be selected from experience.

Potential problems for construction and changes to the environment, in particular ground water, should be identified.

GROUND PROPERTIES

The variation in strength of the main strata should be measured so that the strata can be classified and bearing capacity calculated to ensure that there is an adequate factor of safety against failure due to general shear.

The variation in stiffness of the main strata should be measured so that total and differential settlement of the structure can be calculated.

The effects on adjacent properties due to changes in stresses within the ground will be assessed from the ground properties, type and depth of foundation and loads applied.

The permeability of the main strata should be measured and any features of fabric that could affect permeability should be identified. This will permit estimates of ground water flow and rate of settlement to be determined.

Chemical properties should be assessed to check for damage to construction materials and potential contamination.

(ix) Determining potential foundation problems, e.g presence of expensive soil, collapsible or sanitary fills.

(viii) Conducting field test for interpreting engineering properties. i.e, PLT, Pile load Field permeability

(vii) Indentication of problems concerning adjacent existing structure.

(viii) Indentification of enivironmental problems & their solution e.g Ground water regime.

Objectives

(v) Identification of construction problem & their solution. e.g dewatering, rock excavation & sheeting.

(i) To know thickness & sequence of soil/Rock strata. Know as soil stratigraphy.

(ii) Selecting type and depth of foundation system. i.e shallow/deep foundation.

(iii) Evaluting load Bearing Capacity of foundation.

(iv) Recovering sufficient field/Lab data for settlement prediction under foundation.

(iv) Location of ground water Table & problem related to flacutuation.

1.4. THE DESIGN PROCESS

STRUCTURAL ENGINEERING

A structural engineer specifies, tests and examines materials to be used in a structure.

GEOTECHNICAL ENGINEERING

Decisions are taken on properties of natural materials formed by geological processes. The quantity and variability of material is significantly greater than that in the structure.

DESIGN PROCESS

1. Project requirements
2. Study of the environment
3. Preliminary design solution and selection of materials
4. Assessment of cost
5. Site investigation
6. Modelling of structure and foundations
7. Verification of design and costs
8. Optimisation of design
9. Final evaluation

CONFIRMATION OF DESIGN

1. Monitoring
2. Revaluation

Project Requirements

A process of familiarisation by obtaining information from the client, reviewing codes of practice, regulations, technical literature and in house knowledge.

Purpose, function and service life of the structure.

Regulations that apply throughout the life of the structure including pre construction activities such as ground investigation.

Time to commission the structure.

Study of the Environment

A study (desk study) is made of the topographical, geological, meteorological and seismic features of the site.

This study should include identification of possible limitations such as shallow mine workings, solution cavities, restrictions due to underground features such as tunnels and adjacent foundations.

Uncertanity:-
(i) Soil is hetrogenous (ii) Large Extent of soil is large (iii) Interperation of data.
Remedies
(i) Adpoting conservative design (ii) Knowledge of local geology. (iii) observing & monitoring conditions during constrcion
(iii) Be ready to change design during changed condition. (iv) Accepting risk of failure, 100% relaibility not possibele

Preliminary Design Solution and Selection of Materials	Preliminary calculations for possible options for suitable structures and foundations that satisfy project requirements and environmental restrictions. Potential hazards and critical factors are identified. Material selection based on experience and judgement.
Assessment of Cost	Estimate of costs of design and construction based on preliminary designs. Adjust preliminary design if any savings can be made.
Site Investigation	A site investigation (walk over survey) is made to confirm the findings of the desk study and the assumptions made in the preliminary design. The information from the walk over survey and preliminary design is used to design a ground investigation. The ground investigation is undertaken to identify the various ground strata, obtain representative design parameters of strength, stiffness and permeability and identify any potential hazards due to derelict or contaminated land, ground water movements, mining activities and natural features.
Modelling of Structure and Foundations	The structural loadings, material properties and ground characteristics are used in a mathematical model of the structure to confirm the adequacy of the design. An adequate design is one which satisfies the safety and functional requirements, is economic and can be built. If the modelling process highlights changes to the design then alternative designs and costs and possibly additional ground investigation are required. The mathematical models used should be validated and an assessment made of their suitability. A sensitivity study is carried out to assess the effects of changes in material and ground properties.
Verification of Design and Costs	The final design and costs are verified.

Optimisation of Design	Detailed design drawings are produced, optimising all aspects of the design. Temporary works are considered as part of the design process since they can influence the final design. The construction sequence is considered and critical factors identified for monitoring purposes.
Final Evaluation	A final evaluation of all aspects of the design including the site investigation, ground characterisation, the structure and foundations, mathematical modelling and construction sequence is made based on experience and practice.
Monitoring	Monitoring points, hazard levels and procedures will have been identified at the design stage. Instruments, including levelling points, will be installed prior to and during construction at key points. This will include redundant instruments to cater for failures of instruments. Monitoring programmes and responsibilities will be specified. Actions to be taken should hazard levels be achieved should be clearly defined.
Revaluation	Any major difference between anticipated construction and actual construction should be identified and the design reassessed. Any displacements or stresses measured during the monitoring exercise that exceed the maximum permitted in the design should be identified and the design reassessed and possibly changed.

⇒ Factors Affecting Soil Investigation Work. / Scope of Work.
(i) Size & Type of structure (loading) (ii) General characteristics of soil in the site area / already available data.
(iii) Time and money / finances available. (iv) Degree of risk and safety requirement. (Nuclear plant & Building).

* Project Assessment:-
(i) Type of structure, locations, dimension, Type of loading etc. (ii) Type of construction.
(iii) Allowable settlements (raft, shallow found.) (iv) Existing topography & any proposed grading / Level
(v) Presence of various development / Access

⇒ Framework of S.I:-
(i) Desk Study / Literature Research (ii) Reconissance / walk over Survey (iii) Preliminary Investigation
(iv) Detailed Investigation (v) During Construction / Post construction.

* Desk Study
(i) History of site / soil deposition (map of geology) (ii) Soil Survey Reports (iii) Geotechnical Reports of near area.
(iv) Historic G.W.T Data (v) Remote Sensing / Arial Photographs

1.5. The Requirements

Client's

The client is primarily concerned with the serviceability of the structure throughout the period of operation by the client.

The structure has to be safe for the purpose for which it is designed.

Adequate services have to be provided, the structure has to be supported in such a way that it does not hinder the client's operation and expose the client to third party claims by users of the structure and owners of adjacent properties.

The structure will settle but the total and differential settlement must be limited to prevent damage to the structure and ensure that it 'looks' safe. There is a limit to the amount of movement that can be tolerated even though the structure is still safe.

Statutory

Statutory requirements are given in national and local codes of practice, regulations and standards.

These include the minimum depth of foundations to allow for seasonal changes of ground water, the effects of temperature and trees.

Limits can be given for the maximum differential settlements and total settlement.

Regulations may be imposed to limit the effect on the environment.

Specifications may given for loads including earthquake loads, and factors of safety.

There may be constraints imposed by other bodies on the effect any construction may have upon their property.

Environmental Considerations

These may not be requirements but actions could be taken if they are not considered at the design stage.

The effects of any site operations, including ground investigation and construction as well as the operation of the structure, on ground water and the environment must be considered.

This can include ground water contamination, gas, chemical contamination and areas of scientific interest.

1.6. DESK STUDY

PURPOSE

A desk study is carried out in order to determine the available information and become familiar with the project.

SOURCES OF INFORMATION

Information in the public domain includes geological maps, topographical maps and records maintained by the library.

Local authorities, statutory bodies, the Geological Survey, mining companies will have information that can often be purchased.

Experience of local contractors and consultants is useful.

GENERAL

The type of information required is the same no matter the size or complexity of the project but very often the amount of information gathered will depends on the size of the site, the complexity of the project and the time available.

SITE LOCATION

The actual location and boundaries of the site should be established and marked up on a topographical map which will be later used in the site reconnaissance.

MAPS AND OTHER RECORDS

Topographical and geological maps are used to identify man made surface features such as fences, power lines, roads and buildings; natural surface features such as streams, springs, scarps, landslides, vegetation and marshland; man made sub surface features such as mine workings and tunnels; and natural sub surface features such as drift deposits and solid deposits.

Historical maps are used to identify previous users of the site and changes that have occurred.

Maps of services including water, sewerage and storm water, electricity, gas, telephones are used to identify potential problems during a ground investigation. However, they are often incomplete or even wrong. On larger investigations it may be necessary to make use of services such as water.

Aerial and historical photographs can often show features not shown on maps or easily recognised from a site reconnaissance.

USES AND RESTRICTIONS

There are a number of restrictions imposed by Acts of Parliament which include Town and Country Planning Act, Building Regulations, Rights of Light, Way and Support and Ancient Monuments.

In addition there are restrictions imposed which may not be clearly identified as Acts of Parliament which include mineral rights, burial grounds, environmental aspects, industrial restrictions, sites of scientific interests

CONSTRUCTION RECORDS

In house experience and experience of other construction companies can provide useful background information.

ARCHIVE MATERIAL

Local newspapers, historical societies proceedings and local library archive material can often provide useful sources of information on changes that have taken place on the site and problems that may have occurred.

1.7. SITE RECONNAISSANCE

PURPOSE

A site reconnaissance is carried out to confirm the findings of the desk study, determine changes that have taken place but not recorded and record differences between available data and actual findings.

There are two reasons for the reconnaissance. The first concerns the site investigation in which all aspects of the environment are viewed. The second concerns the ground investigation in which features are identified that could hinder or help the investigation process.

EQUIPMENT

Before undertaking a reconnaissance it is necessary to obtain permission for access which could require a key.

Current topographical and geological maps should be marked with the site boundaries and major structures. These are used together with a compass and site plan, to mark the site plan on the ground.

A notebook should be used to record all changes but, in addition, it is prudent to photograph the site.

The location of services can often be traced from manholes and other access points.

PROCEDURE

Walk over the site area and adjacent ground looking for features highlighted in the desk study and features not shown on available data.

Set out the site plan to view the location in relation to existing features.

Record any additions or changes to boundaries, buildings, transmission lines, roads, railways and water courses.

Record any features that may obstruct the ground exploration process including telephone lines, trees, transmission lines, manholes, old foundations and made ground.

Make a note of all access points to the site. Check that they are wide enough for drilling rigs. Locate the owner of any locked access point.

Note any evidence of mineral workings, drainage systems, the state of buildings in the area particularly look for evidence of subsidence. This will cause differential movement of structures giving rise to cracks. It may be caused by inadequate foundations on soft soils, mining subsidence and sinkholes.

2.4. Deep Exploration Techniques

Rotary Rig

This is the main method of carrying out ground investigation and is essential for creating holes in rocks. It is used to drill holes in all ground conditions and is usually operated by a two or three man crew.

75 mm to 150 mm diameter boreholes can be drilled from 1 to 250m in soils though the most common depths are between 1 and 30m. It is used in investigations for shallow and deep foundations in soils.

Purpose

The rig is used to create boreholes for in situ tests, take samples (disturbed and undisturbed), rapid exploration and install instruments.

Equipment

A rotary rig can take many forms but essentially they all operate in the same way. A mast is erected over the borehole. This mast is used to support the drill tools. The hole is advanced either by a rotating bit or downhole hammer. They are connected to the surface with drill rods. These drill rods are connected to a kelly bar which is supported by a wire rope passing over the mast and connected to an hydraulically operated winch. A hydraulic or manual chuck is used to grip the kelly bar.

This chuck is turned by a hydraulic motor which is either on top of the drill rods (top drive) or around the rods (hydraulic spindle). The rods are pushed into the ground by their weight with additional thrust from hydraulic rams.

Drilling tools include downhole hammers, core bits, drag bits and rock rollers.

Operation

The hole is advanced by the action of the rotating bit or bit driven by a down hole hammer breaking, grinding or cutting the ground. The particles are removed by the flushing medium which is pumped down to the drill bit with a pump.

Casing is usually required in unstable soils and deep holes. It ensures hole stability, reduces friction between the tool and borehole sides and tends to keep the hole vertical. There must be sufficient clearance between the boring tool and casing to prevent suction developing below the boring tool.

Note the natural drainage pattern, that is the direction and dip of slopes, evidence of streams and springs, diversions to the drainage system and lines of storm water drains. The type of vegetation can often indicate the nature of the near surface ground water conditions.

Note any areas of man made ground and identify whether it is construction, domestic or toxic fill.

Look for evidence of natural ground movement including erosion, sinkholes and landslides. Sloping uneven ground, trees growing at an angle, tension cracks, deviation in fence lines indicate areas of landslides.

Look for evidence of soil types from natural exposures such as river banks, cliffs and escarpments, quarry faces, vegetation and low flat lying areas crossed by rivers.

1.8. DESIGN OF A GROUND INVESTIGATION

PLANNING

The philosophy of any ground investigation plan is to produce a cost effective, flexible solution which is technically correct and will produce quality information.

The purpose is to verify and expand the existing information retrieved from the desk study and site reconnaissance to enable a safe, economic design to be produced.

The exploration programme will be based on known information about the site, foundation types and depths.

Specifications will be given for the types of equipment and tests, borehole locations and depths, sample/test locations and depths and safety precautions. Acceptance criteria will have to be specified.

Costs will depend on the specifications, type of contractor and type of contract.

There should be two ground investigations. The first is too gain an overall understanding of the ground conditions and verify the information all ready obtained. The second is more detailed and based on the results of the first investigations.

SITE ORGANISATION

The magnitude of the investigation will dictate the amount of personnel required. Site staff include those representing the client, the Engineer, who are responsible for ensuring the work is carried out according to the specification, and those representing the contractor who are responsible for ensuring that the work is done within the budget and to the specification. This can give rise to conflict and therefore it is important to establish good working relationships.

The resident engineer acts on behalf of the client to ensure a quality assurance programme is followed and the investigation complies with the specifications. He should check the interpretation of the ground investigation data and ensure that it is satisfies the design requirements. He may have a team of engineers and geologists working for him on larger projects. On small projects the resident engineer will not be present at all times during the investigation. In that case he has to place trust in the contractor.

The site agent represents the contractor to ensure that work is carried out according to specification and within budget. He will be aware of the contract details, ensure that the quantities are agreed and produce the factual report.

The site agent may be assisted by technicians who will carry out specialist in situ tests and by engineers/geologists who will carry out and interpret in situ tests, describe soil and rock and ensure that the exploratory operations are correct.

On larger contracts which require interpretative reports a technical manager will be responsible for describing the soil/rock, data processing and producing the factual report and interpretative reports.

CONTRACT

There are three ways of selecting a contractor:- by tender, nominating and naming.

Tender documents, including the specifications and bill of quantities, are submitted by two or more contractors. This can give value for money but the successful tenderer should be selected for their technical qualities, their experience of the type of work and the ability to do the work within the time specified.

Selective, competitive tendering is the best method to ensure competent experienced companies carry out the work required to the satisfaction of the Engineer and client.

A nominated contractor is usually a contractor who is known to produce the quality work required or who can carry out specialist work. Nominated sub contractors can be specified in the main contract which implies that the main contractor takes no responsibility for the nominated sub contractor.

A named contractor is similar to a nominated contractor but they are the preferred contractor. Another contractor may undertake the work. A named sub contractor is the responsibility of the main contractor.

There are four types of contractor involved in ground investigation:- main contractors who undertake exploratory work, in situ and laboratory testing and engineering interpretation of the data, drilling contractors, specialist testing contractors and engineering contractors.

SPECIFICATIONS

There are a number of specifications covering general aspects of the work. These include the Institution of Civil Engineers and client's own specifications.

The specifications must cover access, hours of working, restrictions or hazards, facilities for all technical staff, disposal of waste, supervision of exploratory work, experience of staff, type of report and key dates such as starting and finishing site work and time of submitting report.

On larger projects it may be necessary to specify a store for samples and a laboratory.

Exploratory and test methods will be carried out according to codes of practice such as BS5930 and standards such as BS1377. Specifications may have to be written for more specialist tests and instrumentation.

A quality assurance programme may be required.

The type of report, factual or interpretative, must be specified. A factual report covers the field operations and includes results of laboratory tests and borehole logs. An interpretative report includes a factual report but also will include an assessment of the ground conditions. In that case the contractor will have to have access to design information.

Bill of Quantities

The Bill of Quantities is used to estimate the cost of the ground investigation works at the tender stage and act as the basis for calculating quantities for payment.

It will include rates for personnel, equipment hire, day works, drilling, testing and reporting. The drilling and testing rates are often sub divided to cover all aspects of any one operation for example moving between boreholes, drilling to various depths, standing time, chiselling, sampling and backfilling holes. In situ tests can include items for preparing the test pocket as well as the test.

Borehole Location

The location of the boreholes depends on the type and importance of the of the structure, the topography, obstructions at the surface and in the ground and the information required.

The number of boreholes required for a structure such as a building depend on a number of factors so general guidelines can not be given. However, a minimum of three boreholes is required for interpretation of strata. Three boreholes are the minimum for a bridge abutment. Boreholes for linear projects such as pipelines and roads are located at between 50 and 1000m depending on the length of the project. Investigations into the stability of slopes require at least three boreholes down the line of the slope.

Boreholes, and trial pits in particular, should not be placed at the location of any foundations.

Borehole Depths

The depths of the boreholes depends on the project and the depth to rock. It may be necessary to prove rock but on most projects boreholes are limited to a specified depth or rock.

Generally boreholes should be extend to at least the depth of the zone of influence of the foundation. Thus for a shallow foundation for a building this would be 1.5 times foundation width plus the depth. For piled foundations the boreholes should extend beyond the base of the piles. At the time of specifying the ground investigation the size and depth of foundation is unknown. Thus some boreholes should extend beyond the likely depth to ensure that any changes in foundation design can be accommodated.

Boreholes for roads built at or below ground level should extend to 2 - 3 m below road formation. Boreholes for roads built on embankments must extend to the same distance as those for foundations.

Boreholes for pipelines extend to 0.5m below the pipe invert.

Boreholes used for investigating potential or actual landslides must extend below the potential failure surface.

Boreholes for structures on poor ground must prove the base of the poor ground.

Sample Spacing

Samples can be bag, tube or core samples. The type of sample taken depends on the type of ground and the specification. There are specialist sampling devices for difficult ground conditions.

Generally bag samples are taken for cohesionless soils, tube samples for clays and core samples for rocks but every attempt must be made to obtain the best quality sample so that tests can be carried out to determine parameters for foundation design.

Samples are usually taken every time there is a change in strata or 1.5m whichever is less. The spacing increases with depth. On more sensitive projects continuous sampling may be required.

Samples of water are taken every time there is a strike.

FIELD OPERATIONS

2.1. PHILOSOPHY

PURPOSE

Exploratory techniques, which include boreholes and trial pits are designed to obtain information about the spatial variation of ground type and properties.

Disturbed and undisturbed samples are recovered to allow the ground to be described and tested in the laboratory.

In situ tests are carried out to obtain ground parameters at the time of the field operations.

The soil description together with classification tests are used to produce sections showing the main strata. Representative samples are taken from those strata for further tests to determine the strength, stiffness and permeability of the ground.

2.2. SHALLOW EXPLORATION TECHNIQUES

TRIAL PITS

Trial pits are used for shallow visual investigations and to obtain samples from the top few metres of soil. They are a very economical means of obtaining information rapidly.

Trial pits are used to obtain detailed information of the top layers of soil, determine rock head if it is near the surface and obtain class 1 samples.

They are normally 1 to 3m deep but can extend to 6m. The depth is limited because of the method of excavation which is either by hand or machine. In exceptional circumstances deeper pits are dug.

The depth is also limited because of possible collapse especially in water bearing sands and gravels.

No one should enter a trial pit unless they can guarantee that the pit will not collapse. It may be necessary to use some form of retaining structure.

There is no limit to the size of the pit but the excavated soil will be disturbed when replaced hence the ground would be unsuitable for constructing shallow foundations. The size should be limited. On occasions trenches rather than pits are dug so that sub surface features such as karst can be identified.

HAND AUGER

A hand auger can be used to drill holes to a shallow depths and obtain disturbed samples and undisturbed samples. It can be operated in restricted areas.

Up to 200 mm diameter holes can be drilled to a maximum depth of six metres. The depth is restricted because of the time it takes to lower and raise the auger.

The holes have to be supported in unstable ground, perhaps with bentonite. It is difficult to auger in water bearing sands and gravels.

2.3. Medium Exploration Techniques

Light Percussion Rig (soft ground rig, cable tool rig, shell and auger)

This is the main method of carrying out site investigation in the UK. It is used to drill holes in all soils and weak rocks. It is usually operated by a two man crew. The rig is towed by a cross country vehicle.

150 mm to 300 mm diameter boreholes can be drilled from 1 to 80m in soils though the most common depths are between 1 and 30m. It used in investigations for shallow and deep foundations in soils.

Purpose

The rig is used to create boreholes for in situ tests, take samples (disturbed and undisturbed) and install instruments.

Equipment

An A frame is erected over the borehole. A wire rope connected to a motorised winch passes over a pulley at the top of the A frame and is connected to a boring tool used to advance the hole.

Boring tools include shells (to retrieve clay soils and dry sands), balers (to remove water and wet soils), clay cutters (to remove clay) and chisels (to drill through rocks and boulders)

Operation

The hole is advanced by repeatedly raising and dropping the boring tool. The tool is removed from the hole repeatedly to remove the soil. The boring tool penetrates the ground because of the weight of the tool and the drop height. Additional weights can be added in the form of sinker bars.

Casing is usually required in unstable soils and deep holes. It ensures hole stability, reduces friction between the tool and borehole sides and tends to keep the hole vertical. There must be sufficient clearance between the boring tool and casing to prevent suction developing below the boring tool.

Dynamic Probing

This is the same system used for dynamic probing (see in situ testing) but instead of a cone a hollow tube is hammered into the ground to retrieve a class 1 sample.

Bit Types

Core bits are used for sample recovery in all ground conditions. The bits can either be diamond or tungsten carbide.

Drag are used to create open holes in soils and weak rocks. They take the form of tungsten carbide tipped blades.

Rock rollers are used to create open holes in soils and rocks. They are made from tungsten carbide tipped wheels which rotate as the drill rods are turned.

Percussion bits are used to create open holes in weak rocks.

Augers, which can be single or continuous solid or hollow, are used in soils. These are screwed into the ground with no flush.

Flushing Medium

The purpose of a flushing medium is to remove particles, cool the drill bit

The problems associated with the medium are the viscosity causing increased pumping pressure and erosion and softening of the borehole walls.

Air flush operates at about 1000m^3/min. It gives rise to bit wear and erosion. In some ground (especially fissured) there can be significant losses of pressure and no return.

Water flush operates at a lower flow rate (24 - 50 m^3/min) and pressure but it can cause softening.

Mud flushes include bentonite and polymer based muds. They form a cake on the borehole wall helping to stabilise the wall. The density can be increased by suitable fillers leading to further support. They are more viscous and operate at a lower velocity than water flush.

Mist and foam flushes are mixtures of air, water and mud which have some of the advantages of each of the other flushes on their own.

2.5. SAMPLING

PURPOSE

Samples are taken to obtain specimens for determining the physical, chemical and mechanical characteristics of the ground in the laboratory.

TYPES

Samples can be either jar, bag, tube, continuous, core or block.

Ideal Sampler

The ideal sampler must be thin walled to reduce the area ratio since the greater the ratio the greater the possibility of compacting the soil, have a small taper angle to reduce bearing failure at the base of the sampler and smooth walls to reduce friction between the ground and the sampler.

