GEOTECHNICAL INVESTIGATIONS

GUIDELINES

VERSION 1.3

UNOPS Geotechnical Investigations

Version 1.3 - 2019

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Acknowledgments

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The UNOPS Geotechnical Investigations Guidelines is a product of collective hard work and dedication. The following people were part of the project team that developed Version 1.3 of this publication:

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Revisions

The following changes are incorporated in Version 1.3

• In section 1.2, under the list of basic concepts designers and contractors need to understand soil as an engineering material, added point 5 - "Location of the Water table".

• In section 3.2, the title of Table 3 is amended and descriptions of major divisions under Fine-grained soils 50% or more passing the No.200 (0.074 mm) sieve has been amended.

• In section 4.5.2.3, the following item is added, "Any protection to adjacent building and infrastructures, if there is risk of damage due to the future works on the site".

in the list of Typical main recommendations.

• In section 5.1.3, under the list of Advantages the following item is added, "Allow to assess the location of the water table".

• In section 5.4.1 under the list for sample labels, the following item is added, "The top and the bottom of the sample should be well indicated on the case of the sample".

• In section 6, added, section 6.7: Other Geotechnical Problems.

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List of Abbreviations

CPT	Cone Penetrometer Test
SPT	Standard Penetration Test
DCP	Dynamic Cone Penetrometer
USCS	Unified Soil Classification System
CBR	California Bearing Ratio
BS	British Standards
ASTM	American Society for Testing Materials
AGS	Association of Geotechnical and Geoenvironmental Specialists
FHWA	Federal Highway Administration
ISMF	Implementation Standards Management Framework

List of SI units

m/s	Meters per second
m	Meter
mm	millimiter
ft	feet
kpa	Kilo Pascal
m^2	meter square
kg	kilogram
g	gram
"	inch

How to use this guidance

This publication forms a part of the UNOPS Infrastructure and Project Management Group (IPMG) Implementation Standards Management Framework (ISMF) and should not be applied in isolation, but with consideration for related normative and informative publications within ISMF.

As with each publication that forms part of the IPMG Implementation Standards Management Framework, this publication considers the particular needs of the user. The design facilitates its usage, readability and navigation.

TARGET AUDIENCE

The target audience for this publication are project managers, construction supervisors and others who are managing infrastructure asset projects as it would provide useful guidance that will help in informing their projects. The guidance will provide a basic understanding on how to set up a geotechnical investigation and what should be expected to result from geotechnical investigation.

1. Introduction

This document is intended to be used as guidance for geotechnical investigation carried out during planning and construction of Infrastructure asset.

Its purpose is to highlight the importance of soil investigations for infrastructure engineering, provide background to geological and geotechnical concepts, describe soil types and problem soils, give insight into the laboratory and in situ testing and discuss the reporting of investigations. This publication will encompass all the necessary steps to follow when carrying out a soil investigation and provides context of what to expect whilst undertaking the investigation.

This publication only covers the basic aspects of a soil investigation. For more complex aspects, expert advice should be sought.

Site investigation is recommended to be carried out during the initial stages of the project lifespan. Site investigation involves a sequence of activities/steps of increasing complexity starting with preparatory phase and continuing through to analysis and interpretive phases.

KEY MESSAGE

A well-planned and executed site and soil investigation will lead to cost savings during the construction stages by optimizing designs, and predicting and planning for potential problems

1.1 Soil in infrastructure engineering

Most physical infrastructure structures and facilities are built on and supported by the natural ground and are often constructed from locally sourced natural materials.

From an infrastructure engineering perspective, soil can

- Form the platform to support foundations of physical infrastructure such as buildings and bridges;
- Be a medium in which structures such as tunnels, culverts and basements are built;
- Be used as a construction material to build facilities such as buildings, roads, runways, embankments and dams.

In order to design the facilities and structures, design and construction engineers must obtain detailed knowledge about the type, properties and behaviour of the soils in situ and within the vicinity of the site.