Samples are divided into groups according to the amount of disturbance they create and the type of properties that can be measured.

Sample Quality

Class	Properties		Technique
1	classification	w, γ, SG, PI, PSD	pushed thin wall sampler
	strength	c', ϕ', c_u	some thick walled samplers
	deformation	E, G, m_v	some core barrels
	permeability	k, c_v	
2	classification	w, γ, SG, PI, PSD	thin and thick wall samplers core barrels
3	classification	w, PI, PSD,	clay cutter or auger (dry)
4	classification	PSD, PI	clay cutter or auger (wet)
5	none		cuttings and flushing return

Jar Samples

These are small samples taken as the hole is advanced. They are used to identify the ground type, make preliminary logs and produce test schedules.

Bag Samples	These are large disturbed samples taken for testing and description. Most samples of cohesionless soils are bag samples.
Tube Samples	These are thin or thick walled tubes pushed or hammered into soil (usually cohesive soils). Thin walled tubes can either be piston samplers used with specialist equipment for sampling soft clays or tubes pushed in with rotary rigs from the base of holes. Pushed tubes are specially made to minimise disturbance. Thick walled tubes are usually hammered into soil. They may contain a liner to reduce friction.
U100	This is a common thick walled sampler. It has the advantages that it is a simple, robust, cheap sampling device that retain a relatively large sample. The disadvantages include a high area ratio, high friction, poor sample retention and uneven rate of penetration. The sampling is operator dependent, the depth of actual penetration is unknown and the sample may include disturbed soil from the base of the hole unless the hole is cleaned out prior to sampling.
Thin wall tube	This is a thin walled tube pushed into firm to stiff clays either with rods from the surface or using the casing and wireline equipment. It is a simple, rapid sampling tool that has a low area ratio and gives a relatively large sample. The tube is easily damaged because of the jacking forces required which can mean a large reaction system. The sample will be affected by the friction between the tube and the soil and may include disturbed soil from the base of the borehole.
Piston	This is a specialist thin walled tube sampler used to obtain samples of soft clay. It has the advantage that an exact length of a large sample of natural soil is retained. The tube, with a low area ratio is jacked into place, the exact depth being known at all times. The tube can easily be damaged. It is expensive since kentledge is required and is usually operated by a specialist operator.
Continuous Sampler	This is a specialist sampling tool for obtaining continuous samples of soft clay by jacking the equipment from a specialist rig into the ground. Samples are retained with their natural structure since the sampler has a low area ratio and the friction is low. The sampler can easily be damaged. It is complex, expensive and operated by a specialist operator.
Block Samples	These samples are the best undisturbed samples taken where it is possible to get direct access to the ground. They are taken from trial pits and shafts. The samples are usually large and relatively undisturbed.
Core Barrel	This is used to obtain samples of rock and possibly stiff clays and dense sands. It consists of a rotating outer core barrel, a stationary inner barrel, a reaming shell, a core catcher (box or spring) and a core bit. It i medium.

Other Samplers

There are numerous other sampling devices designed for specific soil type or conditions. These include a sand sampler for obtaining undisturbed samples of sand; frozen sampling for obtaining samples of silt and sand; flow through samplers for obtaining continuous disturbed samples rapidly, standard penetration testing equipment to obtain disturbed samples of cohesionless soils.

Sample Application

Type	Size	Installation	Class	Ground
jar	small	cuttings	5	all
bag	large	shell, core	3,4,5	soil
U100	100mm dia 0.5m long	pushed jacked	1,2	clay
piston	75 - 200 mm dia 0.5 - 1m long	jacked	1,2	clay
tube	75 - 100 mm dia 0.5 - 1m long	jacked	1,2	clay
core	NX - SX	drilled	2	all
block	up to 1 m	cut	1	all
continuous	50 - 100 mm dia	jacked	2	soil

SAMPLE DISTURBANCE

It is important to minimise disturbance to the ground so that the parameters obtained represent the properties of the ground.

Disturbance is caused during drilling due to stress relief, swelling, compaction, piping and collapse of the borehole.

Disturbance during sampling is caused by stress relief, remoulding, compaction, segregation, fracture, loss, gouging and friction.

Further disturbance is caused during transport and storage by stress relief

MINIMISING DISTURBANCE

It is important to minimise the time of sampling to prevent swelling.

Cohesive samples should be taken from dry holes.

Compaction can be reduced by keeping the casing above the base of the borehole, ensuring that the tubes are clean and smooth and any vent on the sampler is working.

Piping in cohesionless soils can be reduced by maintaining a water balan

Collapse is prevented by using casing, mud and keeping a dry hole above the ground water level.

Distortion of the sample is reduced by using smooth clean tubes, thin wal

FAILURE TO RECOVER

Samples may not be recovered for a variety of reasons including remoulding, pressure above the sample, suction below the sample on removing and the tensile strength of the soil greater than friction between the soil and the tube.

It can be reduced by ensuing a low area ratio, small taper cutting angle,

Other techniques include allowing some swelling to take place after driving the sampler, slight over driving and using a core catcher.

STORAGE

It is important to test the ground as soon as possible after it has been sampled. Water loss, further stress relief, pore pressure equalisation and remoulding due to handling can occur.

Measures can be taken to reduce the problem including keeping the samples at a constant temperature, constant humidity and ensuring the sample is sealed.

Samples must be properly sealed to prevent changes in water content and contamination due to air. Ends of undisturbed samples are sealed with paraffin wax and end caps placed on the tube.

Samples must be properly labelled both inside and outside of the sampler. The site, borehole number, sample number, depth and orientation must be shown.

In Situ Testing and Laboratory testing

3.1 General

Definition

Tests carried out in situ either in the ground from the base of boreholes or at the surface.

Types

Tests are usually grouped according to the type of equipment. There are five groups of in situ tests:- penetrometers, pressuremeters, geophysical, environmental and others. Some tests fall into more than one category.

Penetrometers

These cylindrical devices are pushed or hammered into the ground and the resistance to pushing or the number of blows is recorded and related to the strength and stiffness of the ground.

Dynamic probes include the Standard Penetration Test (SPT), light and heavy dynamic probe (DPT) and the Mackintosh probe.

Static probes include the mechanical friction cone (Dutch cone), the electric friction cone (CPT) and the piezocone (CPTU).

Pressuremeters

Pressuremeters are probes that are installed into the ground below the borehole. An expanding section is inflated and the displacement of the expanding section and the pressure required to cause that displacement are measured.

Prebored pressuremeters (PBP) are those that are lowered into prebored holes and include the Menard pressuremeter (MPM), the Elastometer (OYO) and the high pressure dilatometer (HPD).

Self bored pressuremeters (SBP) are those that are drilled from the base of boreholes into the ground. They include the Cambridge self-boring pressuremeter (CSBP) and the pressiometre autoforuer (PAF-76).

Pushed in pressuremeters (PIP) are those that are pushed into the ground. They include full displacement probes such as the cone pressuremeter and partial displacement probes such as the Stress probe.

Geophysical tests

Geophysical tests can either be used in boreholes or at the surface. They are used for a variety of reasons and tend to be specialised.

Seismic tests are used to measure the transmission of vibrations through the ground which are a function of the stiffness and density of the ground.

Resistivity tests are used to measure the transmission of current through the ground which is a measure of the electrical resistance of the ground.

Environmental probes

Environmental probes are specialist probes used to measure radiation, temperature and contaminants and sample water.

Others

There are a number of other in situ tests which do not fall into the categories given above.

There are a number of plate tests including the surface plate, the screw in plate (used from the base of a hole) and a borehole plate.

The vane test is commonly used to measure the strength of soft clays.

Packer tests are carried out in rock to measure the permeability of rock and estimate the in situ stresses.

APPLICATION

In situ tests are used to measure directly and indirectly parameters for design, change in properties with time and for construction control.

Design Parameters

Intrusive tests are used to obtain stress (DMT, SBP), stiffness (penetrometers and pressuremeters), strength (all tests) and permeability (piezocone, SBP, constant/variable head)

Non intrusive tests are used measure stiffness (surface geophysics)

Instrumentation

Instruments installed in boreholes are used to measure stress (pressure cells), load (load cells), deformation (inclinometers, extensometers), vibration (accelerometers), temperature and flow (piezometers)

Instruments installed at the surface are used to measure vertical and horizontal movements.

Full Scale

Foundations, embankments and other structures are full scale load tests.

ADVANTAGES

Tests are carried out at the in situ stress, density and effect a large mass of ground. Thus the parameters obtained are representative of the in situ conditions.

Some tests are very quick and cost effective allowing flexibility in the planning of the ground investigation.

Tests are used in difficult soils, as controls for construction, to give continuous profiles and to give design parameters directly.

DISADVANTAGES

The boundary conditions are not defined, drainage can occur during a test, the rate of testing is fixed and the stress path is generally fixed.

No sample is obtained for description or further laboratory testing.

Some tests are complex and can be costly.

The results are effected by disturbance during installation and can be a function of operator skill.

Some tests can be modelled but many have empirical rules for interpretation.

3.2. PENETROMETERS

STANDARD PENETRATION TEST (SPT)	The penetrometer consists of a 51 mm dia, 600 mm long tube which can be open ended in sands or conical ended in gravels. The penetrometer is connected to the surface with standard rods and is hammered into the ground with a trip hammer.
Operation	The penetrometer is lowered to base of borehole and driven 450 mm from the base of the hole.
Interpretation	Measurements are taken of the number of blows to drive the first 150 mm and the number of blows for a four further 75 mm. The blow count, N, is the number of blows to drive the last 300 mm. Corrections can be applied for effective stress or depth, rod energy and ground water level. The depth is recorded.
Advantages	This is a cheap, simple, rapid test for which there is an
Disadvantages	The result is sensitive to the drilling, generally there is poor supervision and the results are related to ground parameters by empirical correlations.
Applications	The SPT is used in all soils and weak rocks to produce empirically stiffness and strength of cohesionless soils, liquefaction potential and design parameters. It can be used in clays to measure stiffness and strength but it is more common in sands and gravels.
DYNAMIC PENETROMETER (DPT)	This penetrometer consists of a conical tip connect to rods. The probe is hammered with a small, portable rig.
Operation	The penetrometer is driven continuously from the surface using a standard weight repeatedly dropped a fixed height. Three hammers are available, light, heavy and super heavy, depending on the soil type.
Interpretation	The number of blows are counted to drive the penetrometer 100 mm.
Advantages	This is a simple, cheap test which can be used for profiling.
Disadvantages	The blow count is empirically correlated with soil properties obtained from other tests but the database is limited.

Applications

The DPT is used in areas of difficult access, to obtain soil profiles and estimates of variation in strength.

MECHANICAL CONE TEST

The penetrometer consists of a 36 mm dia, 600 mm long rod with a conical tip (included angle 60°). The surface area of the cone is 10 cm^2 and the friction sleeve area 150 cm^2. The cone is connected to the surface with standard inner and outer rods and it is pushed into the ground with a jack.

Operation

The cone is pushed 300 mm beyond the sleeve and then the cone and sleeve pushed together. Tests are carried out at 300mm centres.

Interpretation

Measurements are taken of the force needed to push the cone and friction sleeve 300 mm. The depth is recorded. The cone resistance, q_c and friction resistance, f_s are used together with charts to obtain soil parameters.

Advantages

Extensive research has been carried out on the interpretation of this simple test for which there is an international standard.

Disadvantages

The results are sensitive to cone wear, deviation of the rods and friction between the inner and outer rods. Proper calibration procedures are required.

Applications

The cone is used in all soils and weak rocks to produce empirically stiffness and strength of soils and design parameters. It can be used to estimate the thickness of strata.

ELECTRICAL CONE TEST (CPT)

The penetrometer consists of a 36 mm dia, 600 mm long rod with a conical tip (included angle 60°). The surface area off the cone is 10 cm^2 and the friction sleeve area 150 cm^2. The cone is connected to the surface with standard rods and an electric cable. It is pushed into the ground with a jack.

Operation

The cone is pushed continuously into the ground.

Interpretation

Automatic measurements are taken of the force on the tip and sleeve as the cone is pushed into the ground. The depth is recorded. The cone resistance, q_c and friction resistance, f_s are used together with charts to obtain soil parameters.

$$\text{friction ratio, } f_R = f_s/q_c = f(\text{soil type})$$

$$c_u = (q_c - \sigma_v)/N_k \qquad 5 < N_k < 75$$

Advantages

Extensive research has been carried out on the interpretation of this test for which there is an international standard. Continuous records of data are processed automatically.

Disadvantages

The results are sensitive to cone wear, deviation of the rods and friction between the moving parts of the cone. Proper calibration procedures are required.

Applications

The cone is used in fine to medium grained soils to produce empirically stiffness and strength of soils and design parameters. It can be used to estimate the thickness of strata.

ELECTRIC PIEZOCONE TEST (CPTU)

This is similar to the electric friction cone but it contains a porous element(s)

The interpretation is improved because of the measure of pore pressure. Dissipation tests can be carried out to determine in situ permeability.

$$q_t = q_c + u(1\text{-}a) \text{ where } a = \text{area ratio}$$

$$c_u = (q_t - \sigma'_v)/N_{kt}$$

$$N_{kt} = 13 + 0.11\ PI$$

FLAT DILATOMETER (DMT)

The dilatometer consists of a 250 mm long 95 mm wide plate with a 50 mm flexible diaphragm on one side. The dilatometer is connected to the surface with standard rods and an electric cable. It is pushed into the ground with a jack.

Operation

The dilatometer is pushed into the ground stopping every 20 cm to carry out a test. A test consists of inflating the membrane so that it moves 1 mm beyond the surface of the blade.

Interpretation

Measurements are taken of the pressure, p_1, required to push the membrane flush with the surface of the blade and the additional pressure , p_2, required to move the membrane a further 1 mm. The depth is recorded. These pressures together with the in situ vertical stress are empirically related to soil properties.

$$Ed = 34.7\,(p_2 - p_1) = f(\text{stiffness})$$

$$Kd = p'_1/\sigma'_v = f(\text{OCR})$$

$$Id = (p_2 - p_1)/((p_2 - u) = f(\text{soil type})$$

Advantages

This is a simple, cheap test which has some theoretical evidence to support the results.

Disadvantages

The ground proprieties are obtained from empirical correlations which tend to be site specific. There is no international standard.

Applications

The dilatometer is used in fine to medium grained soils to produce, empirically, stiffness and strength of soils, in situ stress and soil type.

3.3. PRESSUREMETERS

PRESSUREMETERS

There are three groups of pressuremeter based on their method of installation:-
prebored - those that are lowered into predrilled holes
self-bored - those that are drilled into place
pushed in - those that are pushed into place

MENARD PRESSUREMETER (MPM)

This consist of a 74m diameter pressuremeter that is lowered into a test pocket on drill rods. A control unit which incudes a pressurising system and a manual or automatic recording system is mounted at the surface.

Operation

The test pocket is created by rotary drilling techniques such that the diameter of the pocket does not exceed 110% of the probe diameter. The probe is lowered into the pocket. A test consists of inflating the membrane in increments of stress with records being taken of the corresponding displacement.

Interpretation

A stress strain curve is produced from the recorded applied stress and resulting strain. In addition, the rate of displacement with time is noted. Plots of rate of displacement for each pressure increment and stress against the displacement at the end of each increment are produced.

These plots are used to produce an stiffness from the initial loading of the ground and the limit pressure when the volume of the cavity has doubled.

Advantages

This is a test for which there is a recognised standard. It gives directly design parameters which have been developed over many years of observations of full scale structures.

Disadvantages

The MPM has not been used in all soils therefore it may not be possible to apply design rules universally. The parameters obtained are semi empirical because of the disturbance during installation of the soil to be tested.

Applications

The MPM is used in all ground conditions to obtain design parameters and for construction control in engineered fills.

SELF-BORING PRESSUREMETER (SBP)

This consists of a 74 or 84 mm diameter pressuremeter integral with a drilling system that allows the probe to be drilled to the test location using drill rods attached to a rotary drilling rig at the surface. The probe is operated from the surface.

Operation

The test pocket is created by the probe such that the diameter of the pocket and the probe are the same, that is there should be no disturbance to the ground. A test consists of inflating the membrane in increments of stress or strain with records being taken of the corresponding displacement or pressure. It is usual to carry out unload/reload cycles.

Interpretation

A stress strain curve is produced from the recorded applied stress and resulting strain. Horizontal stress is taken directly from the curve as the point at which the membrane starts to lift off from the body of the probe. The stiffness is half the slope of an unload reload cycle, though it is possible to determine a non linear stiffness profile from the complete cycle. Strength, undrained in clays, drained in sands, is taken from the latter part of the loading curve.

Advantages

The probe is drilled into the ground with minimum disturbance thus soil parameters are obtained directly using analyses based on closed for

Disadvantages

Experienced operators are required. There is no international standard.

Applications

The SBP is used in fine and medium grained soils and weak rocks to obtain ground properties which represent the in situ conditions.

PREBORED PRESSUREMETER (PBP)

These probes are similar to the Menard pressuremeter but the test procedure and analysis are similar to that of the self-boring pressuremeter.

PUSH IN PRESSUREMETER (PIP)

This consists of a pressuremeter integral with a cone that allows the probe to be pushed to the test location using cone rods attached to a cone truck at the surface. The probe is operated from the surface.

Operation

The test pocket is created by the probe such that the diameter of the pocket and the probe are the same but the process of installation causes disturbance since creating the pocket is, in effect, a cavity expansion. A test consists of inflating the membrane in increments of stress or strain with records being taken of the corresponding displacement or pressure. It is usual to carry out unload/reload cycles.

Interpretation

A stress strain curve is produced from the recorded applied stress and resulting strain. It is not possible to obtain horizontal stress directly but various empirical correlations exist for different soil types. The stiffness is half the slope of an unload reload cycle, though it is possible to determine a non linear stiffness profile from the complete cycle. Strength is found from the unloading curve in clays and correlations with results from chamber tests in sands.

Advantages

The probe is pushed into the ground causing the same disturbance every time. The test is rapid and pressuremeter and cone results are obtained.

Disadvantages

The probe can only be used in soils in which it is possible to push the cone. There is no international standard and limited experience of the use and interpretation.

Applications

The PIP is used in fine and medium grained soils to obtain ground properties empirically and theoretically.

3.4. OTHER IN SITU TESTS

VANE TEST

This consists of a vane connected to the surface with rods. The vane is turned by a torque meter.

Operation

The vane is used in soft to firm clays. It is pushed to the test depth, rotated until a cylinder of soil is sheared. Further rotation is used to measure the sensitivity of the clay. The vane dimensions (D = diameter, H = height), depth and torque are measured.

Interpretation

$$\text{torque} = 0.5^* D^2 H\,[1 + D/(3H)]\,c_u$$

$$c_u = \frac{T}{\pi D^2 \left(\frac{H}{2} + \frac{D}{6}\right)}$$

for $H = 2D$ $\quad c_u = 0.273 \frac{T}{D^3}$

Advantages

The in situ strength and remoulded strength are obtained rapidly and simply.

Disadvantages

No account is taken of anisotropy and drainage. Only total stress tests can be carried out.

Applications

The vane test is used to measure the undrained strength of soft clays.

PLATE

This consist of a 150 to 1000 mm diameter plate which is loaded using a jack reacting against kentledge (blocks, tension piles, vehicle).

Operation

Tests can be carried out at the surface (conventional plate testing), at the base of boreholes (borehole plate) and below boreholes (screw plate). The plate is place on a bed of mortar to ensure that contact between the plate and the ground is good. Increments of load are applied and the resulting displacement measured using gauges supported remotely from the loading system.

Interpretation

A stress strain curve is produced from the recorded applied load and resulting displacement. This curve is used to define the non linear stiffness profile.

$$\text{surface plate, } s = q_n \frac{B\,(1 - \upsilon)^2}{4E} \times \pi$$

$$\text{borehole plate, } s = q_n \frac{B\,(1 - \upsilon)^2\, I_d}{4E} \times \pi$$

$\nu = 0.5$ for ... ; $= 0.3$ for ...

Advantages

The test is in effect a mini foundation so the results represent the response of the ground subject to a foundation loading.

Disadvantages	It is an expensive, slow test that gives limited information.
Applications	It is used to model foundations on fill and soils.

3.5. Permeability Tests

Permeability Tests

These tests are used to measure the ambient pore pressure and permeability. They can take the form of constant, rising, falling head tests, packers tests and pumping tests.

Open Hole Tests

A piezometer is installed in a sand pocket within a borehole. The sand pocket is sealed top and bottom so the exact length of the pocket is known.

Operation

The water level in the stand pipe connecting the piezometer to the surface is monitored with time. The water level can either be maintained (constant head), allowed to rise (inflow) or fall (outflow).

Rising and Falling Head

$$k = \frac{A}{F(t_2 - t_1)} \ln (H_1/H_2)$$

Advantages

The simple test can be used in low permeability soils. The volume of soil does not change during the test.

Disadvantages

It takes time to reach equilibrium conditions and during that time the effective stress varies.

Constant Head

$$k = \frac{q}{F H_c}$$

Advantages

The test is accurate in cohesionless soils where the effective stress remains constant.

Disadvantages

Volume changes and possibly hydraulic fracture can occur.

Packer Tests

Inflatable packer(s) are installed in a borehole at the test depth. The packers are inflated, usually by air pressure, and water is injected under pressure into the cavity between the packer(s).

Operation

Tests are carried out in rocks. Water is pumped into the test zone sealed by one or two inflatable packers. The water is pressurised in stages. Measurements are taken of flow, pressure with time and depth.

Interpretation

$$k = \frac{Q}{2\pi L H_t} \ln (L/r) \qquad L > 10r$$

$$k = \frac{Q}{2\pi L H_t} \sinh^{-1} (L/2r)$$

L = length of zone
Q = quantity of flow
r = radius of zone
H_t = dynamic head
$= H_p + H_m + H_w - H_c$

Advantages

This is a simple rapid test.

Disadvantages

The test zone is undefined and prone to leakage. Test results are approximate measurements of variable horizontal permeability which are difficult to interpret.

Applications

Tests are used to measure rock permeability, grout intake, degree of fissuring and hydraulic fracture.

FIELD PUMPING TESTS

A pumping well is installed to the full depth of an aquifer. Two lines of at least four observation wells are drilled at right angles with the pumping well at their junction. The observation wells are spaced at ten times the pumping well radius. A submersible pump and well screen are installed in the well.

Operation

The water level in the well is lowered by pumping and the water level is maintained until a constant discharge is achieved. The flow and water levels in the wells together with the depth and thickness of the aquifer are recorded.

Interpretation

Confined aquifer

$$k = \frac{q}{2\pi h_o (s_1 - s_2)} \ln (r_2/r_1)$$

Unconfined aquifer

$$k = \frac{q}{\pi (s_1^2 - s_2^2)} \ln (r_2/r_1)$$

Advantages

The in situ, mass permeability is obtained.

Disadvantages	It is an expensive, time consuming test.
Applications	It can be used in all ground conditions to obtain mass permeability.

3.6. GEOPHYSICAL TESTS

GEOPHYSICAL TESTS

Geophysical tests are used to determine geological structure, profile bou

They are based on a contrast of physical properties of the ground including density, elasticity, electrical conductivity and magnetic susceptibility. They detect the Earth's magnetic field or induced fields.

Limitations

It can be difficult to interpret tests in areas of complex geology and heterogeneous ground. The tests are affected by background noise. The depth of features and lack of contrast may influence the results.

Methods

Methods include seismic reflection, seismic refraction, resistivity, magnetic and gravitational. Seismic and resistivity methods are the most common in geotechnical engineering.

MAGNETIC

This is a qualitative method based on the variation in the earth's field used to measure buried features. It is affected by complex geology.

GRAVITY

This is a qualitative method based on the variatio

SEISMIC

The vibrations transmitted by a source which can be a falling weight, explosion or hammer are observed using geophones connected to testing equipment.

Operation

The geophones are placed in the ground at a set distance from the source. A seismic shock wave is generated and the time recorded for the vibrations to reach the geophones.

Waves

Several waves are generated including longitudinal (P), transverse (S), Rayleigh and Love waves. P waves are the most useful.

P waves

Spherical fronts are generated with the particles vibrating parallel to the direction of travel. They are the fastest waves through the ground.

$$V_p = \frac{[E(1 - v)]^{0.5}}{[(1 - 2v)(1 + v)]^{0.5}}$$

S waves

Spherical fronts are generated with the particles vibrating perpendicular to the direction of travel both vertically and horizontally.

Rayleigh waves

These are surface waves which may arrive first at the geophones.

Love waves

These travel through the surface layer and are unimportant.

SEISMIC REFRACTION

When a wave passes from one strata to another it is refracted. The refraction angle is a function of the ratio of the speed of travel through each of the layers.

Interpretation

$$\frac{\sin i}{\sin r} = \frac{V_o}{V_1}$$

i is the angle of incidence, r the angle of refraction
V_o, V_1 the speed through the two layers

The critical angle of refraction is 90^o at which the angle of incidence (sine) equals the ratio of the velocities.

The wave can either arrive directly, be reflected off the boundary or be refracted if V_1 V_o. In the latter case the wave is reflected back to the surface because of irregularities in the boundary.

The minimum distance to the first geophone is 2 * depth * tan i.

Advantages

The equipment is light and portable and can be used to give a

Disadvantages

It is an expensive test that requires expertise and has limited application.

Applications

It is used to detect bedrock and measure mass moduli.

SEISMIC REFLECTION

This method can be used in boreholes or at the surface, particularly offshore.

Borehole methods include well shooting where the shot is at the surface and detectors are at the top and bottom of a layer, cross hole where the source is in one hole and the receivers are in an adjacent hole and continuous logging in which a sonde is lowered down the hole. The sonde includes pulse generators and geophones.

Offshore methods are based on various methods of generating the signal including sparkers, boomers, pingers, sonar and air guns.

RESISTIVITY METHOD

Potential electrodes are used to generate a signal using a AC or DC source. Geophones and a resistivity meter are used to monitor the transmission of the signal through the ground.

Operation

Four co linear electrodes are set in the ground with two forming the source and two the receivers. There are three configurations:- Wenner, Schlumberger and Central.

Wenner $X = 2Y = Z$

2 Y is the distance between the two receiving electrodes.
X and Z are the distances between the outer source electrodes and the adjacent receiving electrodes.

Schlumberger Y = constant and $X = Z$ and increasing

Central $(X + 2Y + Z)$ and $2Y$ are constant, X and Z are varied

Measurements are taken of the position of the electrodes and the voltage across the receivers.

Interpretation

It is a measure of the electrical resistivity of the ground which is a function of porosity, pore fluid resistivity and ground resistivity.

The measured potential equals K V/I where V is the supply voltage and I the current.

Method	K
Wenner	$2\pi a$

Schlumberger	$\frac{\pi (L - I)}{2I}$
Central	$\frac{2\pi}{[b(1/(a(a + b)) + 1/(d(d + b)))]}$

Advantages

It is cheap simple test to carry out.

Disadvantages

It is not a very accurate test, needs additional information from borehole logs and is affected by electrical services.

Applications

It is used in two ways:- electrical sounding by fixing the central point and moving the outer electrodes and profiling by keeping a fixed separation and moving the configuration. It can be used to detect geological boundaries, depth to ground water level, economic deposits and buried features..

3.7.. LABORATORY TESTS - GENERAL

DEFINITION

Tests are carried out on undisturbed and disturbed samples in the laboratory.

PURPOSE

Tests are used to produce parameters for design and classify the ground types.

Routine tests are undertaken as part of the initial studies and to identify representative strata.

Complex tests are carried out on representative strata to produce design parameters.

Classification tests include description, distribution, plasticity and compaction tests.

Tests for design requirements include strength, compression, consolidation

TYPES

Tests are grouped according to the parameters they measure.

Classification tests include water content, Atterberg Limits, particle size

Strength tests include triaxial, direct shear, vane and CBR tests.

Stiffness tests include triaxial and oedometer tests.

Permeability tests include triaxial, oedometer and permeameter tests.

In addition there are chemical tests.

Test methods are usually specified (e.g. BS1377) and well documented (Head).

ADVANTAGES

A sample is obtained which allows a description to be complete and several tests to be carried out.

The stress path can be varied since the parameters obtained are a function of effective stress.

Most tests are to recognised standards.

The element of soil tested is well defined.

DISADVANTAGES

Properties are affected by sample disturbance due to drilling, sampling and transport.

The samples are small therefore may not be representative of the natural fabric which could affect the mass properties. Results are extrapolated from the small sample to the in situ mass.

Samples are taken from selective horizons therefore the results are discontinuous.

Some tests are expensive and time consuming.

Tests are carried out some time after the sample is taken possibly when the site works are complete.

3.8. Classification Tests

Classification	Used to describe the soils to enable borehole logs to be produced and soil horizons to be estimated.
Water Content	The strength and stiffness of a cohesive soil are a function of the water content.
Plasticity Indices	These are carried out on cohesive soil to classify the type of soil (clay or silt) and estimate the degree of plasticity.
	They are used as classification for earthworks, a measure of frost susceptibility and as an estimate of the strength and stiffness of the soil.
Specific Gravity	This is not normally carried out since most soil particles have an SG of between 2.65 - 2.75.
Particle Size Distribution	Sieve analyses are carried out on cohesionless soils to determine the uniformity coefficient, for filter design and estimate the aquifer potential.
	Sedimentation tests are carried out on cohesive soils though this may is not so common because of the time and cost.
Chemical Tests	These are necessary to check for contaminants, check for sulphates which could attack concrete and ensure that ground water is not polluted.
Sampling	Samples can be taken from drill mud, ground water, and soil from boreholes and in flow into piezometers.
Tests	Sulphate tests are carried out whenever concrete foundations are proposed since sulphate attacks hardened concrete.

The pH value is important since there is a possibility of alkali aggregate reaction and acid attack on concrete.

Organic matter could affect cement hydration. It allows peats to be classified.

Chloride can affect cement hydration and cause efflorescence.

There are a number of specialist tests not normally carried out in soil mechanics laboratories to determine hazardous and toxic materials from contaminated sites.

COMPACTION

Field compaction increases strength and stiffness, reduces permeability and eliminates collapse of engineered fills.

Tests are carried out as to determine whether soils are suitable as engineered fills, provide parameters for construction control and landfill barriers.

Tests include the 2.5kg (Proctor), 4.5kg (AASHO), vibrating hammer and moisture condition value tests.

Results

Results include the maximum dry density and optimum water content, the dry density v water content relationship, the relative density and the percentage air voids.

Disadvantages

Generally the test results are not repeatable and are not related to field compaction.

PAVEMENT DESIGN

Tests are carried out to determine the strength of the sub base, potential to swell and check for frost susceptibility.

Tests include the CBR, swelling potential and frost heave tests.

CBR

A standard plunger is forced into the soil at a standard rate and the load need to produce a standard penetration is compared to a standard load. This ratio is used with empirical design rules to design pavement thickness. The CBR can be correlated with PI and PSD.

TRL Frost Heave

This test measures the change in height of a specimen at the point of freezing.

3.9. Strength Tests

Strength

Tests used to derive bearing capacity, earth pressures, slope stability and classification.

Tests include CBR, unconfined compression, vane shear, direct shear, triaxial and ring shear.

Unconfined Compression

This is a simple, quick test on 38 mm diameter specimens of saturated firm/stiff clays to give the undrained shear strength. It is no longer a common tests and should be only used for classification purposes.

Vane Shear

This is a simple, quick test carried out in the ends of U100 tube specimens of soft clays to give undrained shear strength. It should be carried out routinely.

Direct Shear

A rectangular prism of soil is subject to shearing along a

Sizes include 60 mm square for sands, silts, clays, 100 mm square as 60 mm and 300 mm square for sands and gravels.

The normal force, shear force, dilation and displacement are measured.

It is a simple test carried out on cohesionless soils since it is relatively easy to prepare specimens.

There is no control over drainage, displacements are small, there is a predetermined failure with a varying area, a fixed stress path and the stresses on the failure plane are unknown.

Triaxial

A cylindrical specimen is subject to an isotropic stress. The axial stress is increased and measurements taken of displacement and pore pressure or volume change.

It is possible to control axial stress, cell pressure, pore pressure and displacement.

Specimens can be 38 or 100 mm in diameter with a length to diameter ratio of 2.

Measurements are taken of cell pressure, axial pressure, displacement, rate of displacement, pore pressure, cell volume change and specimen volume change.

Tests can be simple or complex since there are a number of variables. Most tests are strain controlled but the more sophisticated tests are known as stress path tests. Tests can be carried out on fine to medium grained soils and soils containing some gravel size particles.

Tests include quick undrained, consolidated drained, consolidated undra

Quick Undrained

These are the most common type of test on clays to give undrained strength.

Multi Stage

This test is used for limited and large specimens. The cell pressure is increased in three stages with the axial stress being increased in each stage. It is a test to give the undrained strength of clays. The tests are carried out at a constant rate of displacement under total stresses.

Consolidated Undrained

The test is used to measure the effective and total strength, stiffness and permeability of clays. The tests are carried out at a constant rate of displacement.

Consolidated Undrained

The test is used to measure the effective strength, stiffness and permeability of clays and sands. The tests are carried out at a constant rate of displacement with tests in clays being slow. It is not a common test for sands because of the difficulty of preparing specimens.

Stress Path

These specialist tests carried out on sands and clays allow the stresses and strain rate to be varied to give effective strength and stiffness parameters under different conditions. They are expensive.

Other Tests

Suction tests in which the ambient suction in the specimen is measured are used to estimate in situ stresses.

Extension tests give the strength on unloading.

Ko consolidation tests allow specimens to be anisotropically consolidated to model in situ conditions.

Definition of Strength

There are a number of definitions of strength the most common being peak strength which is halve the maximum deviator stress.

It is possible in some soft clays for samples to be so ductile that a maxim stress is not reached. In that case the stress at 20% axial strain is defined as the compression strength.

Post rupture strength is the strength of strain softening soils which exhibit a post peak plateau at large strain.

Residual strength is the strength mobilised at very large strains usually associated with land slides. It can be measured in ring shear tests and multi reversal direct shear tests.

Undrained shear strength of clays is the current strength in terms of total stresses and is used for classification, bearing capacity and immediate slope stability.

Drained shear strength for clays and sands is used for long term stability and bearing capacity of sands. It can be used to predict short term stability if an estimate is made of pore pressure.

3.10. PERMEABILITY TESTS

PERMEABILITY

Falling head tests are carried out on fine grained soils but they are no longer recommended because of varying effective stress and preferred drainage paths down the side of the specimen.

Constant head tests are used for coarse grained soils.

Triaxial and Rowe cells are known as hydraulic cells. They are used to measure axial, radial outflow and radial inflow permeability at different hydraulic gradients and effective stresses. A pressure is imposed and the flow monitored.

Flow pump tests are similar to the hydraulic cell tests but a flow is imposed and the pressure variation measured.

3.11. Deformation Tests

DEFORMATION

Tests are carried out to measure stiffness for settlement calculations and consolidation for rate of settlement.

Oedometer

Total stress increments are applied for 24 hrs on 75 mm diameter, 19 mm thick specimens of clay. Usually there are five loading and two unloading increments. Measurements are taken of deformation with time as pore pressures dissipate.

Coefficients of compressibility and consolidation are obtained for each loading increment.

Rowe Cell

Up to 300 mm diameter specimens of clay are contained in a rigid wall chamber. A vertical loading through a flexible or rigid membrane can be applied to the specimen. A back pressure can be applied to ensure saturation. Axial effective stress increments are applied and the dissipation of pore pressure and deformation are measured with time.

Coefficients of compressibility and consolidation are obtained for each loading increment.

Local Strain

Triaxial specimens of clay and sand are subjected to changes in effective stress. The deformation of the middle third of the specimen is monitored by gauges attached to the specimen.

Non linear stiffness profiles are obtained.

These are specialist tests but give more realistic values of stiffness.

TESTING SCHEDULE, FACTUAL, AND INTERPRETATIVE REPORT

4.1 DEFINITIONS

TESTING SCHEDULE

This the schedule of laboratory tests.

It is prepared by the Engineer on larger contracts using data from the field operations, desk studies, reconnaissance and design proposals.

It is prepared by the ground investigation contractor on smaller contracts.

FACTUAL REPORT

This contains a report of the site works including a site plan showing borehole, profile and trail pit locations.

It also includes a list of all test results including the interpretation according to the relevant standard and, if no standard is available, a description of the method of interpretation and references.

It includes the borehole logs which are a summary of all site operations including depth of layers, soil description, in situ test results and ground water information.

There is likely to be a summary of the findings from the ground investigation and an assessment of the geological information for the area.

The factual report will be used to check that the ground investigation was carried out in accordance with the contract documents and provide data for subsequent interpretation.

INTERPRETATIVE REPORT

This report includes a factual report.

The data from the factual report will have been used to produce cross sections showing the representative strata and ground water profiles.

A summary of the results of the in situ and laboratory tests will be used to produce typical design parameters.

4.2 Test Results

General

This is normally specified by the geotechnical advisor who will either be working for the client, consultant or contractor. On small jobs the contractor is often invited to produce his own schedule. This can lead to problems of liability and cost unless the contractor is known to have experience and be reliable.

Laboratory tests are scheduled once the site works have started and samples become available for testing.

They should be written as an interactive process with the driller's logs so that a complete three dimensional picture of the site and its properties can be developed.

Not all samples will tested in the first instance. Some will be retained for further testing once results of the first set of tests are available. Once a sample is opened and tested it may be discarded therefore it must be appreciated that there is a limited amount of soil to be tested.

The quantities of soil required for each test are specified in the relevant standard. It may not be possible to carry out all the desired tests because of the limited amount of sample and because of the effects of fabric and grain size on the specimen required. For example it is more usual to carry out triaxial tests on 100 mm diameter specimens of stony clays rather than the preferred 38 mm specimens. Thus half the sample would be used for one test.

Testing should be started as soon as possible since the properties, especially water content, undrained shear strength and stiffness of clays, will change with time.

Sands

Generally the description of sand together with the results of in situ tests are usually sufficient to determine the engineering properties.

PSD and chemical tests on sands may be required if permeability or contamination is a concern.

Specific Gravity is assumed to be 2.6 - 2.72.

Direct shear tests may be specified especially if the sand is to be used as a fill. It is necessary to specify the normal stresses (usually three) and the density required. The rate of loading is usually fixed.

Constant head tests are used to give estimates of the permeability of sands.

The problem with testing sands is that it is difficult to recreate the in situ density in the laboratory since the in situ density is unknown. Estimates can be made from in situ tests such as SPT or CPT. The strength, stiffness and permeability of sand is a function of the density.

CLAYS

Classification tests on clay include water content, plastic and liquid limits and undrained shear strength.

Ideally, the limits and water content should be carried out on every undisturbed sample but this may limit the amount of specimen for other tests.

Water content should only be specified for undisturbed samples since disturbed samples dry out. It should be determined as soon as possible after the sample has been delivered to the laboratory.

PSD is not usually carried out on clays unless the results are to be used in the description.

Specific Gravity is assumed to be 2.65 - 2.72.

Undrained shear strength should be determined for design of shallow and piled foundations and slope stability. There should be sufficient tests in each stratum to enable a profile to be drawn. Ideally 38 mm specimens should be tested with three specimens at each level.

Consolidated undrained triaxial tests with pore pressure measurements are carried out on representative samples so that the effective strength parameters can be determined for piled foundations, long term stability and earth pressures.

Samples can either be isotropically or anisotropically consolidated the latter being used to try and recreate the in situ conditions. These may not be known.

Multi reversal slow direct shear tests are used to determine residual strength of clays. Ring shear tests are better since the direction of loading remains the same though experience has shown that the strength measured in the direct shear test is the same as that backfigured from a stability analysis.

Consolidated drained triaxial tests can be carried out instead of undrained tests but they do not yield as much information and take longer to run.

Stress path tests are specified on larger projects if non linear stiffness profiles are required and the effect of loading path is critical.

Oedometer tests are carried out to determine stiffness and rate of settlement.

Triaxial permeability tests are carried out to determine the permeability of clays where drainage is likely to be important. This could include testing clays for landfill barriers, retained clays and settlement rates.

Falling head tests are no longer acceptable.

Chemical tests are routinely carried out if concrete is to be used in the foundations and where there is a possibility of contamination.

VERY SOFT CLAYS

These materials are particularly difficult to sample and test.

Most in situ tests are designed for soils with strengths greater than that of soft clay. Therefore they are not sensitive enough for these soft deposits .

Most laboratory measuring equipment is too insensitive to measure the properties of these soils

The behaviour of the soils may not follow conventional theories of soil mechanics but rather act as viscous materials though with consolidation the properties will change with time and then the clays conform to conventional theories.

RESIDUAL SOILS

Tests on these materials depend on the dominant component since residual soils can vary from near intact rock to clay through heterogeneous mixtures of boulders, gravels, sands, silts and clays.

In situ tests are commonly specified since the amount of soil tested is greater than that tested in the laboratory hence the results are more representative of the heterogeneous deposit.

MADE GROUND

These materials are extremely variable, cause significant construction problems and can be difficult to identify.

Properties of coarse grained fills are determined from in situ tests.

Properties of medium to fine grained made ground are measured in the same way as properties of clays and sands

Made ground can be affected dramatically by changes in water content which can cause collapse if the fill is loose, decomposition if the fill is organic and loss of fines if water is flowing. Tests may have to be carried out on soaked specimens to determine the worst conditions.

An alternative field test is the skip test. This may test a more representative sample of made ground.

4.3 FACTUAL REPORT

INTRODUCTION

The factual report will include an introduction, site plan, borehole logs and results of in situ and laboratory tests.

The client, contractor and sub contractors will be identified together with the site location.

SITE PLAN

This will show the positions of the boreholes, trial pits and profiles.

The plan should be drawn to scale indicating the direction of north.

Ideally it should be a topographical map showing the features relevant to the site which could affect any proposed structure especially any variations between existing maps and the actual features

DESCRIPTION OF WORKS

This will be an introduction to the borehole logs which will contain all information obtained from the exploratory holes. It will include references to any standards used to describe the soils and carry out in situ tests.

BOREHOLE LOGS

These are the most important part of the report and should conform to a standard so that others using the report have confidence in the data and can draw the same conclusions about soil type and properties.

The logs must include the following information

job no
site name
borehole number
grid reference
ground level
client
contractor
driller
the type of rig
date of drilling
borehole diameter, casing depths, delays, chiselling
sample number, type and depth
in situ test number, type and depth
soil description, levels and depths
in situ test results
water strikes

Details of Drilling

The drilling details include the depth to each stratum and the elevation of each stratum.

The strata levels are identified from the driller's records and the geologist's description.

The level reached at the end of each shift must be clearly show together with the depth of casing.

If water is struck it is usual to wait twenty minutes before drilling to ascertain the rate of inflow. Water strikes and water levels at the end and beginning of a shift must be shown.

Sample numbers, types and the depths to the top and bottom of the samples must be indicated.

In situ test numbers, types and depths to the top and bottom of the test zone must be shown. Test results can be shown if they arc simply a number (e.g. SPT blow count, vane shear strength) otherwise they will be submitted in a separate table.

Chiselling times and any other factors, including delays, which influenced the drilling must be shown.

It should be possible to use the borehole log to justify the quantities shown in the Bill of Quantities.

Soil Description

Drillers often refer to soils by their colour, main type (e.g. sand, clay), strength or density, subsidiary type (e.g. silty, sandy) and local name.

A geologist will describe a sample in detail according to a standard identifying basic soil type, particle size, visual description, particle nature and plasticity, composite soil type, density or strength, structure and colour. Strength or density is taken from laboratory (e.g. triaxial) or in situ tests (e.g. SPT).

The soil description is very important since it permits an initial assessment of the engineering properties of the soil (strength, stiffness and permeability), allows the main strata to be identified and highlights any key features which will influence the soil behaviour (e.g. laminations).

In Situ Test Results

The simple results of in situ tests are shown on the logs. These include blow counts from dynamic penetrometer tests and vane shear strength.

Other in situ tests will be described separately but all in situ test results given in the form of curves should indicate the site location, borehole number, test number and top and bottom of test section. There should be sufficient data to allow a reassessment of the test.

Pressuremeter Tests

The report should include the test curves, calibrations, type of test, rate of testing and interpretation of tests.

The interpretation will depend on the type of test and the parameters required.

MPM tests will include the test curve, creep curve, Menard modulus and modified limit pressure.

PBP (prebored) tests will include the test curve, shear modulus, stress and strain range over which the modulus is measured. Strength either undrained (clays) or drained (sands) may be derived from empirical correlations.

SBP tests will include the test curve, total horizontal stress, shear modulus, stress and strain range over which the modulus is measured and strength either undrained (clays) or drained (sands).

PIP tests will include the test curve, shear modulus, stress and strain range over which the modulus is measured and strength either undrained (clays) or drained (sands).

Permeability Tests

The report should include the test curves showing the rate of inflow/outflow

The coefficient of permeability should be quoted together with the method used to calculate the coefficient, the dimensions of the test zone and the factors used to calculate the coefficient.

Profiles

The results of cone tests are reported separately from the borehole logs though they may be used in the interpretation of the strata

A static cone profile will include the site location, profile number, profile elevation, type of cone, rig type, operators, date of profile and variation of cone resistance, friction (and pore e pressure) with depth.

A dynamic cone profile will include the site location, profile number, profile elevation, type of cone, rig type, operators, date of profile and variation blow count with depth.

Cone profiles are usually carried out by specialist sub contractors. They will also provide charts to assist in the interpretation of the data. These will include variation of soil type with cone resistance and friction ratio, undrained shear strength and cone resistance and density and cone resistance.

4.4 INTERPRETATIVE REPORT

PURPOSE

The aim of this report is to produce recommendations for design parameters and highlight any potential problems relating to construction and post construction.

This report combines the factual report, design proposal and theory.

It is often prepared before a design has been finalised and therefore must be, at best, very general. The conclusions of the report may change as the design proposal is formalised.

The parameters required depend on the problem to be solved, the confidence in the source of the data and the amount of data available. The problem may not be clear therefore alternative proposals may be necessary.

The aim is to produce cross sections slowing the variation of strength, stiffness and permeability through each layer. Not all information will be reported and some information will be used which comes from other sources.

GUIDELINES

Ground properties arc often assumed to be constant through a layer even though they will change.. This assumption is made because many design methods cannot accommodate non linear profiles.

It may be prudent to subdivide a thick layer to take into account increases (decreases) in properties with depth and give each sub layer constant values

The parameters chosen can be the worst credible or most likely. This is not the same as the lowest and average. Results from laboratory tests have to be reviewed together with geological descriptions, empirical correlations and theories of soil mechanics

Worst Credible

The worst credible condition represents the worst condition that could be reasonably be expected to occur.