It is well documented that one of the largest risks to infrastructure projects is the uncertainty in soil and ground conditions, which can lead to either inadequate (and unsafe) or over-conservative designs (unnecessarily expensive), which in turn can lead to unforeseen construction delays and costs. This is not a sustainable use of resources.

1.2 Soil investigation in project lifespan

Soil investigation informs many stages of infrastructure project lifespan such as feasibility, planning, design, construction, operation and maintenance as represented in **Figure 1: Project lifespan and investigation phases (p. 11)**.

Soil investigation has the following impacts during the various stages of the development of infrastructure asset:

- **Feasibility Stage:** The regional/local geology, topography, hydrology and seismology informs the technical feasibility and also has an impact when determining the sustainability of the project
- **Design Development Stages:** The geotechnical properties of the soil and rock is determined to inform the design and constructability of the infrastructure asset.
- **Construction Stages:** Soil investigation information is used in the planning of construction activities; for quality control purposes; and to manage design modifications due to differing or unforeseen site conditions.
- **Operation and Maintenance Stage:** The properties of the soil, both in situ and in construction materials, are used to determine the serviceability parameters of the infrastructure, as well as the maintenance regime required to ensure optimal use of resources during the life of the asset.

Soil and ground properties in the stages of the project, listed above, are determined by conducting soil investigations that typically involve field observations, field-testing, sampling and laboratory testing. Soils may be described differently across the diverse fields of engineering based on the purpose of the soil. Engineers' descriptions give engineering terms that will convey some sense of a soil's current state and probable susceptibility to future changes, such as in loading, drainage, structure and surface level. The classification and description of soils is considered in section **3. Soil types (p. 19)** of this document.

After the field observations, sampling and testing during the investigation, the results are documented in a report, the Soils Investigation Report, which will contain both factual data collected and interpretive data. For purposes of this guidance, the term Geotechnical Report will be used as a general term to cover all types of reporting relating to the soils investigation. Further discussions on reporting are covered in **Figure 1: Project lifespan and investigation phases (p. 11)**, which provides a high-level summary of the overall picture of a project's life cycle with its relevant stages of soil investigation. More detail can also be found in section **1.3 Geotechnical reports (p. 12)** and section **4. Site investigation (p. 21).**

Experience and professional judgement is required to interpret the results of the investigation and to predict the behaviour of the soils. To understand soil as an engineering material, designers and contractors need to acknowledge five basic concepts:

1. Soil in nature is a heterogeneous (varied or not uniform) and anisotropic (properties differ in direction) material.
2. Soils are composed of particulate material and its engineering properties are influenced by the particle size, shape, composition, moisture content, density and structure (bedding, stratification, joints or fissures, voids).
3. The in situ properties of soils are affected by the layers of the soil and rock strata, lying above and below, and its history of loading and unloading, and state of consolidation.
4. Sampling of soils generally leads to some level of disturbance of the natural in situ state and hence can lead to very different results that can be measured between in situ and laboratory tests.
5. Location of the Water Table

Conducting the appropriate soil investigation required at the particular stage of the project helps to understand the soil properties and will allow an accurate Report to be compiled.
Figure 1: Project lifespan and investigation phases (p. 11) provides a high-level summary of the overall picture of a project's life cycle with its relevant stages of soil investigation.