Choosing the worst credible can lead to reductions in factor of safety if there is sufficient confidence in the quality and amount of data.

The worst credible may be the obvious choice for very sensitive projects though this could lead to over design.

Most Likely

The most likely condition represents the typical variation of parameters and is most commonly used for design if there is sufficient data available.

Average Plots

Tests results often show scatter which may be natural but more often is due to variations introduced during sampling, storage, testing and interpretation.

Some engineers will plot an average line and take that as the most likely condition. The average will include high and low results which may not be representative of the soil.

Some engineers plot the average line and then disregard the lowest and highest 5 or 10%. This can only be justified by statistical analysis therefore there must be sufficient tests to justify this. Even if there are enough tests the variation may not be due to natural variations only, hence there is no justification in selecting (or rejecting any data).

Choice of Parameter

The selection of soil data depends on the parameter to be chosen and the location of the layer.

Settlement of structures will be governed by the weakest layer.

Stability of structures will be governed by the average strength.

Stability of slopes may be governed by the weakest layer.

For clays the important design parameters are undrained shear strength for foundation design and immediate stability of slopes, effective strength parameters for long term stability, void ratio versus $\log_{10}\sigma'_v$ rather than coefficient of compressibility for settlement and coefficient of consolidation for rate of settlement.

For sands the important design parameters are angle of friction and modulus of elasticity both of which are obtained from cone tests.

Theoretical Observations

Constitutive models are used to develop theoretical relationships. As an example Cam Clay can be used to develop theoretical relationships between water content and stiffness and strength for clays.

Undrained shear strength is a function of over consolidation ratio and current effective stress.

Angle of shearing resistance is a function of density of sands.

Empirical Observations

There are many published data bases of soil properties some of which are general while others are soil specific.

A plot of strength against depth using Skempton's equation will give a lower bound curve

$$(s_u/\sigma'_v) = 0.11 + 0.37 \text{ PI}$$

An upper bound curve can be produced from OCR determined from oedometer tests.

$$(s_u/\sigma'_v) = (0\ 37 + 0.11 \text{ PI}) \text{ OCR}^{0.8}$$

Angles of shearing resistance are found to correlate with PI.

COMMON ERRORS IN INTERPRETATION

The interpretation of results is often based on experience but it is possible to make use theoretical models d empirical correlations to assist in rejecting/selecting data. However, there are several common errors which can give rise to problems during design and construction.

Made Ground

A common error is the misinterpretation of soil type. This can be very important if made ground is identified as soil since it could lead to and underestimate of strength and more significantly compressibility.

Undrained Shear Strength

An undrained angle of shearing resistance and cohesion is quoted when three or more specimens from one sample are tested.

The cohesion, when used in an undrained analysis, produces a conservative design and the parameters, when used in an effective stress analysis produce non conservative solutions.

The increase h1 strength with normal stress even though there is no drainage permitted is primarily associated with partial saturation which gives rise to apparent drainage.

The partial saturation may be as in situ but it is more likely to reflect changes that have occurred since sampling.

It is better to use the average maximum shear stress taken from the specimens tested unless there is a significant difference in water content.

An estimate of the degree of saturation from the water content will give an indication of the degree of saturation.

Neglect specimens that have significantly different water contents.

Effective Strength Parameters

Effective strength parameters are often quoted in terms of cohesion and angle of shearing resistance. These parameters are found by fitting a straight line to three or more results of triaxial tests usually expressed in the form of Mohr's circles.

The line is drawn tangential to the circles or, if there is no fit, tangential to one or more

In practice, the failure envelope is curved. Thus the angle of shearing resistance reduces and the cohesion increases as the normal stress increases.

In some cases the effects of consolidation can cause a specimen to change from overconsolidated to normally consolidated leading to loss of cohesion. In that case a tangential line to three circles will give high cohesion and low shearing resistance.

It is more conservative to assume the cohesion is zero and fit a line that passes through the origin.

It is better to carry out tests on a number of samples taken from the same soil as identified from the classification tests and plot all the results together. A curve is then fitted to all the data

The angle of shearing resistance can be compared to that estimated from the plasticity index using published correlations.

Stiffness

Stiffness is the most important parameter for foundation design since buildings are designed to be serviceable not fail yet less effort is made to determine and apply the correct value.

Ground has a non linear response, that is the stiffness reduces with strain if a secant stiffness is used. Most design methods assume a linear stiffness therefore the correct secant value has to be chosen.

Stiffness is either taken from empirical correlations with SPT (sands) or shear strength (clays) or measured in the oedometer test (clays).

Rate of Settlement

Rate of settlements for foundations and embankments on clays are usually estimated from coefficients of consolidation determined from small samples in which drainage is vertical. In practice the fabric and preferred drainage path (often horizontal) results in a much greater permeability therefore settlements are much faster.

SPT Blow Count

The SPT blow count is affected by the depth to the effective stress, efficiency of the system and borehole diameter. Corrections can be applied to take these into account but this is not very common.

Ignoring the corrections tends to lead to an underestimate of the strength of upper layers which can lead to over design of shallow foundations.

Bearing Capacity

A value of bearing capacity is often quoted in interpretative reports. This may apply to foundations at the surface which are one metre wide. The reason for quoting this value is that the foundation design is not known by the contractor.

It is better to quote that variation of strength and use that in bearing capacity formulae which take into account depth and width of foundation since the actual bearing capacity will be greater than that normally quoted.

A. DESK STUDY

A1 **General land survey**

(a) Location of site on published maps and charts.
(b) Air survey, where appropriate.
(c) Site boundaries, outlines of structures and building lines.
(d) Ground contours and natural drainage features.
(e) Above ground obstructions to view and flying, for example, transmission lines.
(f) Indications of obstructions below ground.
(g) Records of differences and omissions in relation to published maps.
(h) Position of survey stations and bench marks (the latter with reduced levels).
(i) Meteorological information.

A2 **Permitted use and restrictions**

(a) Planning and statutory restrictions applying to the particular areas under the Town and Country Planning Acts administered by appropriate Planning Authorities.
(b) Local authority regulations on planning restrictions, Listed buildings and buildings bye-laws.
(c) Board of Trade regulations governing issue of industrial development certificates.
(d) Rights of Light, support and way including any easements.
(e) Tunnels, mine workings, abandoned, active and proposed; mineral rights.
(f) Ancient monuments, burial grounds, etc.

A3 **Approaches and access (including temporary access)**

(a) Road (check ownership).
(b) Railway (check for closures).
(c) By water.
(d) By air.

A4 **Ground conditions**

(a) Geological maps.
(b) Geological memoirs.
(c) Flooding, erosion, landslide and subsidence history.
(d) Data held by central and local authorities.
(e) Construction and investigation records of adjacent sites.
(f) Seismicity.

A5 **Sources of material for construction**

(a) Natural materials.
(b) Tips and waste materials.
(c) Imported materials.

A6 **Drainage and sewerage**

(a) Names of sewerage, land drainage and other authorities concerned and by-laws.
(b) Location and level of existing systems (including fields, drains and ditches), showing sizes of pipes, and whether foul, storm-water or combined.
(c) Existing flow quantities and capacity for additional flow.
(d) Liability to surcharging.
(e) Charges for drainage facilities.
(f) Neighbouring streams capable of taking sewage or trade effluents provided they are purified to the required standard.
(g) Disposal of solid waste.
(h) Flood risk:- to proposed works; caused by proposed works.

A7 **Water supply**

(a) Names of authorities concerned and bye-laws.
(b) Location, sizes and depths of mains.
(c) Pressure characteristics of mains.
(d) Water analysis.
(e) Availability of water for additional requirements.
(f) Storage requirements.
(g) Water source for fire fighting.
(h) Charges for connections and water.

(i) Possible additional sources of water.
(j) Water rights and responsibilities.

A8 **Electricity supply**

(a) Names of supply authorities concerned and regulations.
(b) Location, capacity and depth of mains.
(c) The voltage, phases and frequency.
(d) Capacity to supply additional requirements.
(e) Transformer requirements.
(f) Charges for installation and current.

A9 **Gas supply**

(a) Names of supply authorities concerned and regulations.
(b) Location, sizes and depths of mains.
(c) Type of gas, thermal quality and pressure.
(d) Capacity to supply additional requirements.
(e) Charges for installation and gas.

A10 **Telephone**

(a) Address of local office.
(b) Location of existing lines.
(c) Telephone requirements.
(d) Charges for installation.

A11 **Heating**

(a) Availability of fuel supplies.
(b) Planning restrictions (smokeless zones).
(c) District heating.

B. Site Reconnaissance

B1 **Preparatory**

(a) Whenever possible, have the following available: site plan, district maps or charts, and geological maps and aerial photographs.
(b) Ensure that permission to gain access has been obtained from both owner and occupier.
(c) Where evidence is lacking at the site or some verification is needed on a particular matter, for example, flood levels or details of changes in site levels, reference should be made to sources of local information such as: Local Authority, Engineer's and Surveyor's Offices, early records and local inhabitants.

B2 **General information**

(a) Traverse whole area, preferably on foot.
(b) Set-out proposed location of work on plans, where appropriate.
(c) Observe and record differences and omissions on plans and maps; for example, boundaries, buildings, roads and transmission lines.
(d) Inspect and record details of existing structures.
(e) Observe and record obstructions; for example, transmission lines, telephone lines and ancient monuments, trees subject to preservation orders, gas and water pipes, electricity cables, sewers.
(f) Check access, including the probable effects of construction traffic and heavy construction loads on existing roads, bridges and services.
(g) Check out and note water levels, direction and rate of flow in rivers, streams and canals, and also flood levels and tidal and other fluctuations, where relevant.
(h) Observe and record adjacent property and the likelihood of its being affected by proposed works.
(i) Observe and record mine or quarry workings, old workings, old structures, and any other features which may be relevant.

B3 **Ground information**

(a) Study and record surface features, on site and nearby, preferably in conjunction with geological maps and aerial photographs, noting as follows:
   (1) Type and variability of surface conditions.
   (2) Comparison of surface lands and topography with previous map records to check for presence of fill, erosion, or cuttings.
   (3) Steps in surface which may indicate geological faults or shatter zones. In mining areas, steps in the ground are probably the results of mining subsidence. Other evidence of mining subsidence should be looked for, compression and tensile damage in brickwork, buildings and road; structures out of plumb; interference with drainage patterns.
   (4) Hounds and hummocks in more or less flat country which frequently indicate former glacial conditions; for example, till and glacial gravel.
   (5) Broken and terraced ground on hill slopes which may be due to landslides; small steps and inclined tree trunks can be evidence of creep.
   (6) Crater-like holes in chalk or limestone country which usually indicate swallow holes filled with soft material.
   (7) Low-lying flat areas in hill country which may be sites of former lakes and may indicate presence of soft silty soils and peat.
(b) Inspect and record details of ground conditions in quarries, cuttings and escarpments, on site and nearby.
(c) Assess and record, where relevant, ground water level or levels (often different from water-course and lake levels), positions of wells and springs, and occurrence of artesian flow.
(d) Study and note the nature of vegetation in relation to the soil type and to the wetness of the soil (all indications require confirmation by further investigation). Unusual green patches, reeds, rushes, willow trees and poplars usually indicate wet ground conditions.
(e) Study embankments, buildings and other structures in the vicinity having a settlement history.

B4 **Site inspection for ground investigation**

(a) Inspect and record location and conditions of access to working sites.
(b) Observe and record obstructions, such as power cables, telephone lines, boundary fences and trenches.
(c) Locate and record areas for depot, offices, sample storage, field laboratories.
(d) Ascertain and record ownership of working sites, where appropriate.
(e) Consider liability to pay compensation for damage caused.
(f) Locate a suitable water supply where applicable and record location and estimated flow.
(g) Record particulars of lodgings and local labour, as appropriate.
(h) Record particulars of local telephone, employment, transport and other services.

C. Borehole Location and Depth

Area of investigations	Boring layout	Boring Depth
Structural foundations	Low rise buildings on good ground	minimum number
	Low rise buildings on poor ground	2-4 holes/structure (a) prove depth of poor ground (b) 1.5 x width (c) rock
	Medium rise	trial pits must be outside structure
	Large structures	extensive
	Bridge site	2-3 holes/abutment
Slopes		3-5 holes on critical line below failure surface along each section to establish data for stability analysis
Linear structures	50 m - 1 km	roads 2-3m below formation level runways 6m below formation level pipelines 0.5m below formation level
New or expanded land	Borings at most critical disposal facility areas 4-6 borings along each section to establish data for stability analysis. Trial pits for examination of near surface soils and waste.	
Facility structure	Minimum of four borings at corners plus one in the interior. Trial pits for examination of near surface soils and waste	Advance for a minimum of (9.1m)
Retention ponds	Preliminary borings at 90m centres. Intermediate borings along the centre line at critical facilities (cut-off, outlet and inlet structures). Trial pits for examination of near surface soils and waste	Add borings to a minimum of 0.5-1 times the width of the embankment or to the relatively hard stratum
Containment barriers	Preliminary borings at 150m spacing. Intermediate borings for a final spacing. Trial pits for examination of near surface soils and waste	Extend a minimum of (3 m) into stratum with the design hydraulic conductivity

D. MINIMUM NUMBER OF BORINGS

Acreage Area(Acres)	Total	Deep borings
<10	4	1
10-49	8	2
50-99	14	4
100-200	20	5
>200	24 plus 1 boring each additional 10 acres	6 plus 1 boring each additional 10 acres

Advance borings into a relatively incompressible soil to depths where the increase in stress is 10% or less of the existing effective overburden stress, establish where foundation failure is unlikely settlement is not a key design factor. Advance to below active or potential failure surface or to a depth

E. SAMPLING

Method	Depths
Auger boring	Depends on equipment and time available, practical depths being up to about 35 m
Rotary drilling Wash boring Percussion drilling	Depends on equipment, most equipment can drill to depths of 70 m or more
Test pits and open cuts	As required, usually less than 6 m

QUALITY CLASSIFICATION FOR SAMPLING

Quality class (as BS5930)	Soil properties that can be determined reliably (BS 5930)	Sampling method
1	Classification, moisture content, density, strength, deformation, and consolidation characteristics	*Soils sensitive to disturbance*: thin wall piston sampler *Soils insensitive to disturbance*: thick or thin wall open sampler *Soil containing discontinuities (fabric) affecting strength, deformation, and consolidation*: large diameter thin or thick wall sampler (piston or open)
2	Classification, moisture content and density	Thin or thick wall open sampler
3	Classification and moisture content	Disturbed sample of cohesive soils taken from clay cutter or auger in dry borehole
4	Classification	Disturbed sample of cohesive soils taken from clay cutter or auger in boreholes where water is present
5	None, sequence of strata only	Disturbed samples of non-cohesive soils taken from shell in cable percussion boring or recovered as debris flushed from rotary drilling or wash boring

TYPES OF SAMPLES

Method	Application	Sample Quality	Advantages	Disadvantages
U100 mm diameter open tube	firm to stiff clays stony clays clayey silts weak rocks	1 - 2 2 - 3 1 - 2 4 - 5	Simple robust equipment usually dynamically driven. Types with detachable liner convenient for sample storage. Provide a reasonably large sample. Inexpensive. Rapid. Widely accepted and used. Can be used in exceptional circumstances to obtain Class 3 samples of weak rocks and clayey sands.	High area ratio (30%) and friction on inside of tube produces sample disturbance. Disturbed material at base of borehole passes into sampler. Accurate control of sampler penetration is difficult. Sample retention is not as good as with piston sampler, but a sample retaining catcher can be fitted. Quality often dependent on care taken by driller. Produces disturbed samples in soft and hard soils. In sensitive soils Class 3 samples are obtained.
Thin walled driven tube (75, 100, 250 mm)	fine firm soils	1 - 2	Simple equipment, driven as open tube, but with much lower area ratio (10%). Inexpensive. Rapid.	Area ratio better than open tube, but friction on inside of sampler tube can produce sample disturbance. The sampler cutting edge is easily damaged by granular particles and hard layers. Disturbed material at base.
Thin walled pushed tube (75, 100 mm)	clay soils	1 - 2	Area ratio 10%. Rapid.	Need reaction for pushing. Sample cutting edge easily damaged.
Piston Sampler	soft to firm clays sands above water table	1 - 2 2 - 3	Sample disturbance reduced over open tube samplers, including the effects of stress relief at the base of a borehole. Good sample retention. Accurate control of sample length and depth No extraneous material enters the sample tube. Available in various diameters (75, 100, and 250 mm).	Expensive when compared with open tube samplers, particularly in large diameters. Equipment is specialised and requires careful maintenance and operation for good results. Static thrust is required for penetration. Specialised technicians required. Slower sampling then open-tube equipment.
Bishop sand sampler	silts and sands	2 - 3	Provides means of securing samples of fine grained soils from below the water table in a relatively undisturbed conditions	Depends on successful cleaning of sampler the base of the borehole without 'blowing' inside the casing. Compressed air must be available. Sample diameter small (50 mm). Expensive. Time consuming. Specialist technicians required.
Continuous soil samples	soft alluvial soils	1 - 2	Continuous sample for descriptive purposes.	Complex, inexpensive equipment and costly to operate, particularly the

			Split samples may be dried to reveal detailed structure. Samples may be photographed for permanent record. Limited to 18 m.	Swedish foil sampler. Two sets of samples may be required (one for description and one for sampling). If samples are for strength tests, the 66-mm dia. Delft system is required. Alluvial soils require confirmation using sounding method as the equipment is damaged by stones, dense silts, sands or gravels. Not widely available.
Block sampling	all soils and weak rocks	1 - 2	Large, orientated, representative sample in mechanically undisturbed condition for special tests. Representative volume of structured material	Great care required. Time consuming. Expensive, particularly below 4 to 5m in depth. Specialist technicians required. In some closely-fissured weak rocks serious disturbance is inevitable. Can suffer sever disturbance from stress relief.
Bag samples	all soils and weak rocks	5	Cheap.	Limited to classification tests.

F. BROAD CLASSIFICATION OF SOILS ACCORDING TO GEOLOGICAL ORIGIN

Classification and Process of Formation	Description	Nature of Deposits
Residual	Chemical weathering of parent rock with little or no movement of particles	Product of complete weathering is a clay whose type depends mainly on the weathering process. Products of partial weathering are more stony and depend more on rock type. Soil becomes more compact, more stony and less weathered with increasing depth.
Alluvial	Materials transported and deposited by water action	Vary from finest clays to very coarse gravel and boulders. Soils usually show pronounced stratification. River gravels are usually rounded.
Colluvial	Materials transported gravity	Includes screes, avalanches, landslips, hillside creep, downwash material, and solifluxion deposits. Varies from clays to boulders. Material is usually heterogeneous with a wide range of particle sizes. Often termed hillwash or head deposits.
Glacial	Materials transported by gravity.	Glacial till and morain deposits usually have broad gradings ranging from clay to boulders. Grain size in the outwash material decreases with distance from the source of melt water. Stratification in morains and till is usually heterogeneous but out-wash deposits give rise to laminated (varved) silt and clay in glacial lakes. Grains are typically angular.
Aeolian or Loessial	Materials transported and deposited by wind	Highly uniform gradation with indistinct or no stratification. Typically silt or fine sand sized but sometimes the surface is covered by a single layer of pebbles. Loess typically has a secondary structure of vertical racks, joints and root holes.
Organic	Formed in place by growth and decay of plants	Peats are dark coloured, fibrous or amorphous and highly compressible. Mixtures of fine sediment organic matter produce organic silts and clays.
Volcanic	Ash and pumice deposited in volcanic eruptions	Silt sized particles along with larger volcanic debris. Particles are highly angular and often vesicular. Weathering produces a highly plastic, sometimes expansive clay. The weathered consolidated deposits sometimes form a light easily-worked stone.
Evaporites	Materials precipitated or evaporated from solutions of high salts content	Forms cemented soils or soft sedimentary rocks. Includes oolites precipitated from calcium in sea

G. Schedule of laboratory test on soil

Soil

Category of Test	Name of Test	Remarks
Classification	Moisture content	Frequently carried out as a part of other soil tests. Read in conjunction with liquid and plastic limits, gives an indication of the shear strength and compressibility of cohesive soil.
	Liquid and plastic limits (Atterberg limits)	Used to classify cohesive soil and as an aid classifying the fine fraction of mixed soil.
	Linear Shrinkage	
	Specific gravity	Used in conjunction with other tests, such as sedimentation and consolidation. Values commonly range between 2.55 and 2.75. A more accurate value is required for air voids determination. Only occasional checks are needed for most British soils for which a value of 2.65 is assumed unless experience of similar soils shows otherwise. Determination of specific gravity may be necessary where spoil heap material is concerned or soils have come from sites overseas.
	Particle size distribution: (a) sieving	Sieving methods give the grading of soil coarser than silt. The proportion passing the finest sieve represents the combined silt/clay fraction.
	(b) sedimentation	The relative proportion of silt and clay can only be determined by means of sedimentation tests which should be carried out when there is a real need for this information.
Chemical	Organic matter	Detects the presence of organic matter able to interfere with the hydration of Portland cement in soil : cement pastes.
	Sulphate content of soil and ground water	The tests assess the aggressiveness of soil or ground water to buried concrete. (See remarks on test for pH value.)
	pH value	To measure the acidity of alkalinity of the soil or water. It is usually carried out in conjunction with sulphate content tests. This test and the one above should be performed as soon as possible after the samples have been taken.
	Carbonate content	Reference describes method using the Collins' calcimeter. Useful for estimating the chalk content of soils.
	Chloride content	
Compaction	Dry density of soil	Measures the mass of solids per unit volume of soil. Most of on site these tests are used to establish the dry density of soil, either naturally occurring or compacted fill, taken from near the surface. Some, however, can be applied to samples obtained from depth, and these tests are used when the density of the soil is required in conjunction with other tests.
	Dry density/water content	This test indicates the degree of compaction that can be achieved at different moisture contents.

	Relative density of cohesionless soil	
Pavement Design	California bearing ratio (CBR)	This is an empirical test used in conjunction with the design of flexible pavements. The test can be made either in situ, or in the laboratory.
	TRL frost heave test	A laboratory test used to determine the susceptibility to frost heave of a specimen of compacted soil.
Strength	Triaxial compression: (a) undrained (b) consolidated undrained (c) consolidated undrained with measurement of pore water pressure (d) consolidated drained	By far the most commonly used of these tests is the standard undrained test which gives s_u. There is a large amount of experience in its use. Many partly empirical methods are available to utilise the parameters in the design of foundations and other sub-structures. The remaining tests are used to obtain effective strength parameters. The tests are normally carried out on nominal 100 mm or 40 mm diameter specimens, as appropriate..
	(f) multi-stage triaxial test	The test is useful where there is a shortage of specimens. Its main use is with 100 mm nominal diameter specimens, only one of which can be prepared from each sampling tube
	(g) stress path	These test allow a sequence of consolidation and loading or unloading to be modelled thus representing in situ conditions. Local strain stiffness tests allow non linear stiffness profiles to be obtained which represent actual field behaviour.
	Unconfined Compressive Strength	This simple test is a rapid substitute for the undrained strength triaxial test, although it is suitable only for saturated non-fissured cohesive soil.
	Laboratory vane shear	An alternative to undrained triaxial test for soft clay where the preparation of the specimen sometimes has an adverse effect on the measured strength of the soil.
	Direct shear box:- (a) immediate (b) consolidated immediate (c) drained	These tests are an alternative to triaxial tests and are the most common tests for sands. One of their main disadvantages is that drainage conditions cannot so easily be controlled. Another is that the plane of shear is predetermined by the nature of the test. One of their advantages is that specimens of non-cohesive soil can be more readily prepared that in the triaxial test. The small 60 mm square shear box is suited only to soil containing particles smaller than 3.35 mm. For coarser soils, the large 305 mm square box should be used. This is suitable for soil which contains particles that exceed 37.5 mm.
	Residual shear strength:- (a) multiple reversal shear box (b) triaxial test with pre-formed shear surface (c) shear-box test with pre-formed shear surface (d) ring shear test	The residual shear strength of clay soil is increasingly used in slope stability problems. The multiple reversal shear box test is the one which is most commonly used and recent evidence suggest that it gives parameters relevant fro design. This latter test tends to give lower parameters than the former.