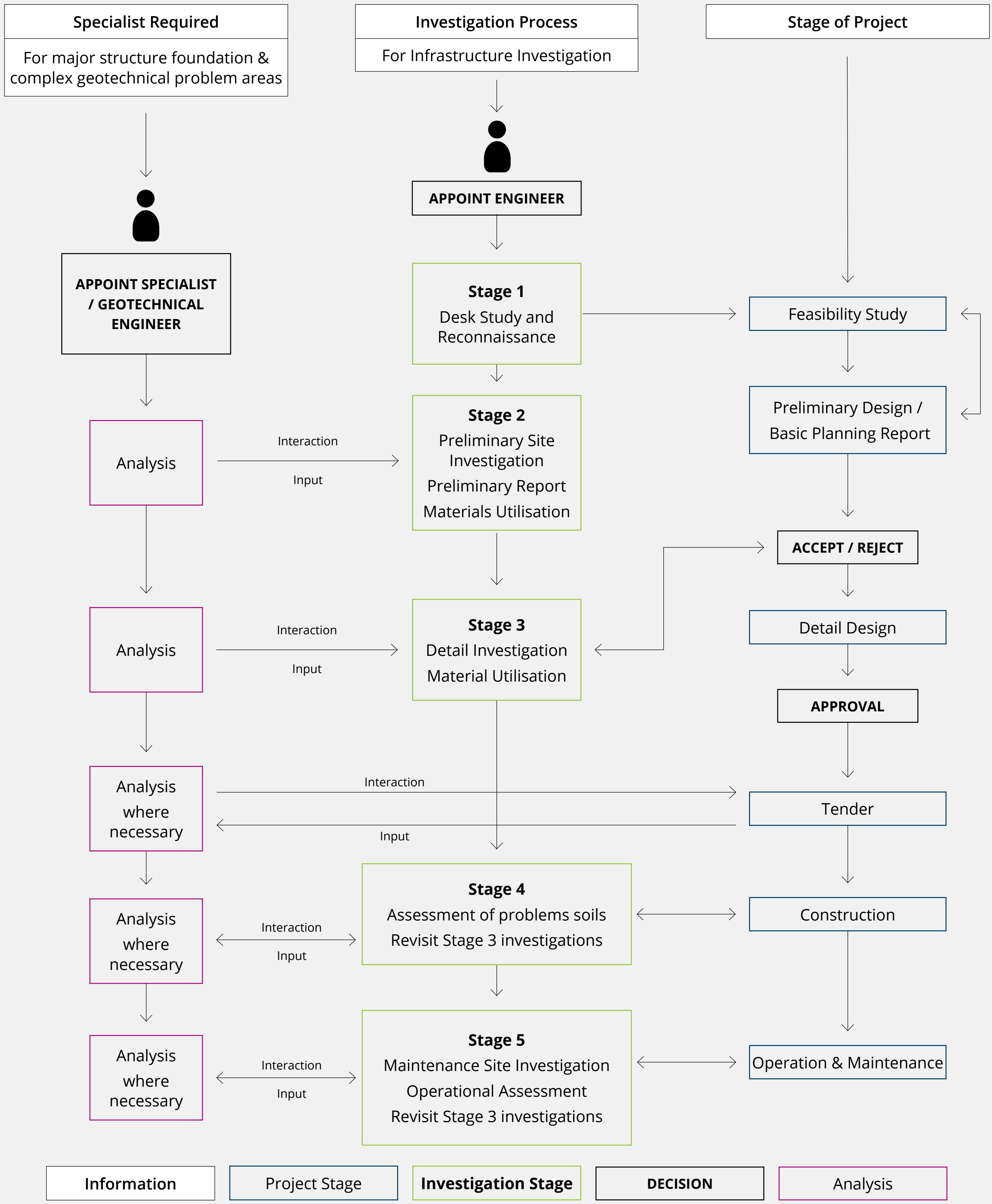


Figure 1: Project lifespan and investigation phases

1.3 Geotechnical reports

Geotechnical Reports are typically prepared by a geotechnical engineer or specialist in the field and informs the design as well as construction planning (construction methods/construction sequence), operation and maintenance of the asset.

The designer or Contractor's interpretation of the information directly influences the construction methods and construction sequence of the infrastructure, which is often vital to the success of the project. If the geotechnical report is ambiguous or fails to identify the ground conditions, the result is often a changed condition claim by the Contractor. These construction claims can entail lengthy delays, increased cost, disputes and lawsuits. The information contained in this guidance is often referred to during the design period, construction period, and frequently after completion of the project (for evaluating contractual dispute claims or during infrastructure maintenance). Therefore, the report should be clear, concise, and accurate.

It is common to find unexpected soil changes or underground obstructions, which are not addressed in the soil investigation and geotechnical report, and are only discovered during construction stage. This can lead to expensive and time-consuming delays which affects both the contractor and client, and which can compromise the safety of the infrastructure.

The primary interest in the geotechnical report are the soil's mechanical properties- strength, stiffness and permeability. These depend primarily on the nature of the soil, the current stress, the water content and unit weight.

Generally, the design engineer needs to know several critical soil properties and associated information such as (Washington, n.d.):

- What is the allowable soil bearing pressure?
- What is the expected settlement potential and potential for differential settlement?
- What is the active soil and passive soil loading?
- What is the angle of internal friction/cohesion and shear strength?
- Where is the groundwater table and its evolution?
- Will piling foundations be required, and the size depth, possible negative skin friction and the pile group effects on bearing capacity?
- Will there be voids (Karst), obstructions or unstable soils?
- The risk of soil liquefaction under seismic loads/Dynamic loads.
- Can the in situ soil be used for backfill or other construction material?
- Are hazardous wastes or corrosive chemicals present?
- Are contaminated soils (man-made or natural occurrence) present?
- Do any seepage problems exist? What soil improvements are possible?

From the view of the contractor, the Geotechnical Report will be used to determine the soil conditions to accurately estimate the costs and time for a competitive bid. The contractor will generally look for the following information in the report (Washington, n.d.):

- Where is the ground water and is there a requirement for dewatering?
- Is there rock drilling required or blasting?
- Can the ground be ripped with a bulldozer or excavator? What excavation equipment and methods will be most effective?
- Is there enough space on the project site to store backfill materials?
- Can the in situ material be used for backfill or other construction materials?
- Will the in situ material need to be processed (screened/crushed/modified/stabilised)?

- How much material must be procured and imported?
- How steep can the excavation slopes be cut?
- Will obstructions be expected?
- What compactive effort and equipment is needed?
- Will excavation shoring or stabilisation be required?

2. Basic geological concepts

Geological sciences may appear to be of lessor importance to a contractor involved in the practical details of constructing an infrastructure asset.

However, a basic knowledge of geology allows engineers and contractors to evaluate rock and soil bearing capacity, slope stability, rock excavation methods and equipment, as well as geological hazards such as sinkholes, Karst, seismic activity, landslides, among others.

Since soils are formed as a result of geological processes and events, the properties and behaviour of a soil depends on the geological history resulting in its formation. It is therefore an important consideration when investigating soils to be aware of the geological events and history leading to the formation of a particular soil type. (Pelger, n.d.)

2.1 Formation of rocks and soils

Elementary earth sciences have shown that rock is classified as either igneous, sedimentary, or metamorphic, and the formation of rocks and soils generally follow a natural cycle as indicated in **Figure 2: The rock cycle (p. 16)**

Soils are formed and conditioned by the following geological, climatic and environmental processes, which determines its properties:

- Breakdown of parent rock by weathering, decomposition and erosion;
- Transportation to site of final deposition by gravity, water, ice, wind;
- Final deposition environment such as flood plain, river terrace, glacial moraine, lacustrine or marine; and
- Subsequent history of loading and drainage conditions - surcharge due to ice or overlying deposits, change from saline to freshwater, leaching, contamination.

2.1.1 Igneous rocks

Igneous rocks are formed by the cooling of the molten magma found deep beneath the surface of the earth. There are two types of igneous rocks namely Intrusive and Extrusive. Intrusive igneous rock consists of molten magma that remains far beneath the earth's surface, cools slowly and consequently contains large crystals (such as granite). Extrusive igneous rock erupts at the earth's surface, as a lava flow, for example, and cools rapidly into small crystals (such as pumice).

2.1.2 Sedimentary rocks

The second class of rocks, sedimentary, is the consolidated and cemented product of the disintegration and decomposition by weathering of igneous, other sedimentary or metamorphic rocks. Mechanical cementation or chemical precipitation at the earth's surface produces the actual sedimentary rock, for example; sandstone is a cemented material, sand, formed into rock.