Deformation	Consolidation:- (a) one-dimensional consolidation properties (oedometer test) (b) triaxial consolidation (c) Rowe consolidation cell	These tests yield soil parameters from which the amount and time of settlements can be calculated. The simple oedometer test is the one in general use and although reasonable assessment of settlement can be made from the results of the test, estimates of the time have been found to be extremely inaccurate with certain types of soil. This is particularly true of clay soil containing layers and partings of silt and sand, where the horizontal permeability is much greater than the vertical. In these cases, more reliable data may be obtained from tests in the Rowe cell which is available in sizes up to 250 mm diameter and where a larger and potentially more representative sample of soil can be tested. Another alternative is to obtain values of the coefficient of consolidation, c_v, from in situ permeability tests and combine then with coefficients of volume decrease, m_v, obtained from the simple oedometer test.
	Elastic modulus	Values of the elastic modulus of soil can be obtained from the stress/strain curve from undrained triaxial compression with the cell pressure equal to the overburden pressure. Experience, however, shows that the results so obtained are often very much lower than the actual values. It is now generally considered that the plate bearing test or back analysis of existing structures yield more reliable results. Local strain stiffness triaxial tests can be used.
Permeability	Constant head Triaxial permeability	The constant head test is suited only to soils with k roughly within the range 10^{-4} m/s to 10^{-2} m/s. For various reasons, laboratory permeability tests often yield results of limited value and in situ tests are generally thought to yield more reliable data.
	Rowe consolidation cell	The Rowe consolidation cell allows the direct measurement of permeability by constant head with a back pressure and confining pressures more closely consistent with the field state, and by both vertical and radial flow.
Corrosivity	(a) Bacteriological tests (b) Redox potential	Undisturbed specimens required in both cases; air-sealed and in sterilised containers for the bacteriological tests.

ROCK

Category of Test	Name of Test	Remarks
Classification	Saturation moisture content (alteration index)	These tests give some indication of properties such as compressive strength, modulus of elasticity, seismic wave velocity resistance to weathering and degree of weathering.
	Bulk density Moisture content Porosity	
	Thin section	Useful to identify rock type, degree of weathering and gives an indication of stress history. Model analysis by point counting of thin sections may give some guidance as to the machineability of rocks.
	Slake-durability	Useful quality index for testing clay-bearing rocks proposed for construction materials.

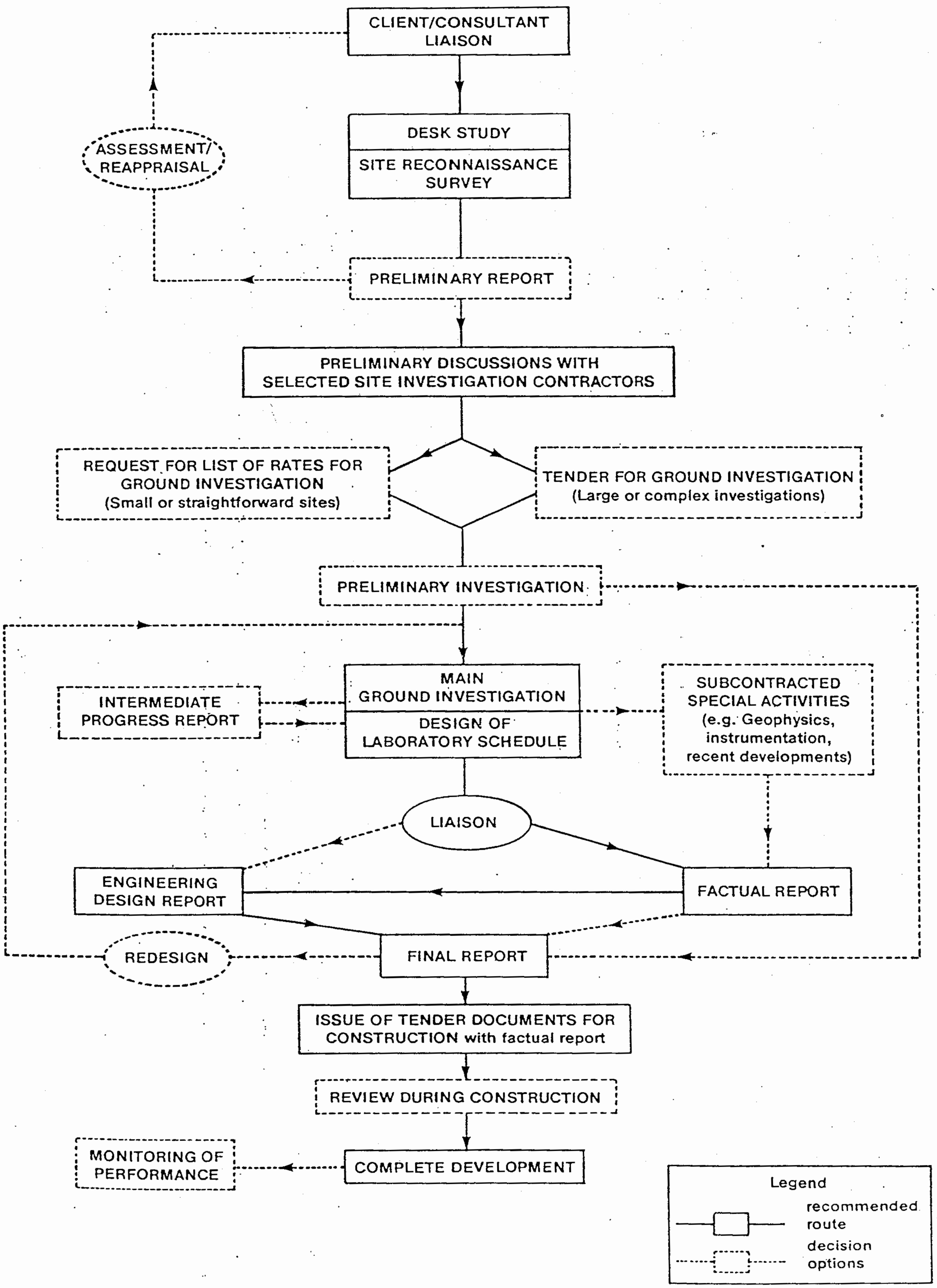
	Carbonate content	Reference describes method using Collins' calcimeter. Useful for the identification of chalk, calcereous mudrocks.
	Swelling test	Gives some indication of moisture sensitivity of rock and possible ranges of induced pressures on tunnel linings.
Dynamic	Seismic velocity Dynamic modulus	Results may sometimes be useful in extrapolating laboratory and field tests to rock mass behaviour.
Strength	Point load test	Quick and cheap laboratory and field indicator strength test. Useful aid to core logging.
	Uniaxial compression	Generally yields data on the test material only. Its value is limited to giving in indication of the upper limit value. The length to diameter ration of 2:1 is a minimum for cylinders.
	Indirect tensile strength test	See remarks on uniaxial compression test.
	Brazilian test	
	Triaxial compression: (a) undrained (b) undrained with measurement of pore water pressure	Specimen size limited by strength. It may be possible to include one or more discontinuities in the specimen. Where intact test specimens are tested, upper strength limits are obtained.
	Direct shear box	Of considerable importance for study of friction on discontinuities. References also cover residual shear strength. Where joints are filled with gouge, the properties of the combined gouge joint should be determined under conditions closely simulating those existing in situ.
Deformation	Static elastic modulus	Absence of representative discontinuities in the specimen would lead to falsely high values of modulus of elasticity. Specimen disturbance and unsuitable testing techniques would lead to falsely low values.
	Creep tests: (a) undrained (b) constant load (c) triaxial	Most meaningful when carried out under multistress conditions.
	Consolidation of rock	mass containing gouge material
Permeability	Triaxial cell test	Makes use of a modified Hoek-Franklin cell.
	Centrifugal test	Considerably faster than other methods.
	Radial test	A measure of the degree of fracturing of the rock material.

H. Foundation types and typical usage

Foundation type	Use	Applicable soil conditions
Shallow foundations (generally $D/B \leq 1$)		
Spread footings, wall footings	Individual columns, walls	Any conditions where bearing capacity is adequate for applied load. May use on a single stratum; firm layer over soft layer or soft layer over firm layer.
Combined footings	Two to four columns on footing and/or space is limited.	Same as for spread footings above.
Mat foundations	Several rows of parallel columns; heavy column loads; use to reduce differential settlements	Soil bearing capacity is generally less than for spread footings, and over half the differential settlements plan area would be covered by spread footings.
Deep foundations (generally $D_f/B \geq 4$)		
Floating pile	In groups of 2 supporting a cap which interfaces with column(s)	Surface and near surface soils have low bearing capacity and competent soil is at great depth. Sufficient skin resistance can be developed by soil-to-pile perimeter to carry anticipated loads.
Bearing pile	Same as for floating pile	Surface and near surface soils not relied on for skin resistance competent soil for point load is at a practical depth 8-10m
Drilled piers or caissons	Same as for piles; use fewer; For large column loads	Same as for piles. May be floating or point bearing (or combination). Depends on depth to competent bearing stratum.
Retaining structures		
Retaining walls, bridge abutments	Permanent material	Any type of soil but a specified zone in backfill is usually controlled fill
Sheeting structures (sheet pile)	Temporary or permanent for excavations, marine cofferdams for river work	Retain any soil or water. Backfill for waterfront and cofferdam systems is usually granular for greater drainage

I. REFERENCES

ASTM Standards Vol. 4.08 Soil and Rock; Building Stones; Geotextiles
BLYTH, F.G.H. and DE FREITAS, M.H. (1974) A Geology for Engineers, Arnold, London
BS 1377 : 1990 Methods of test for soils for civil engineering purposes
BS 5930 : 1981 Site Investigation
BS 8002 : 1994 Retaining Structures
CLARKE, B G (1995) Pressuremeter testing in geotechnical design, Blackie, Glasgow
CLAYTON, C.R.I., SIMONS, N.E. and MATTHEWS, M.C. (1982) Site Investigation, Granada
Geol. Soc. of London (1970) 'The logging of rock cores for engineering purposes' Q J Eng. Geol, Vol.3, No.l, pp 1-24
Geol. Soc. of London (1972) 'The preparation of maps and plans in terms of engineering geology' Q J Eng. Geol., Vol.5, No.4, pp 295-382
Geol. Soc. of London (1977) 'The description of rock masses for engineering purposes' Q J Eng. Geol., Vol.10, No.4, pp 355-388
HEAD, K.H. (1980) Manual of Soil Laboratory Testing, Vols. 1, 2 and 3, Pentech Press London
MEIGH, A.C. (1987) Cone Penetration Testing, Butterworth
WELTMAN, A.J. and HEAD, J.M. (1983) Site Investigation Manual, CIRIA


CLIENT/CONSULTANT LIAISON
DESK STUDY
SITE RECONNAISSANCE SURVEY
ASSESSMENT/ REAPPRAISAL
PRELIMINARY REPORT
PRELIMINARY DISCUSSIONS WITH SELECTED SITE INVESTIGATION CONTRACTORS
REQUEST FOR LIST OF RATES FOR GROUND INVESTIGATION (Small or straightforward sites)
TENDER FOR GROUND INVESTIGATION (Large or complex investigations)
PRELIMINARY INVESTIGATION
INTERMEDIATE PROGRESS REPORT
MAIN GROUND INVESTIGATION
DESIGN OF LABORATORY SCHEDULE
SUBCONTRACTED SPECIAL ACTIVITIES (e.g. Geophysics, instrumentation, recent developments)
LIAISON
ENGINEERING DESIGN REPORT
FACTUAL REPORT
REDESIGN
FINAL REPORT
ISSUE OF TENDER DOCUMENTS FOR CONSTRUCTION with factual report
REVIEW DURING CONSTRUCTION
MONITORING OF PERFORMANCE
COMPLETE DEVELOPMENT
Legend
recommended route
decision options

Name of company: A N Other Ltd.	Borehole No. 1 Sheet 1 of 1
Equipment & methods: Light cable tool percussion rig. 200 mm dia. hole to 7.00 m. Casing 200 mm dia. to 6.00 m.	Location No: 6155
Carried out for: Smith, Jones & Brown	Ground level: 9.90 m (Ordnance datum) Coordinates: E 350 N 901 Date: 17–18 June 1974

Description	Reduced level	Legend	Depth & thickness	Samples/tests Depth	Sample Type	Sample No.	Test	Field records
Made Ground (sand, gravel, ash, brick and pottery)	9.40		(0.50) 0.50	0.20	D	1		
Made Ground (red and brown clay with gravel)	9.10		(0.30) 0.80					
Firm mottled brown silty CLAY (Brickearth)	7.90		(1.20) 2.0	0.70–1.15 1.15	U D	2 3		24 blows
Stiff brown sandy CLAY with some gravel (Flood Plain Gravel)	6.25		(1.65) 3.65	2.10–2.55 2.55 3.60–4.05	U D	4 5		50 blows
Medium dense brown sandy fine to coarse GRAVEL (Flood Plain Gravel)	4.60		(1.65) 5.30	3.65 4.00–4.30 4.00–5.00 5.00–5.30	D U B	6 7	S N27 S	No recovery
Firm becoming stiff to very stiff fissured grey silty CLAY with partings of silt (London Clay)	2.45		(2.15) 7.45	5.30 6.00–6.45 7.00–7.45	D U U	8 9 10	N15	Standpipe inserted 5.30 m below ground level 35 blows 44 blows
	End of borehole							

Water level observations during boring

Date	Time	Depth of hole, m	Depth of casing, m	Depth to water, m	Remarks
18 Jun	1615	7.00	0.00	3.65	casing withdrawn
24 Jun	1200	0.00	0.00	2.37	standpipe readings
27 Jun	0915	0.00	0.00	2.33	
27 Jun	1420	0.00	0.00	2.11	
28 Jun	1000	0.00	0.00	2.46	
1 Jul	1015	0.00	0.00	2.46	

SPT: Where full 0.3 m penetration has not been achieved, the number of blows for the quoted penetration is given (not *N*-value).

Depths: All depths and reduced levels in metres. Thicknesses given in brackets in depth column.

Water: Water level observations during boring are given on last sheet of log.

Sample/test key
- D Disturbed sample
- B Bulk sample
- W Water sample
- ▌ Piston (P), tube (U) or core sample; length to scale
- S Standard penetration test
- V Vane test
- C Core recovery (%)
- r Rock Quality Designation (RQD %)

Remarks: Water added to facilitate boring from 0.50 m to 7.00 m. Borehole back filled with natural spoil from 7.00 m to 5.30 m, gravel to 0.80 m, clay to 0.50 m, a concreted cock box to ground level.

Logged by:

Scale:

Typical logs of data from a light cable percussion borehole

Aid to identification of rocks for engineering purposes

This table follows general geological practice, but is intended as a guide only; geological training is required for the satisfactory identification of rocks. Engineering properties cannot be inferred from rock names in the table.

Grain size, mm	Bedded rocks (mostly sedimentary): Grain size description		At least 50 % of grains are of carbonate (LIMESTONE and DOLOMITE (undifferentiated))	At least 50 % of grains are of fine-grained volcanic rock		Obviously foliated rocks (mostly metamorphic): Grain size description		Rocks with massive structure and crystalline texture (mostly igneous)	Grain size description					Grain size (mm)
More than 20 20 6 2	RUDACEOUS	CONGLOMERATE Rounded boulders, cobbles and gravel cemented in a finer matrix Breccia Irregular rock fragments in a finer matrix	Calcirudite*	Fragments of volcanic ejecta in a finer matrix Rounded grains AGGLOMERATE Angular grains VOLCANIC BRECCIA	SALINE ROCKS Halite Anhydrite Gypsum	COARSE	GNEISS Well developed but often widely spaced foliation sometimes with schistose bands Migmatite Irregularly foliated: mixed schists and gneisses	MARBLE QUARTZITE Granulite HORNFELS Amphibolite Serpentine	COARSE	Pegmatite GRANITE[1] These rocks are sometimes porphyritic and are then described, for example, as porphyritic granite	Diorite[1,2]	GABBRO[3]	Pyroxenite Peridotite	More than 20 20 6 2
2 0.6 0.2 0.06	ARENACEOUS (Coarse / Medium / Fine)	SANDSTONE Angular or rounded grains, commonly cemented by clay, calcitic or iron minerals Quartzite Quartz grains and siliceous cement Arkose Many feldspar grains Greywacke Many rock chips	Calcarenite	Cemented volcanic ash TUFF		MEDIUM	SCHIST Well developed undulose foliation; generally much mica		MEDIUM	Microgranite[1] These rocks are sometimes porphyritic and are then described as porphyries	Microdiorite[1,2]	Dolerite[3,4]		2 0.6 0.2 0.06
0.06 0.002 Less than 0.002	ARGILLACEOUS	MUDSTONE / SILTSTONE Mostly silt SHALE Fissile / CLAYSTONE Mostly clay Calcareous mudstone	Calcisiltite Calcilutite CHALK	Fine-grained TUFF Very fine-grained TUFF		FINE	PHYLLITE Slightly undulose foliation; sometimes 'spotted' SLATE Well developed plane cleavage (foliation)		FINE	RHYOLITE[4,5] These rocks are sometimes porphyritic and are then described as porphyries	ANDESITE[4,5]	BASALT[4,5]		0.06 0.002 Less than 0.002
Amorphous or crypto-crystalline		Flint: occurs as bands of nodules in the Chalk Chert: occurs as nodules and beds in limestone and calcareous sandstone			COAL LIGNITE		Mylonite Found in fault zones, mainly in igneous and metamorphic areas			Obsidian[5]	Volcanic glass			Amorphous or crypto-crystalline
		Granular cemented except amorphous rocks				CRYSTALLINE				colour: Pale ← → Dark				
		SILICEOUS	CALCAREOUS	SILICEOUS	CARBONACEOUS	SILICEOUS		mainly SILICEOUS		ACID Much quartz	INTERMEDIATE Some quartz	BASIC Little or no quartz	ULTRA BASIC	

SEDIMENTARY ROCKS
Granular cemented rocks vary greatly in strength, some sandstones are stronger than many igneous rocks. Bedding may not show in hand specimens and is best seen in outcrop. Only sedimentary rocks, and some metamorphic rocks derived from them, contain fossils.
Calcareous rocks contain calcite (calcium carbonate) which effervesces with dilute hydrochloric acid.

METAMORPHIC ROCKS
Most metamorphic rocks are distinguished by foliation which may impart fissility. Foliation in gneisses is best observed in outcrop. Non-foliated metamorphics are difficult to recognize except by association. Any rock baked by contact metamorphism is described as a 'hornfels' and is generally somewhat stronger than the parent rock.
Most fresh metamorphic rocks are strong although perhaps fissile.

IGNEOUS ROCKS
Composed of closely interlocking mineral grains. Strong when fresh; not porous
Mode of occurrence: 1. Batholiths; 2. Laccoliths; 3. Sills; 4. Dykes; 5. Lava flows; 6. Veins

*A more detailed classification is given in Clark, A.R. and Walker, B.F. *Geotechnique*, 1977, 27(1), 93–99.

NOTE 1. Principal rock types (generally common) are shown in bold type in capitals, e.g. GRANITE. Less common rock types are shown in medium type, e.g. Greywacke.

NOTE 2. Granular rocks may be distinguished from crystalline rocks by scratching with a knife which should remove whole grains from cement matrix in the granular rocks. The separate grains may also sometimes be distinguished using a hand lens.

Siliceous rocks are generally harder and more resistant to scratching than calcareous rocks.

NOTE 3. In the table the boundaries of the heavy lined box describe the conditions to which the rock name applies.

British Soil Classification System for Engineering Purposes

Soil groups (see note 1)			Subgroups and laboratory identification				
GRAVEL and SAND may be qualified Sandy GRAVEL and Gravelly SAND, etc. where appropriate (See 41.3.2.2)			Group symbol (see notes 2 & 3)	Subgroup symbol (see note 2)	Fines (% less than 0.06 mm)	Liquid limit %	Name
COARSE SOILS less than 35 % of the material is finer than 0.06 mm	GRAVELS More than 50 % of coarse material is of gravel size (coarser than 2 mm)	Slightly silty or clayey GRAVEL	G GW GP	GW GPu GPg	0 to 5		Well graded GRAVEL Poorly graded/Uniform/Gap graded GRAVEL
		Silty GRAVEL Clayey GRAVEL	G-F G-M G-C	GWM GPM GWC GPC	5 to 15		Well graded/Poorly graded silty GRAVEL Well graded/Poorly graded clayey GRAVEL
		Very silty GRAVEL Very clayey GRAVEL	GF GM GC	GML, etc GCL GCI GCH GCV GCE	15 to 35		Very silty GRAVEL; subdivide as for GC Very clayey GRAVEL (clay of low, intermediate, high, very high, extremely high plasticity)
	SANDS More than 50 % of coarse material is of sand size (finer than 2 mm)	Slightly silty or clayey SAND	S SW SP	SW SPu SPg	0 to 5		Well graded SAND Poorly graded/Uniform/Gap graded SAND
		Silty SAND Clayey SAND	S-F S-M S-C	SWM SPM SWC SPC	5 to 15		Well graded/Poorly graded silty SAND Well graded/Poorly graded clayey SAND
		Very silty SAND Very clayey SAND	SF SM SC	SML, etc SCL SCI SCH SCV SCE	15 to 35		Very silty SAND; subdivided as for SC Very clayey SAND (clay of low, intermediate, high, very high, extremely high plasticity)
FINE SOILS more than 35 % of the material is finer than 0.06 mm	Gravelly or sandy SILTS and CLAYS 35 % to 65 % fines	Gravelly SILT Gravelly CLAY (see note 4)	FG MG CG	MLG, etc CLG CIG CHG CVG CEG		< 35 35 to 50 50 to 70 70 to 90 > 90	Gravelly SILT; subdivide as for CG Gravelly CLAY of low plasticity of intermediate plasticity of high plasticity of very high plasticity of extremely high plasticity
		Sandy SILT (see note 4) Sandy CLAY	FS MS CS	MLS, etc CLS, etc			Sandy SILT; subdivide as for CG Sandy CLAY; subdivide as for CG
	SILTS and CLAYS 65 % to 100 % fines	SILT (M-SOIL) CLAY (see notes 5 & 6)	F M C	ML, etc CL CI CH CV CE		< 35 35 to 50 50 to 70 70 to 90 > 90	SILT; subdivide as for C CLAY of low plasticity of intermediate plasticity of high plasticity of very high plasticity of extremely high plasticity
ORGANIC SOILS		Descriptive letter 'O' suffixed to any group or sub-group symbol.		Organic matter suspected to be a significant constituent. Example MHO: Organic SILT of high plasticity.			
PEAT		Pt Peat soils consist predominantly of plant remains which may be fibrous or amorphous.					