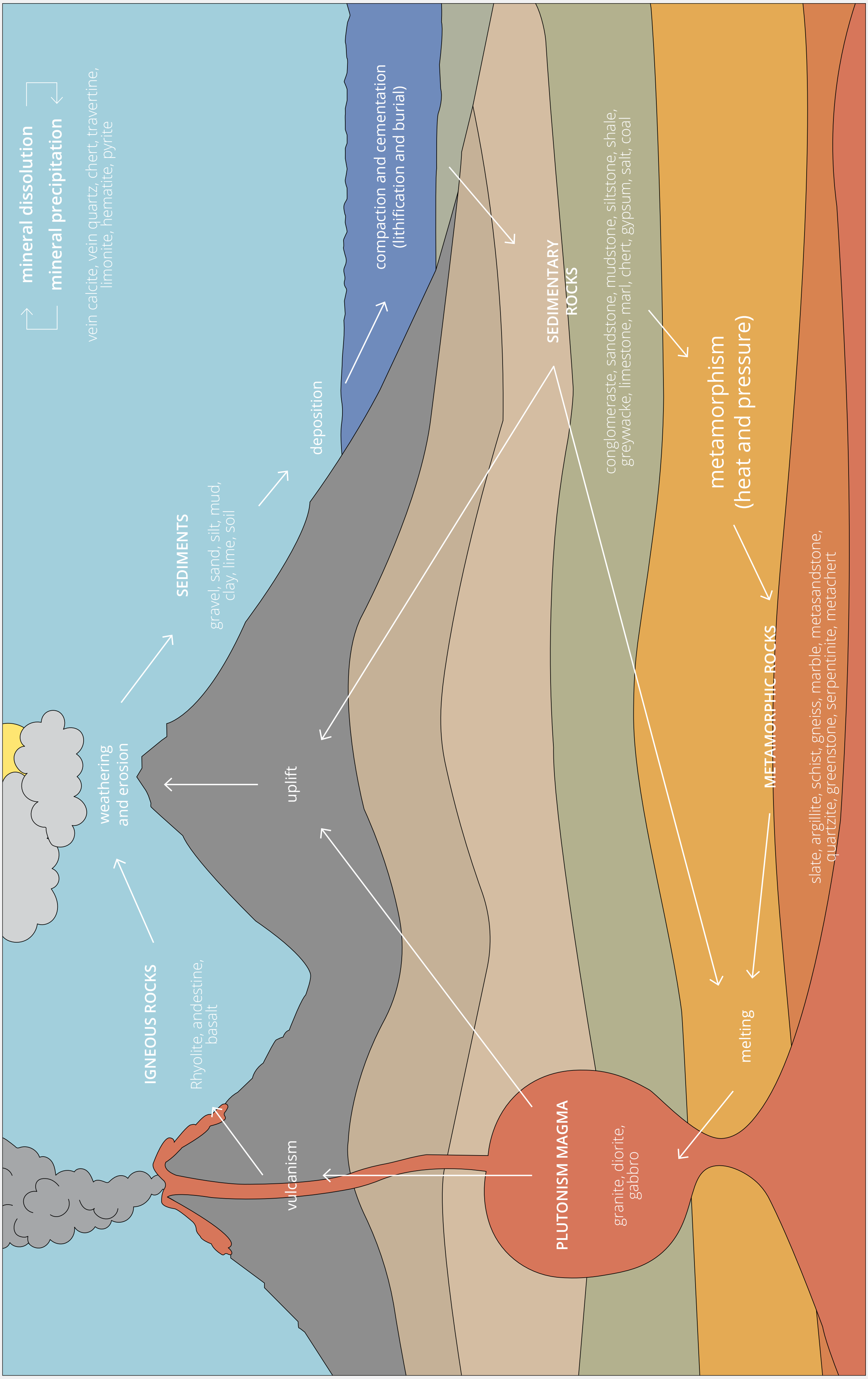


Figure 2: The rock cycle

Small-decomposed rock particles, such as sand, are commonly transported by the wind or by water. As these particles land, or settle to the bottom, they form a horizontal layer. Mechanical or chemical cementation then forms this layer of sand into rock. This rock would be considered to have a horizontal bedding. It is common, however, to see layers of sedimentary rocks, such as limestone, to be vertical or inclined rather than horizontal. The limestone was formed with horizontal bedding, but as the crust of the earth moves and deforms (over millions of years) the rock layers may be tilted, folded or faulted.

Sedimentary rocks are divided into two categories namely clastic and non-clastic. Clastic rocks are sedimentary rocks formed from the sediment of eroded parts of other rocks. Non-clastic rocks are typically carbonate rocks formed from chemical precipitates out of solution.

2.1.3 Metamorphic rocks

The third class of rocks, metamorphic rocks, are formed from existing igneous, sedimentary or other metamorphic rocks by heat and pressure below the earth's surface. The forming of igneous and metamorphic rock may reverse itself. For example, limestone, a sedimentary rock, can be changed to marble, a metamorphic rock, by heat and pressure below the earth's surface.

In summary, igneous rocks are formed from molten magma found deep beneath the earth; sedimentary rocks cement small-decomposed rock particles together; and heat and pressure below the earth's surface changes other rocks into metamorphic rock.

Table 1: Rock classification (p. 17) shows the commonly occurring rock types and **Table 2: Recommended usage of common rock types (p. 18)** shows the physical characteristics of common rock types and their recommended usage.

IGNEOUS	Granite, Gabbro-Diorite, Basalt, Felsite, Obsidian, Pumice, Scoria
METAMORPHIC	Gneiss, Schist, Slate, Marble
SEDIMENTARY: CLASTIC	Shale (Claystone), Siltstone, Sandstone, Conglomerate, Limestone, Glauconite, Lignite, Tuff
SEDIMENTARY: NON-CLASTIC	Chert, Iron Deposits, Gypsum, Halite

Table 1: Rock classification

	ROCK TYPE	TOUGHNESS	HARDNESS	DURABILITY	CHEMICAL STABILITY	CRUSHED SHAPE	SURFACE CHARACTER	DENSITY (G/CM)	USE AS AGGREGATE		USE AS BASE COURSE OR SUBBASE
									CONCRETE	ASPHALT	
IGNEOUS	Granite	Good-Very Good	Good	Good	Excellent	Excellent	Good	2.65	Fair-Good	Fair-Good**	Good
IGNEOUS	Gabbro-Diorite	Excellent	Excellent	Excellent	Excellent	Good	Good	2.96	Excellent	Excellent	Excellent
IGNEOUS	Basalt	Excellent	Excellent	Excellent	Excellent	Fair-Good	Good	2.86	Excellent	Excellent	Excellent
IGNEOUS	Felsite	Good	Good	Good	Questionable	Fair-Good	Fair-Good	2.66	Poor*	Fair	Fair-Good
IGNEOUS	Obsidian	Poor	Good	Good	Questionable	Very Poor	Very Poor	2.3-2.4			
IGNEOUS	Pumice	Very Poor	Very Poor	Poor	Questionable	Good	Poor	<1.0			
IGNEOUS	Scoria	Poor	Poor	Poor	Good	Good	Poor	Variable			
SEDIMENTARY	Tuff	Poor	Poor	Poor	Questionable	Good	Good	Variable			
SEDIMENTARY	Conglomerate	Poor-Fair	Poor-Fair	Poor-Fair	Good	Fair	Good	2.68	Poor	Poor	Poor
SEDIMENTARY	Sandstone	Variable	Variable	Variable	Excellent	Good	Excellent	2.54	Poor-Fair	Poor-Fair	Fair-Good
SEDIMENTARY	Shale	Poor	Poor	Poor	Questionable	Poor	Good	1.8-2.5	Poor	Poor	Poor
SEDIMENTARY	Limestone	Good	Fair-Good	Good	Good	Good	Good	2.66-2.7	Fair-Good	Good	Good
SEDIMENTARY	Dolomite	Good	Fair-Good	Good	Good	Good	Good	2.66-2.7	Good		
SEDIMENTARY	Chert	Poor	Excellent	Variable	Questionable	Poor-Fair	Fair	2.5	Poor*	Poor**	Poor-Fair
METAMORPHIC	Gniess	Good	Good	Good	Excellent	Good-Fair	Good	2.74	Good	Good	Good
METAMORPHIC	Schist	Good	Good	Good	Excellent	Poor-Fair	Poor-Fair	2.85	Poor-Fair	Poor-Fair	Poor-Fair
METAMORPHIC	Slate	Poor	Poor	Poor	Excellent	Poor	Good	2.72	Poor	Poor	Poor
METAMORPHIC	Quartzite	Excellent	Excellent	Excellent	Excellent	Fair	Good-Fair	2.69	Good	Fair-Good**	Fair-Good
METAMORPHIC	Marble	Good	Poor	Good	Good	Excellent	Excellent	2.63	Fair	Fair	Fair