NOTE 1. The name of the soil group should always be given when describing soils, supplemented, if required, by the group symbol, although for some additional applications (e.g. longitudinal sections) it may be convenient to use the group symbol alone.

NOTE 2. The group symbol or sub-group symbol should be placed in brackets if laboratory methods have not been used for identification, e.g. (GC).

NOTE 3. The designation FINE SOIL or FINES, F, may be used in place of SILT, M, or CLAY, C, when it is not possible or not required to distinguish between them.

NOTE 4. GRAVELLY if more than 50 % of coarse material is of gravel size. SANDY if more than 50 % of coarse material is of sand size.

NOTE 5. SILT (M-SOIL), M, is material plotting below the A-line, and has a restricted plastic range in relation to its liquid limit, and relatively low cohesion. Fine soils of this type include clean silt-sized materials and rock flour, micaceous and diatomaceous soils, pumice, and volcanic soils, and soils containing halloysite. The alternative term 'M-soil' avoids confusion with materials of predominantly silt size, which form only a part of the group.

Organic soils also usually plot below the A-line on the plasticity chart, when they are designated ORGANIC SILT, MO.

NOTE 6. CLAY, C, is material plotting above the A-line, and is fully plastic in relation to its liquid limit.

Field identification and description of soils

	Basic soil type	Particle size, mm		Visual identification	Particle nature and plasticity
Very coarse soils	BOULDERS		200	Only seen complete in pits or exposures.	Particle shape:
	COBBLES		60	Often difficult to recover from boreholes.	Angular Subangular Subrounded Rounded Flat Elongate
Coarse soils (over 65 % sand and gravel sizes)	GRAVELS	coarse	20	Easily visible to naked eye; particle shape can be described; grading can be described.	
		medium	6	Well graded: wide range of grain sizes, well distributed. Poorly graded: not well graded. (May be uniform: size of most particles lies between narrow limits; or gap graded: an intermediate size of particle is markedly under-represented.)	
		fine	2		Texture:
	SANDS	coarse	0.6	Visible to naked eye; very little or no cohesion when dry; grading can be described.	Rough Smooth Polished
		medium	0.2	Well graded: wide range of grain sizes, well distributed. Poorly graded: not well graded. (May be uniform: size of most particles lies between narrow limits; or gap graded: an intermediate size of particle is markedly under-represented.)	
		fine	0.06		
Fine soils (over 35 % silt and clay sizes)	SILTS	coarse	0.02	Only coarse silt barely visible to naked eye; exhibits little plasticity and marked dilatancy; slightly granular or silky to the touch. Disintegrates in water; lumps dry quickly; possess cohesion but can be powdered easily between fingers.	Non-plastic or low plasticity
		medium	0.006		
		fine	0.002		
	CLAYS			Dry lumps can be broken but not powdered between the fingers; they also disintegrate under water but more slowly than silt; smooth to the touch; exhibits plasticity but no dilatancy; sticks to the fingers and dries slowly; shrinks appreciable on drying usually showing cracks. Intermediate and high plasticity clays show these properties to a moderate and high degree, respectively.	Intermediate plasticity (Lean clay) High plasticity (Fat clay)
Organic soils	ORGANIC CLAY, SILT or SAND	Varies		Contains substantial amounts of organic vegetable matter.	
	PEATS	Varies		Predominantly plant remains usually dark brown or black in colour, often with distinctive smell; low bulk density.	

Composite soil types (mixtures of basic soil types)

Scale of secondary constituents with coarse soils

Term		% of clay or silt
slightly clayey / slightly silty	GRAVEL or SAND	under 6
— clayey / — silty	GRAVEL or SAND	5 to 15
very clayey / very silty	GRAVEL or SAND	15 to 35
Sandy GRAVEL / Gravelly SAND		Sand or gravel and important second constituent of the coarse fraction

(See 41.3.2.2)
For composite types described as:
clayey: fines are plastic, cohesive;
silty: fines non-plastic or of low plasticity

Scale of secondary, constituents with fine soils

Term		% of sand or gravel
sandy / gravelly	CLAY or SILT	35 to 65
—	CLAY:SILT	under 35

Examples of composite types

(Indicating preferred order for description)

Loose, brown, subangular very sandy, fine to coarse GRAVEL with small pockets of soft grey clay

Medium dense, light brown, clayey, fine and medium SAND

Stiff, orange brown, fissured sandy CLAY

Firm, brown, thinly laminated SILT and CLAY

Plastic, brown, amorphous PEAT

Compactness/strength

Term	Field test
Loose	By inspection of voids and particle packing.
Dense	
Loose	Can be excavated with a spade; 50 mm wooden peg can be easily driven.
Dense	Requires pick for excavation; 50 mm wooden peg hard to drive.
Slightly cemented	Visual examination; pick removes soil in lumps which can be abraded.
Soft or loose	Easily moulded or crushed in the fingers.
Firm or dense	Can be moulded or crushed by strong pressure in the fingers.
Very soft	Exudes between fingers when squeezed in hand.
Soft	Moulded by light finger pressure.
Firm	Can be moulded by strong finger pressure.
Stiff	Cannot be moulded by fingers. Can be indented by thumb.
Very stiff	Can be indented by thumb nail.
Firm	Fibres already compressed together.
Spongy	Very compressible and open structure.
Plastic	Can be moulded in hand, and smears fingers.

Structure

Term	Field identification
Homogeneous	Deposit consists essentially of one type.
Interstratified	Alternating layers of varying types or with bands or lenses of other materials. Interval scale for bedding spacing may be used.
Heterogeneous	A mixture of types.
Weathered	Particles may be weakened and may show concentric layering.
Fissured	Break into polyhedral fragments along fissures. Interval scale for spacing of discontinuities may be used.
Intact	No fissures.
Homogeneous	Deposit consists essentially of one type.
Interstratified	Alternating layers of varying types. Interval scale for thickness of layers may be used.
Weathered	Usually has crumb or columnar structure.
Fibrous	Plant remains recognizable and retain some strength.
Amorphous	Recognizable plant remains absent.

Interval scales

Scale of bedding spacing

Term	Mean spacing, mm
Very thickly bedded	over 2000
Thickly bedded	2000 to 600
Medium bedded	600 to 200
Thinly bedded	200 to 60
Very thinly bedded	60 to 20
Thickly laminated	20 to 6
Thinly laminated	under 6

Scale of spacing of other discontinuities

Term	Mean spacing, mm
Very widely spaced	over 2000
Widely spaced	2000 to 600
Medium spaced	600 to 200
Closely spaced	200 to 60
Very closely spaced	60 to 20
Extremely closely spaced	under 20

Colour

Red
Pink
Yellow
Brown
Olive
Green
Blue
White
Grey
Black
etc.

Supplemented as necessary with:
Light
Dark
Mottled
etc.

and

Pinkish
Reddish
Yellowish
Brownish
etc.

In situ test methods and general application (after Wroth (1984))

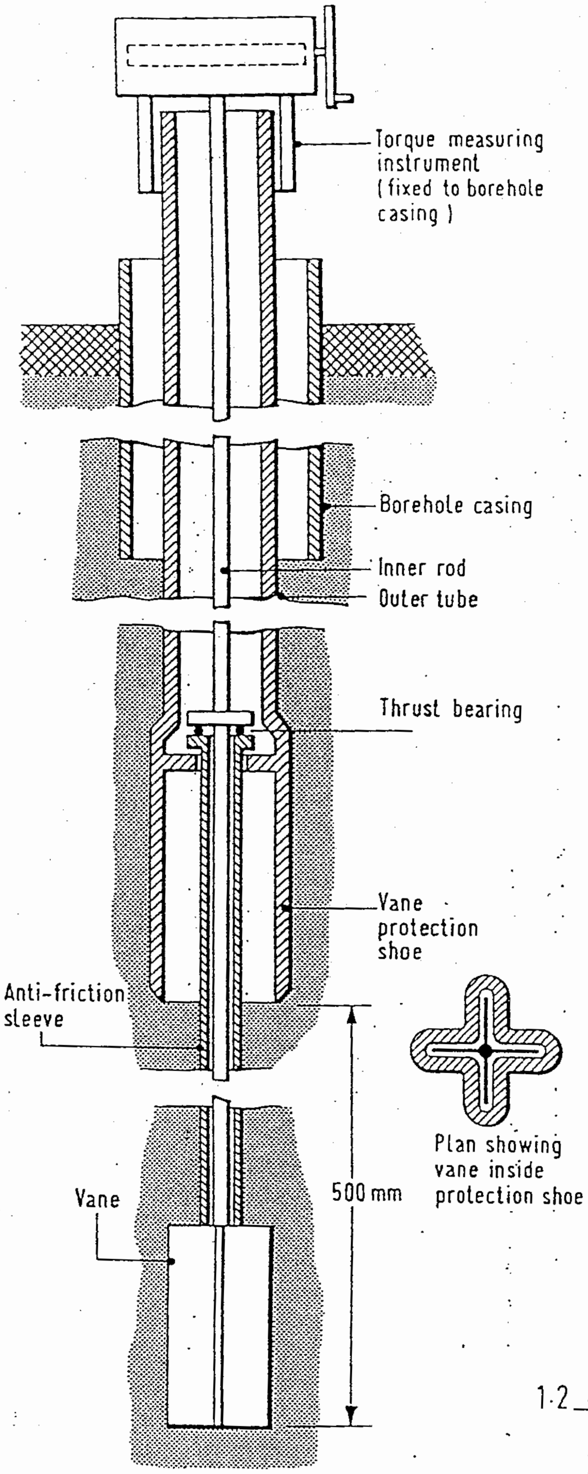
	Soil identification	Establish vertical profile	Relative density D_r	Angle of friction ϕ	Undrained shear strength s_u	Pore pressure u	Stress history OCR and K_o	Modulus: E_s, G'	Compressibility m_v and C_c	Consolidation c_h and c_v	Permeability k	Stress-strain curve	Liquefaction resistance	Reference (in chapter if not give
Acoustic probe	C	B	B	C	C	—	C	C	—	—	—	—	C	Koerner and Lord (1986)
Borehole permeability	C	—	—	—	—	A	—	—	—	B	A	—	—	ASTM STP No. 322, ASTM STP 417
Cone														
Dynamic	C	A	B	C	C	—	C	—	—	—	—	—	C	
Electrical friction	B	A	B	C	B	—	C	B	C	—	—	—	B	
Electrical piezo	A	A	B	B	B	A	A	B	B	A	B	B	A	
Electrical piezo/ friction	A	A	A	B	B	A	A	B	B	A	B	B	A	
Impact	C	B	C	C	C	—	C	C	C	—	—	—	C	Dayal and Allen (1973)
Mechanical	B	A	B	C	B	—	C	B	C	—	—	—	B	
Seismic CPT down-hole	C	C	C	—	—	—	—	A	—	—	—	B	B	
Dilatometer (DMT)	B	A	B	C	B	—	B	B	C	—	—	C	B	
Hydraulic fracture	—	—	—	—	—	B	B	—	—	C	C	—	—	
K_o stepped blade	—	—	—	—	—	—	B	—	—	—	—	—	—	
Nuclear tests	—	—	A	B	—	—	—	C	—	—	—	—	C	ASTM STP 412
Plate load tests	C	C	B	B	C	—	B	A	B	C	C	B	B	ASTM D 1194
Pressuremeter														
Ménard	B	B	C	B	B	—	C	B	B	—	—	C	C	
Self boring	B	B	A	A	A	A	A	A	A	A	B	A	A	
Screw plate	C	C	B	C	B	—	B	A	B	C	C	B	B	Patrick et al. (1980), Dahlberg (1974*a*)
Seismic														
Cross-hole	C	C	B	—	—	—	—	A	—	—	—	B	B	Woods (1986)†
Down-hole	C	C	C	—	—	—	—	A	—	—	—	B	B	Woods (1986)†
Surface refraction	C	C	—	—	—	—	—	B	—	—	—	—	C	Leet (1950)
Shear														
Borehole	C	C	—	B	B	—	C	C	—	—	—	C	—	
Vane	B	C	—	—	A	—	B	—	—	—	—	—	—	
Standard penetration test (SPT)	B	B	B	C	C	—	—	—	C	—	—	—	A	

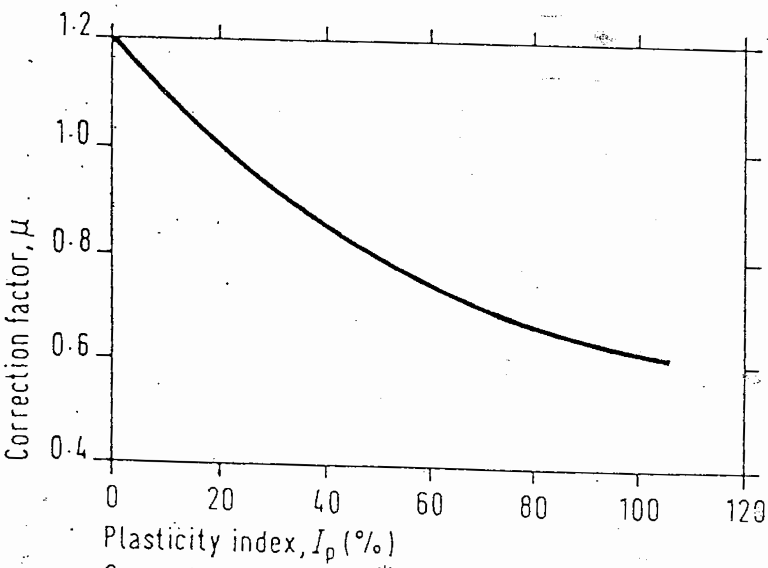
† In ASCE Conference: Use of In Situ Tests in Geotechnical Engineering, GT SP No. 6 (1986).
Code: *A* = Most applicable; *B* = May be used; *C* = Least applicable.

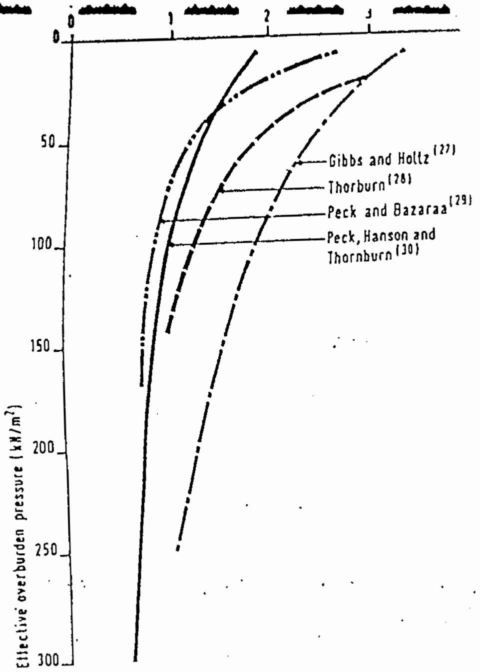
Geophysical methods in ground investigation

Preferred techniques in bold type.

Problem		Example	Method and remarks
Geological	Stratigraphical	Sediments over bedrock. (i) Sands and gravels over bedrock, water table low in sands and gravels. (ii) Sands and gravels overlying clay, water table high in sands and gravels. (iii) Clay over bedrock. Sediments over bedrock generally	*Land* Seismic refraction Resistivity Resistivity or seismic refraction *Marine.* Continuous seismic reflection profiling
	Erosional (for caverns see shafts below)	Buried channel. Buried karstic surface	Seismic refraction. Resistivity for feature wider than depth of cover. Resistivity contouring.
	Structural	Buried fault, dykes	Resistivity contouring. Seismic reflection or refraction. Magnetic gravimetric (large faults)
Resources	Water	Location of aquifer. Location of saline/potable interface.	Resistivity and seismic refraction
	Sand and gravel	Sand, gravel over clay. Gravel banks	*Land.* Resistivity *Marine.* Continuous seismic profiling, side scan sonar, echo sounding.
	Rock	Intrusive in sedimentary rocks	Magnetic. (Weathering may give low resistivity.)
	Clay	Clay pockets	Resistivity
Engineering parameters	Modulus of elasticity, density and porosity	Dynamic deformation modulus Check on effects of ground treatment	Seismic velocity at surface, or with single or multiple boreholes. (Cross hole transmission.) Borehole geophysics
	Rock rippability	Choice of excavation method	Seismic (velocities at surface)
	Corrosivity of soils	Pipeline surveys	Surface resistivity. Redox potential.
Buried artifacts	Cables Pipes	Trenches on land Submarine trenches Submarine pipelines	Magnetometer. Electromagnetic field detectors. Echo sounding, side scan sonar. Side scan sonar, magnetic, continuous seismic profiling (especially if thought to be partially buried) with high frequency pinger
	Shafts, adits and caverns	Shaft, sink holes, mine workings	Resistivity. Magnetometer contouring, infra-red air photography on clear areas. Cross hole transmission. Detailed gravity for large systems


Torque measuring instrument (fixed to borehole casing)
Borehole casing
Inner rod
Outer tube
Thrust bearing
Vane protection shoe
Anti-friction sleeve
Vane
500 mm
Plan showing vane inside protection shoe


1·2
1·0
0·8
0·6
0·4
Correction factor, μ
0
20
40
60
80
100
120
Plasticity index, I_p (%)
Corrected strength, $s_u^* = s_u \times \mu$



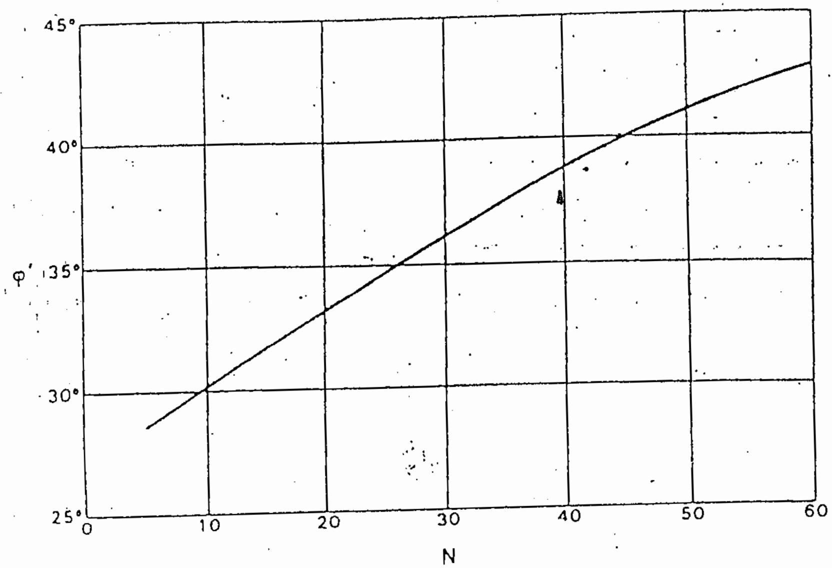
Various correction factors for influence of overburden pressure on SPT N value

Description	Very loose	Loose	Medium	Dense	Very dense
Relative density D_r	0 – 0.15	0.35	0.65	0.85	
SPT N'_{70}: fine	1–2	3–6	7–15	16–30	?
medium	2–3	4–7	8–20	21–40	> 40
coarse	3–6	5–9	10–25	26–45	> 45
ϕ: fine	26–28	28–30	30–34	33–38	
medium	27–28	30–32	32–36	36–42	< 50
coarse	28–30	30–34	33–40	40–50	
γ_{wet}, pcf	70–100†	90–115	110–130	110–140	130–150
(kN/m³)	(11–16)	(14–18)	(17–20)	(17–22)	(20–23)

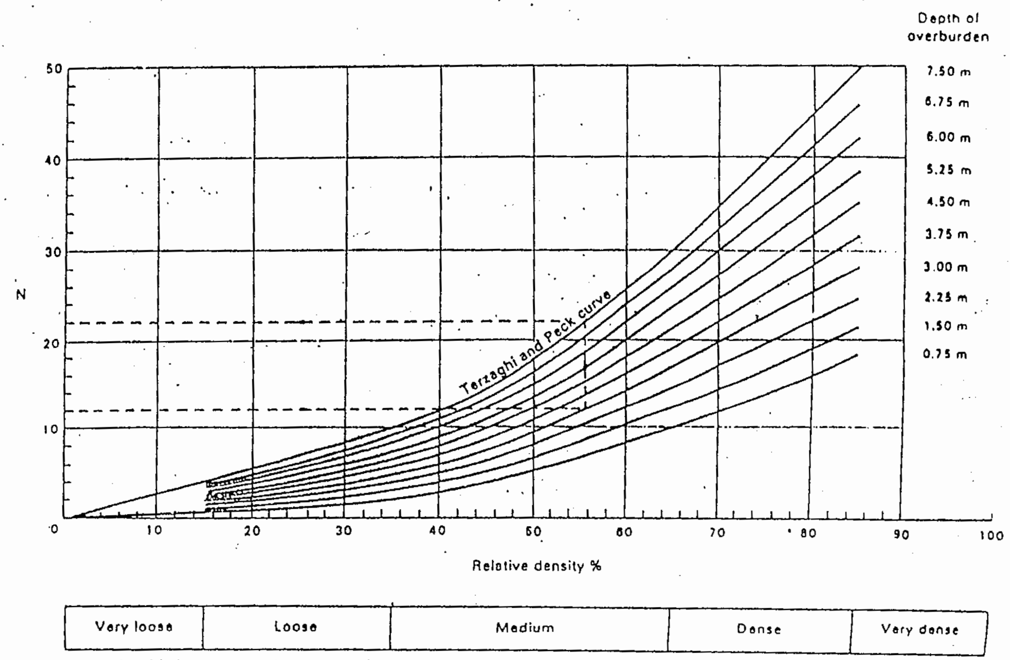
† Excavated soil or material dumped from a truck will weigh 11 to 14 kN/m³ and must be quite dense to weigh much over 21 kN/m³. No existing soil has a D_r = 0.00 nor a value of 1.00—common ranges are from 0.3 to 0.7.

	Very loose	Loose	Medium dense	Dense	Very dense
SPT N value (blows/0.3 m)*	<4	4-10	10-30	30-50	>50
CPT cone resistance (MN/m²)†	<5	5-10	10-15	15-20	>20
Equivalent relative density (%)‡	<15	15-35	35-65	65-85	85-100
Dry unit weight (kN/m³)	<14	14-16	16-18	18-20	>20
Friction angle (degrees)	<30	30-32	32-35	35-38	>38
Cyclic stress ratio causing liquefaction (τ/σ_o')	<0.04	0.04-0.10	0.10-0.35	>0.35	–

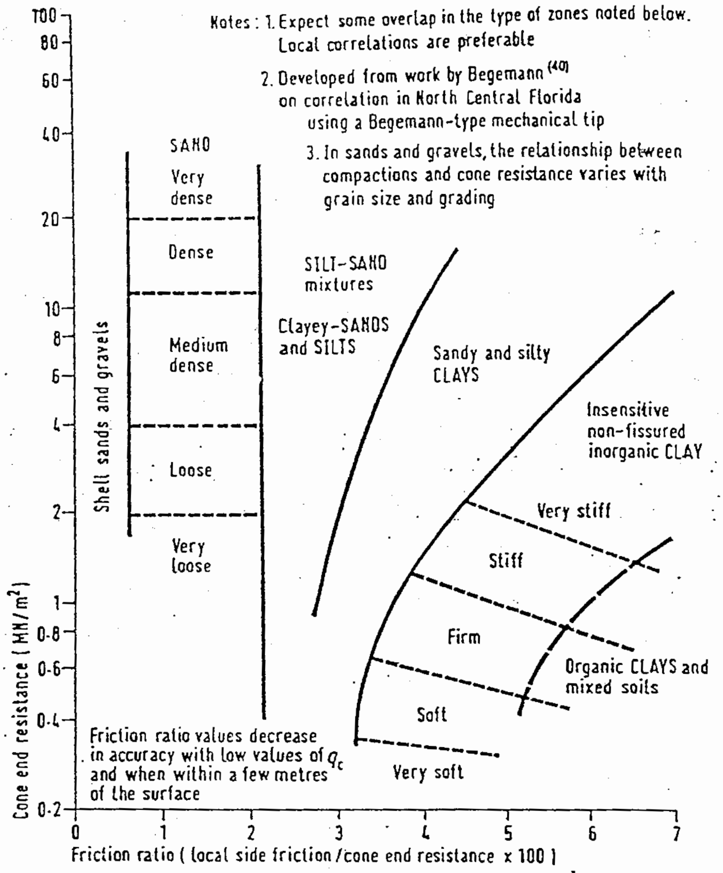
* At an effective vertical overburden pressure of 100 kN/m²
† There is no unique relationship between CPT and SPT values – it should be reassessed at each site
‡ Freshly deposited, normally consolidated sand



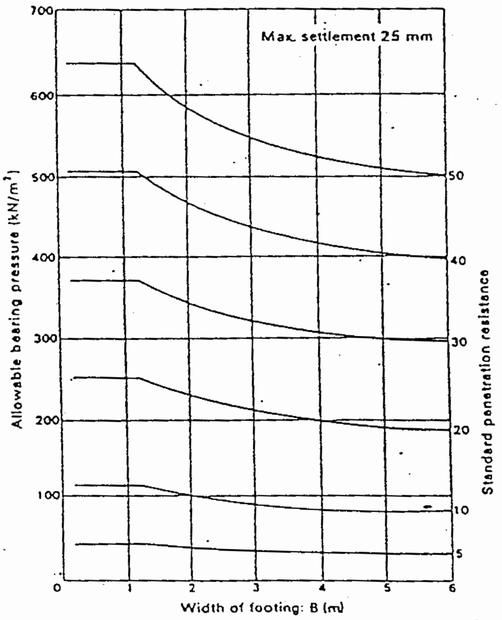
Approximate correlation between standard penetration resistance and shear strength parameter ϕ'. (Reproduced from R. B. Peck, W. E. Hansan and T. H. Thornburn (1974) *Foundation Engineering*, by permission of John Wiley & Sons, Inc.)



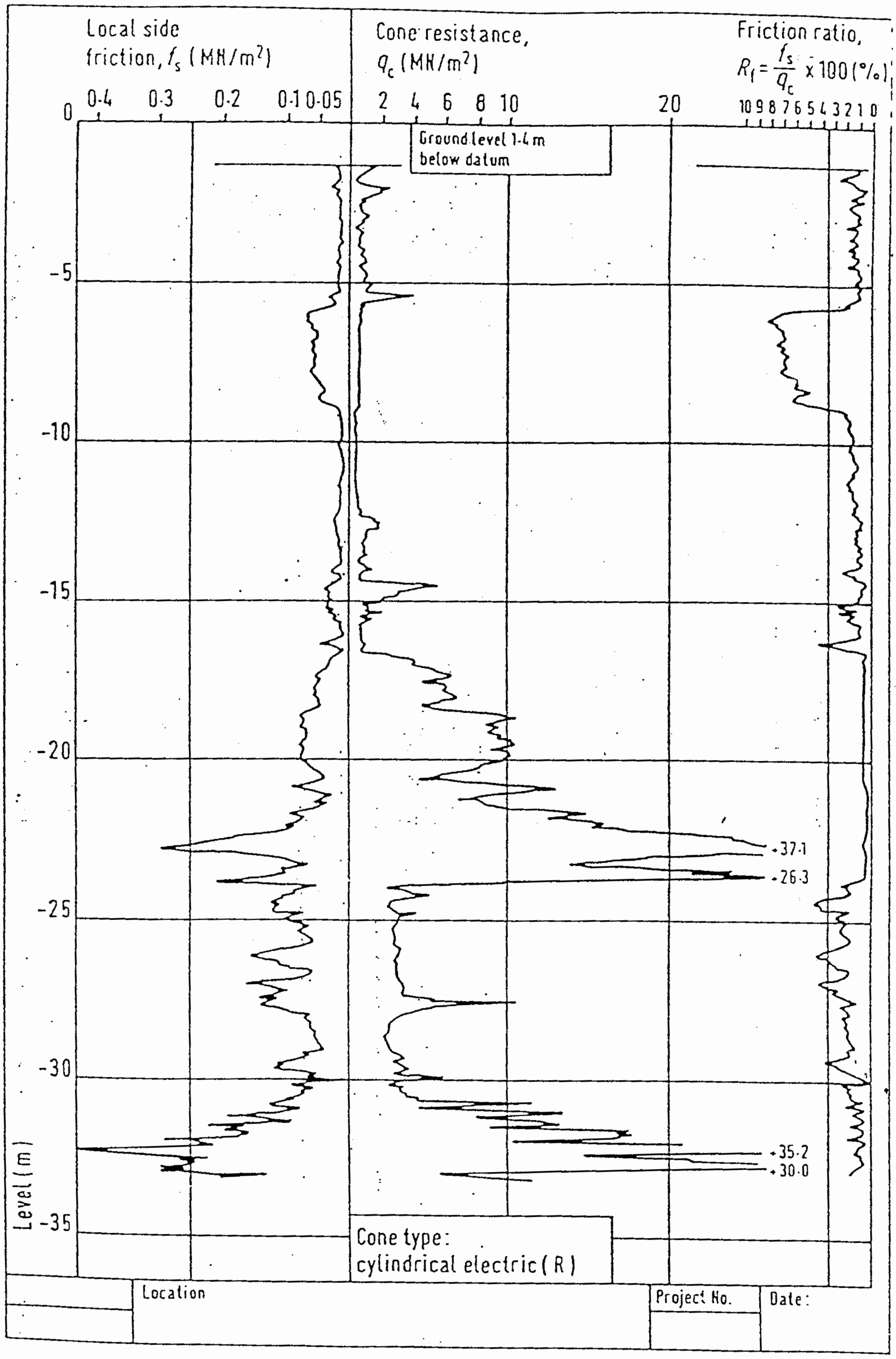
Relationship between standard penetration resistance, depth of overburden and relative density. (Reproduced by permission of Mr. S. Thorburn, Thorburn and Partners, Glasgow.)



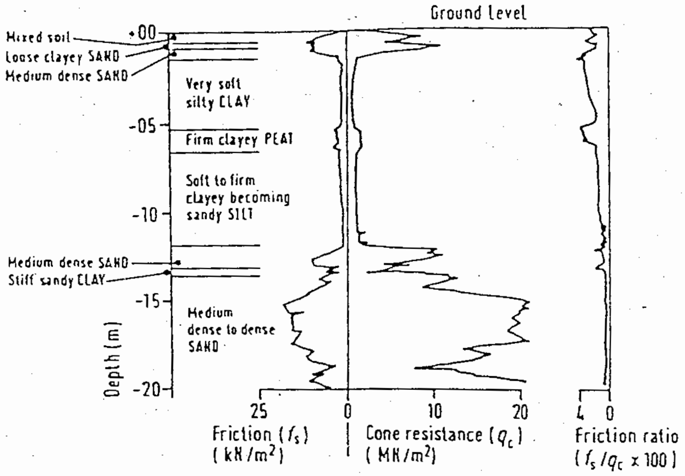
Guide for tentative evaluation of soil type from static cone penetrometer test results using a mechanical tip (after Schmertmann[41])



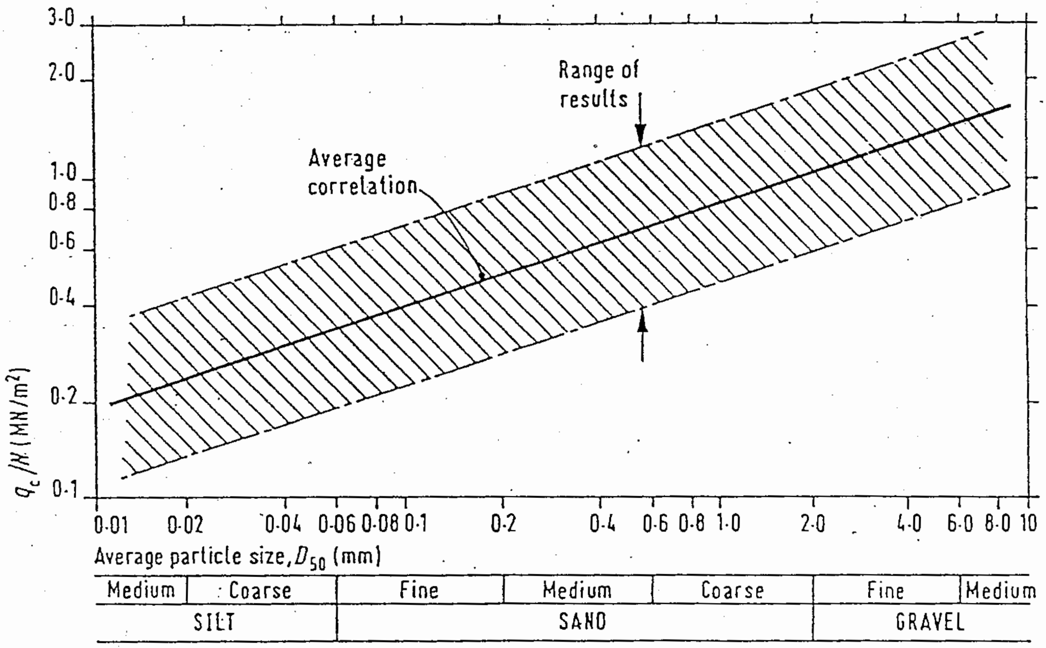
Relationship between standard penetration resistance and allowable bearing pressure. (Reproduced from K. Terzaghi and R. B. Peck (1967) *Soil Mechanics in Engineering Practice*, by permission of John Wiley and Sons, Inc.)

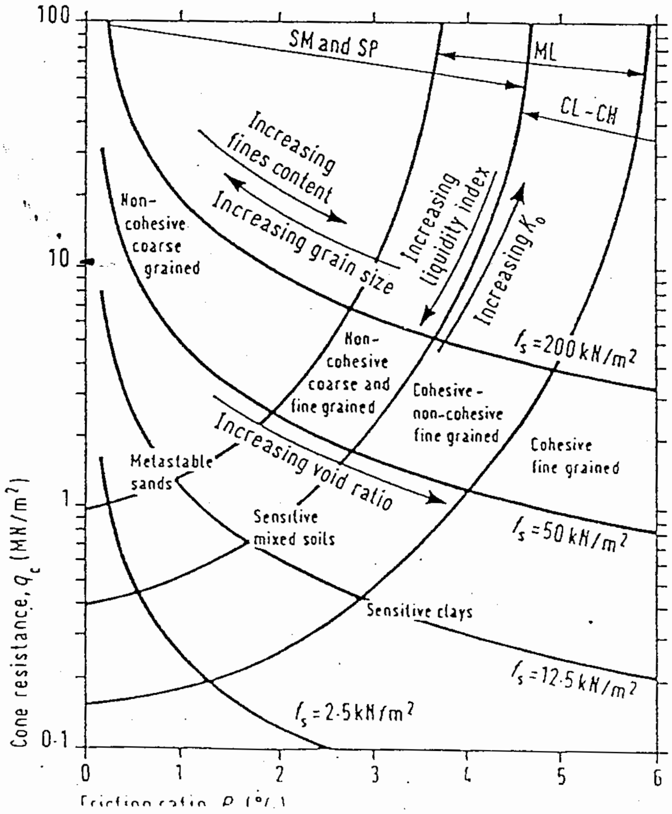


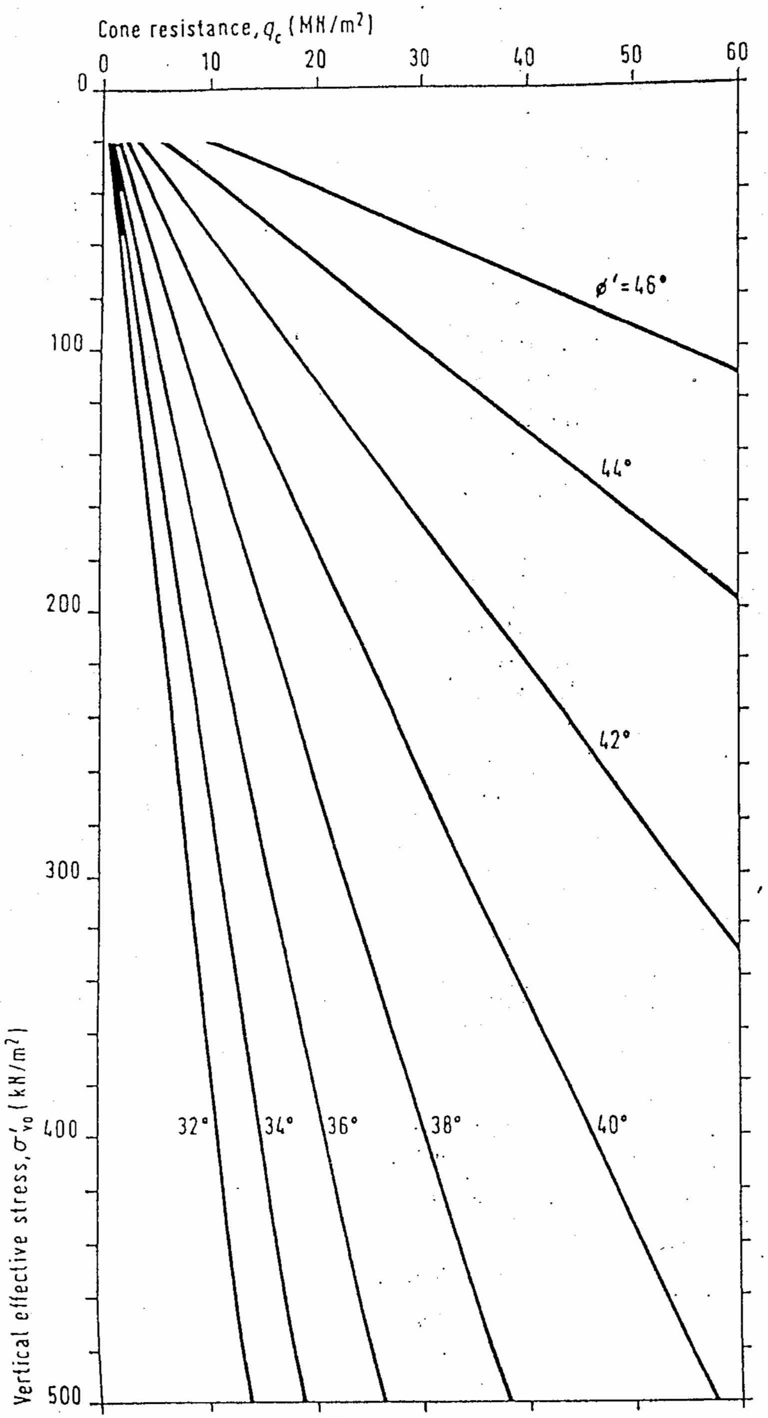
Local side friction, f_s (MN/m²)
0.4 0.3 0.2 0.1 0.05
Cone resistance, q_c (MN/m²)
2 4 6 8 10 20
Friction ratio, $R_f = \frac{f_s}{q_c} \times 100$ (%)
10 9 8 7 6 5 4 3 2 1 0
Ground level 1.4 m below datum
0
-5
-10
-15
-20
-25
-30
-35
Level (m)
37.1
26.3
35.2
30.0
Cone type: cylindrical electric (R)
Location
Project No.
Date:



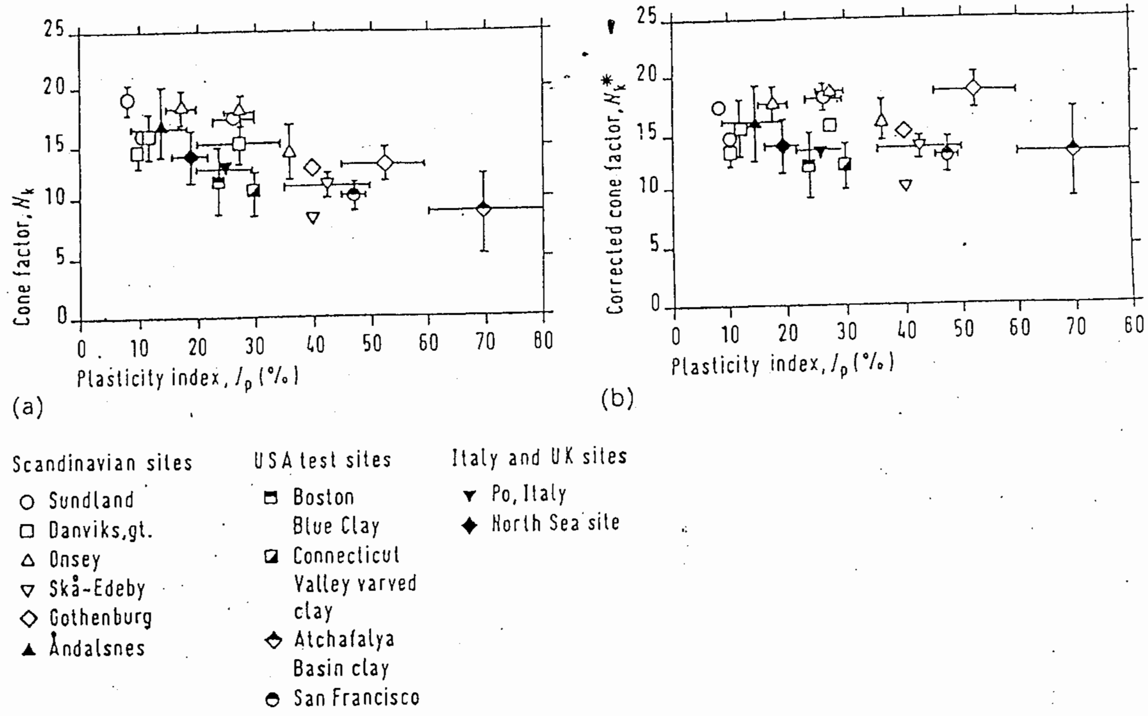
Interpretation of typical result profile from mechanical tip results



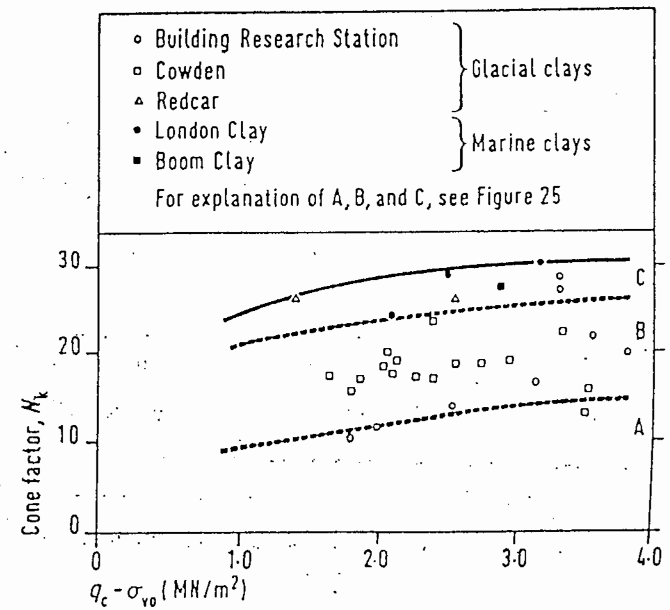




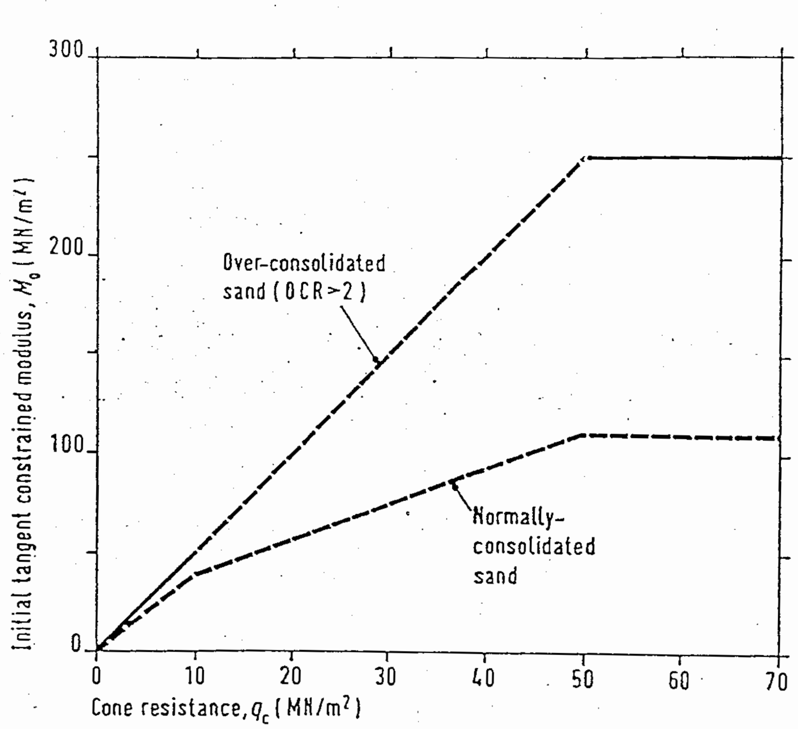
Cone resistance, q_c (MN/m^2)
0 10 20 30 40 50 60
ϕ'=46°
44°
42°
40°
32° 34° 36° 38°
Vertical effective stress, σ'_{vo} (kN/m^2)
0 100 200 300 400 500



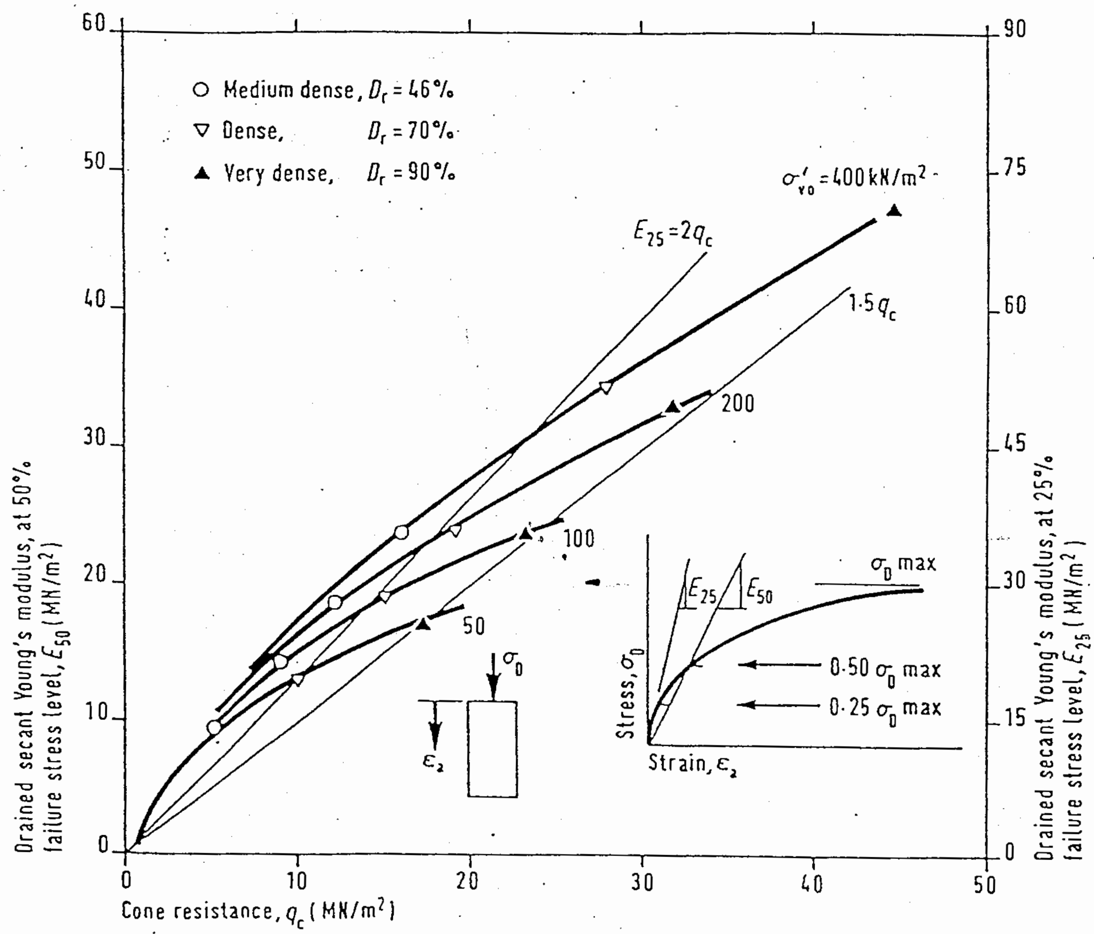
Cone factor, N_k
Plasticity index, I_p (%)
(a)
Corrected cone factor, N_k^*
Plasticity index, I_p (%)
(b)
Scandinavian sites
○ Sundland
□ Danviks,gt.
△ Onsey
▽ Skå-Edeby
◇ Gothenburg
▲ Åndalsnes
USA test sites
Boston Blue Clay
Connecticut Valley varved clay
Atchafalya Basin clay
San Francisco
Italy and UK sites
▼ Po, Italy
◆ North Sea site



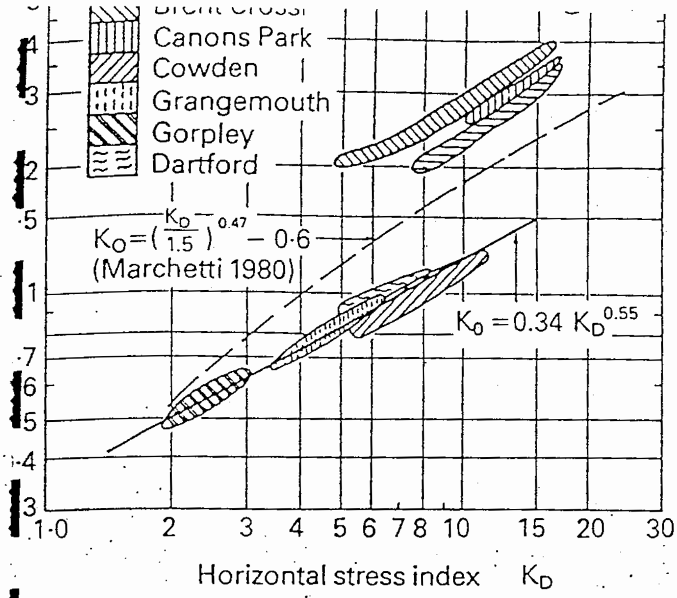
Building Research Station
Cowden
Redcar
Glacial clays
London Clay
Boom Clay
Marine clays
For explanation of A, B, and C, see Figure 25
Cone factor, N_k
$q_c - \sigma_{vo}$ (MN/m^2)
A
B
C

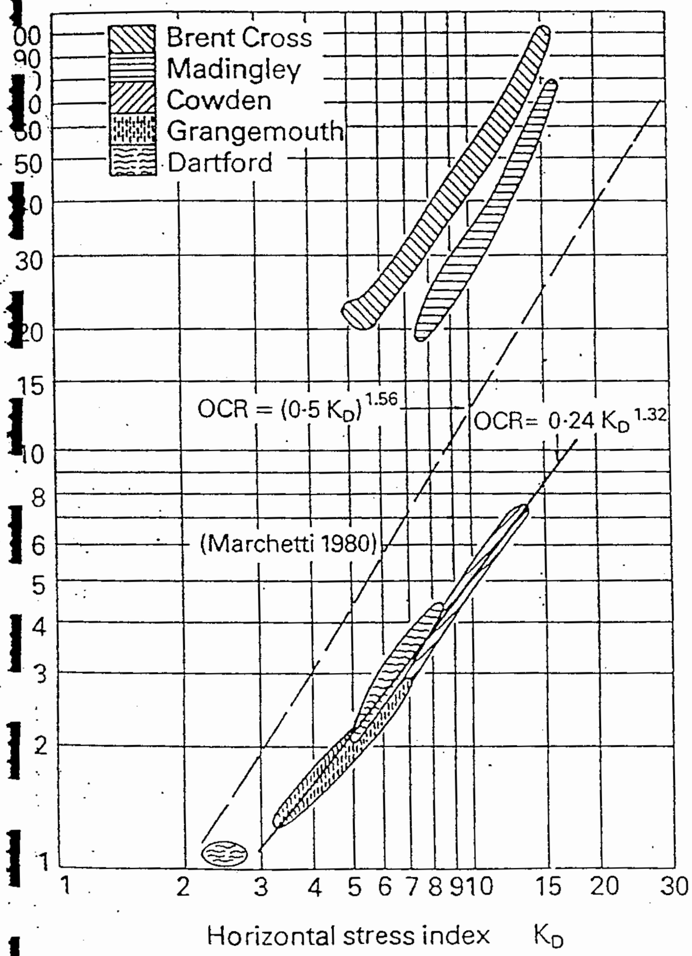


Over-consolidated sand (OCR>2)
Normally-consolidated sand
Initial tangent constrained modulus, M_0 (MN/m²)
Cone resistance, q_c (MN/m²)
0
10
20
30
40
50
60
70
100
200
300



○ Medium dense, D_r = 46%
▽ Dense, D_r = 70%
▲ Very dense, D_r = 90%
σ'_{vo} = 400 kN/m²
$E_{25} = 2q_c$
$1.5q_c$
200
100
50
σ_0
ε_2
σ_0 max
E_{25}
E_{50}
0.50 σ_0 max
0.25 σ_0 max
Stress, σ_0
Strain, ε_2
Drained secant Young's modulus, at 50% failure stress level, E_{50} (MN/m²)
Drained secant Young's modulus, at 25% failure stress level, E_{25} (MN/m²)
Cone resistance, q_c (MN/m²)
0
10
20
30
40
50
60
15
45
75
90





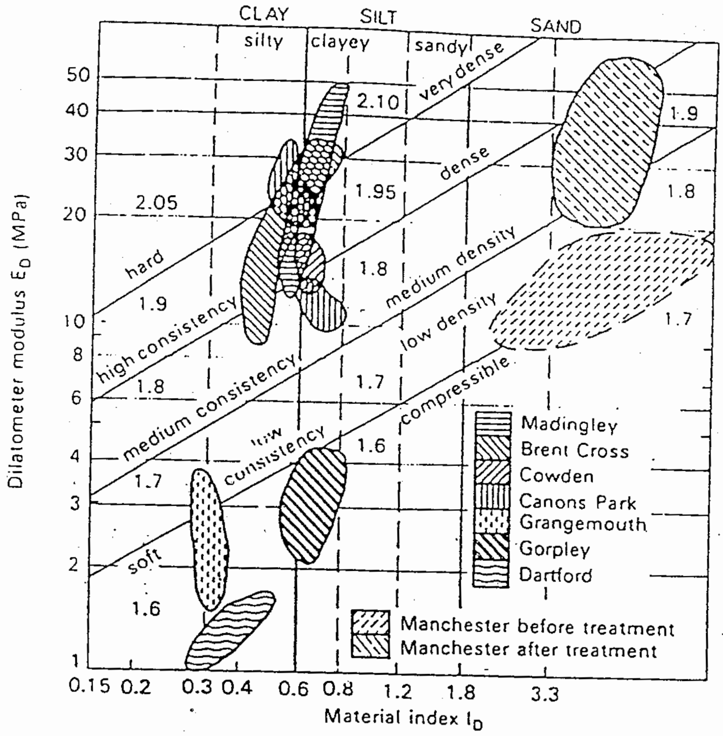
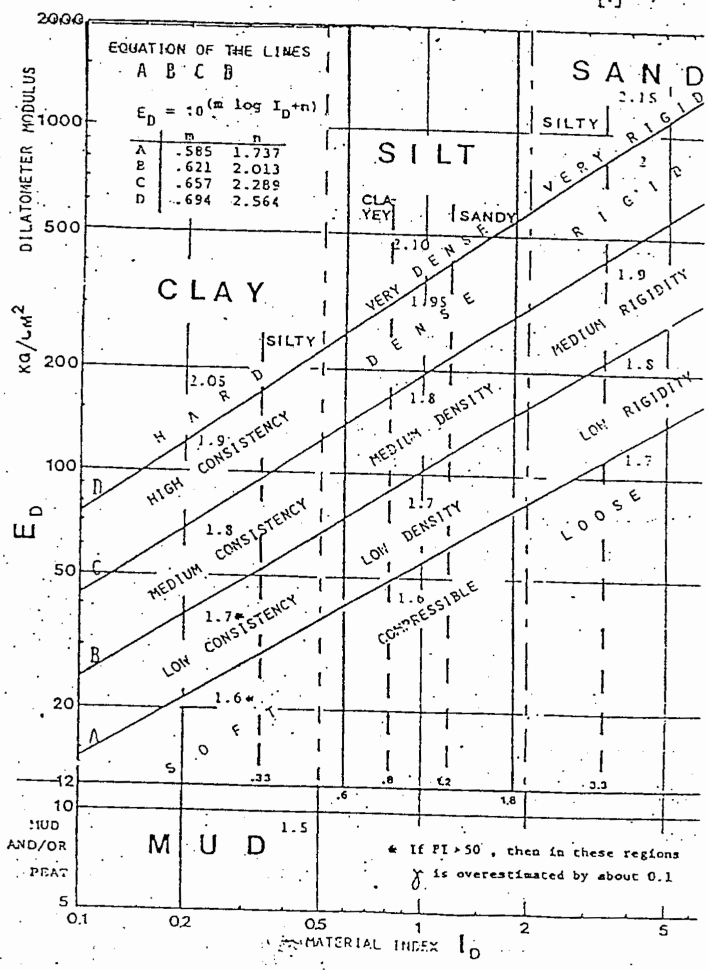
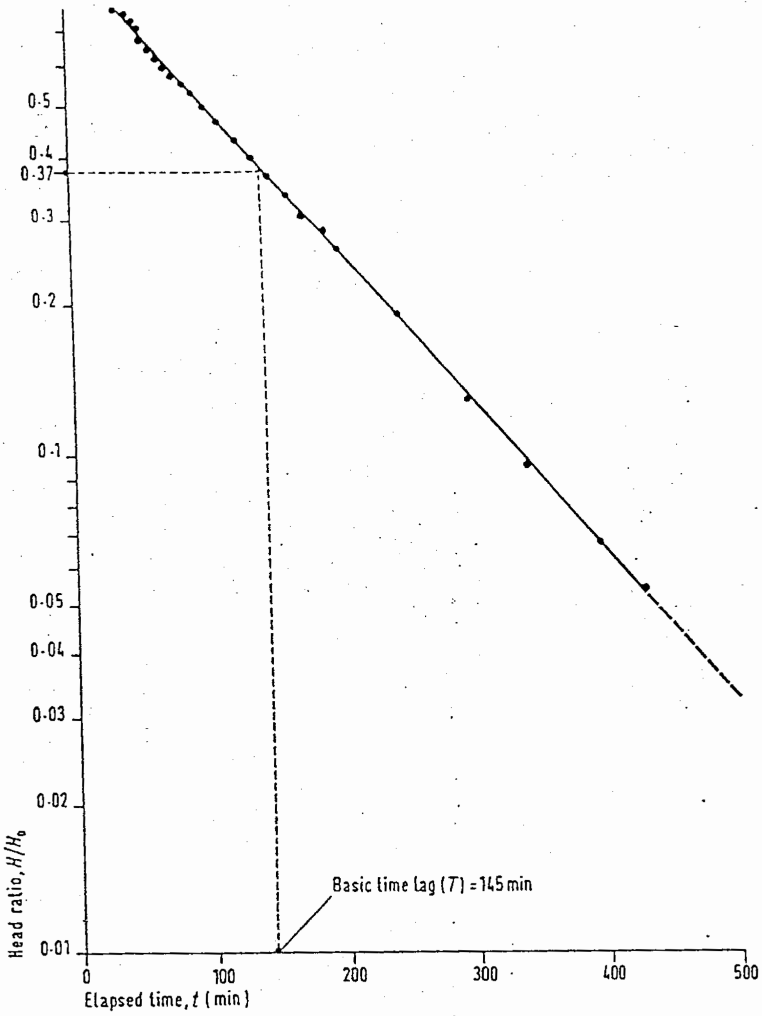
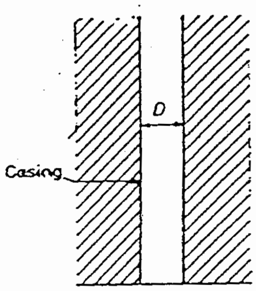


FIG. 15 CHART FOR SOIL DESCRIPTION AND γ EVALUATION [γ]= t/m³



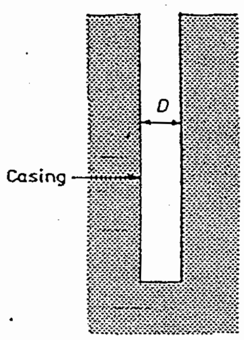


Calculation plot for variable head permeability tests using basic time lag method



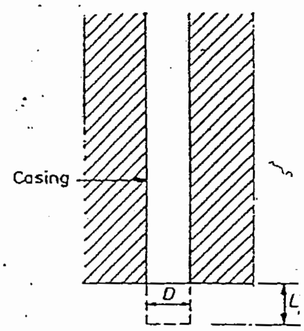
$F = 2D$

(a) Soil flush with bottom at impervious boundary



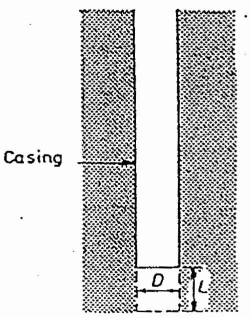
$F = 2.75D$

(b) Soil flush with bottom in uniform soil



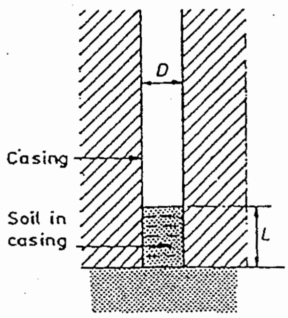
$$F = \frac{2\pi L}{\log_e [(2L/D) + \sqrt{(1 + ((2L)^2/D))}]}$$

(c) Well point or hole extended at impervious boundary



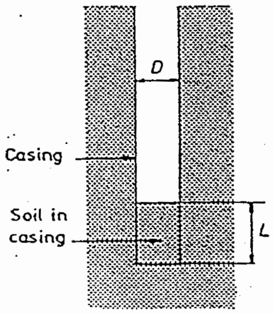
$$F = \frac{2\pi L}{\log_e [(L/D) + \sqrt{(1 + (L/D)^2)}]}$$

(d) Well point or hole extended in uniform soil



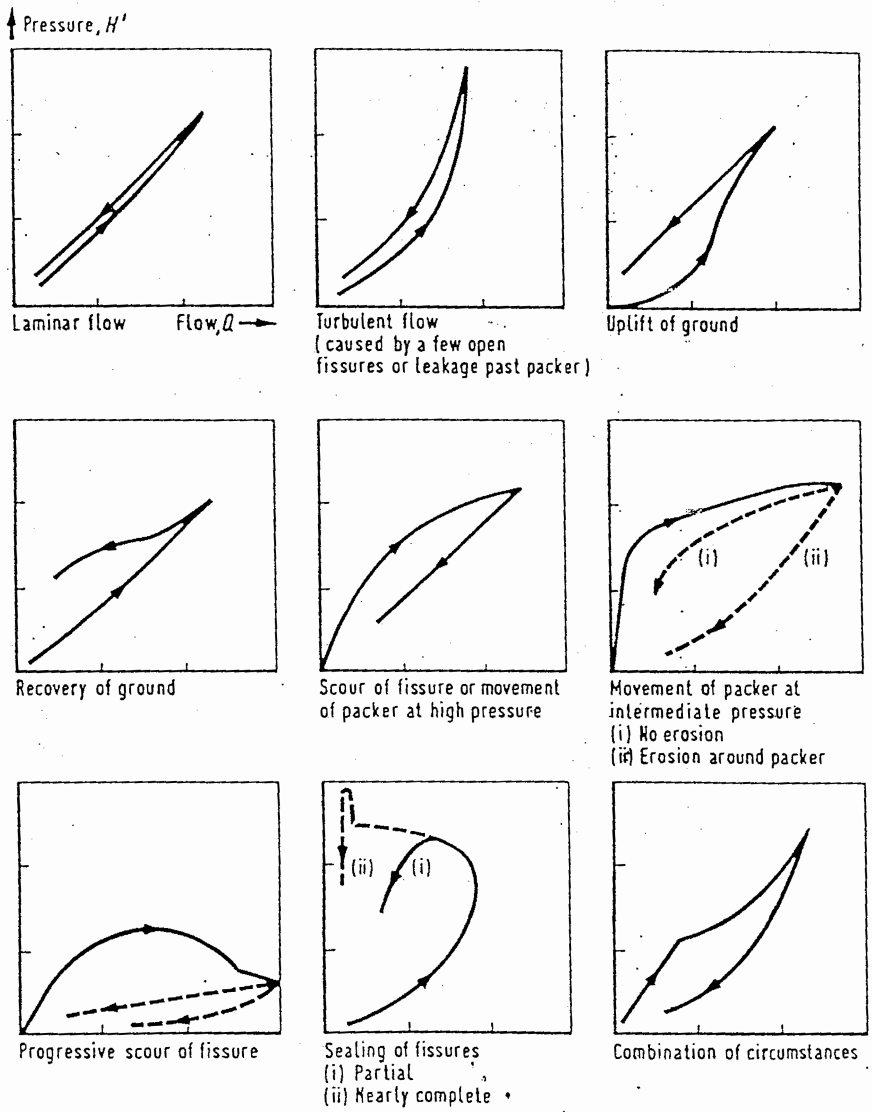
$$F = \frac{2D}{1 + (8/\pi)(L/D)}$$

(e) Soil in casing with bottom at impervious boundary

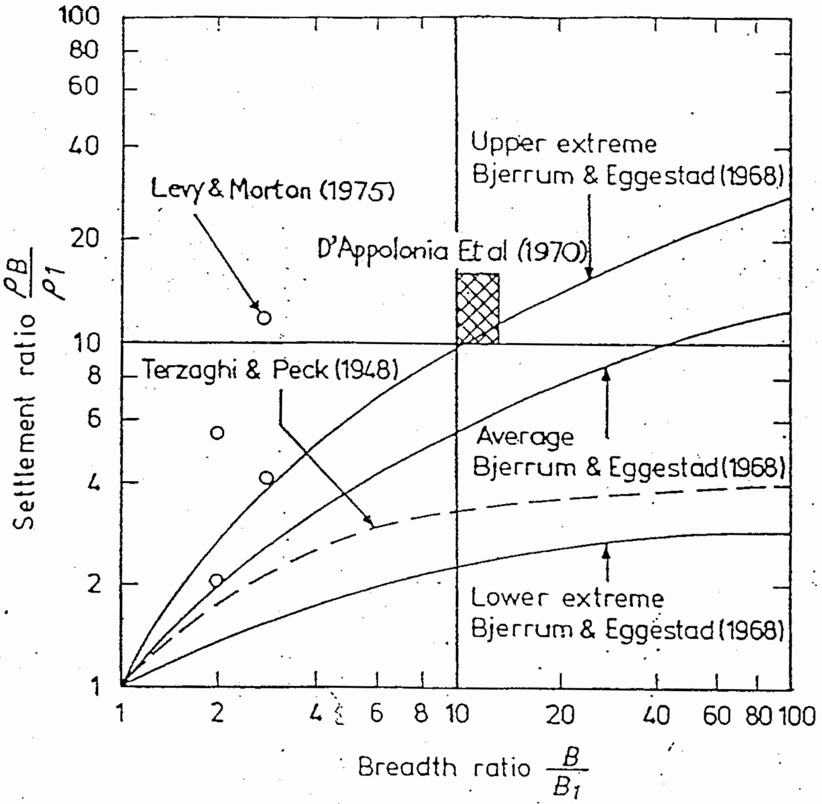


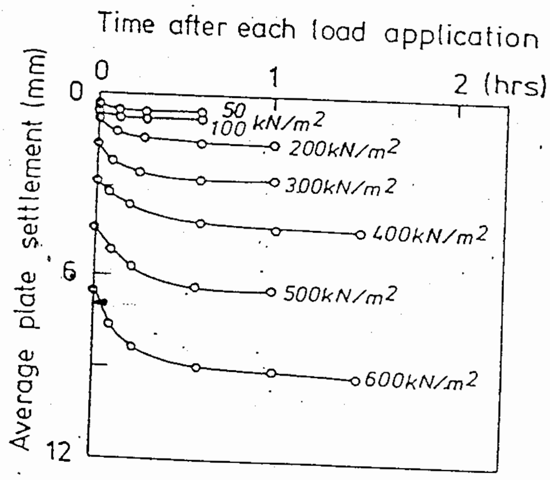
$$F = \frac{2.75D}{1 + (11/\pi)(L/D)}$$

(f) Soil in casing with bottom in uniform soil

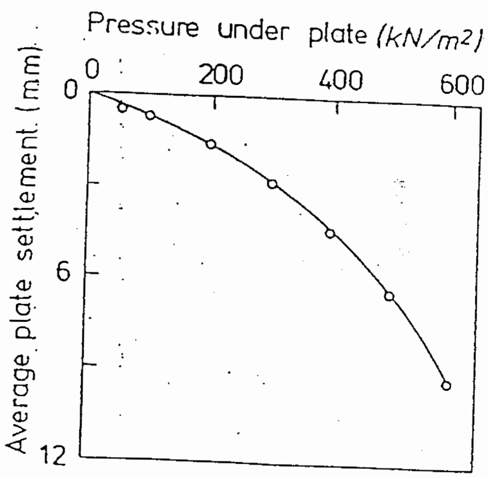


Typical plots for water injection test results (after Muir-Wood and Caste[19])





(b) Time settlement records



(c) Load settlement curve