*Reacts (Alkali aggregate).
**Anti-stripping agents should be used.

Table 2: Recommended usage of common rock types

(Military Soils Engineering, Field Manual 5-410, 23 December 1992)

3. Soil types

Soils and gravels are formed from the weathering, erosion and disintegration of rock material through natural processes.

The weathering process, transportation and depositing of the soils, determines the physical properties of the soil (grain size, shape and size distribution) and the state and structure of the soil (density, moisture content, bedding and voids). Soils are identified and characterised by these physical properties, which are discussed in more detail below.

3.1 Visual identification of soil types

The first step in identifying soils and gravels is to make a visual determination regarding which of the broad categories the soil belongs to. The definitions for these broad categories are as per **Table 3: Broad definition of soil (p. 19).**

SOIL CONSTITUENT	APPROXIMATE SIZE AND DESCRIPTION
Boulder	> 250mm
Cobble	75 – 250 mm
Coarse Gravel	25 – 75 mm
Medium Gravel	9.5 – 25 mm
Fine Gravel	2 - 9.5 mm
Coarse Sand	0.42 – 2 mm
Fine Sand	0.075 - 0.72 mm
Silt	Soil that will pass through a 0.075 mm (sieve #200) opening that is non-plastic or very slightly plastic and exhibits little or no strength when air-dried.
Clay	Soil that will pass through a 0.075 mm (sieve #200) opening that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and exhibits considerable strength when air-dried.
Organic Soil	Soil that contains enough organic particles to influence the soil properties.
Peat	Soil that is composed primarily of vegetable tissue in various stages of decomposition usually with an organic odour, a dark brown to black colour, a spongy consistency, and a texture ranging from fibrous to amorphous.

Table 3: Broad definition of soil

3.2 Classification of soil types

For engineering purposes, soil classification is based on the distribution and behaviour of the fine-grained and coarse-grained soil fractions, in accordance to the Unified Soils Classification System (USCS). **Table 4: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) - ASTM D2487 - 17 (p. 20)** summarises the USCS classification.

	MAJOR DIVISIONS		GROUP SYMBOL	GROUP NAME
Coarse grained soils more than 50% retained on or above No.200 (0.074 mm) sieve	gravel: > 50% of coarse fraction retained on No.4 (4.75 mm) sieve	clean gravel <5% smaller than No.200 Sieve	GW	well-graded gravel, fine to coarse gravel
			GP	poorly graded gravel
		gravel with >12% fines	GM	silty gravel
			GC	clayey gravel
	sand: ≥ 50% of coarse fraction passes No.4 (4.75 mm) sieve	clean sand	SW	well-graded sand, fine to coarse sand
			SP	poorly graded sand
		sand with >12% fines	SM	silty sand
			SC	clayey sand
Fine grained soils 50% or more passing the No.200 (0.074 mm) sieve	silt and clay liquid limit ≤ 50	inorganic	ML	silt
			CL	clay of low plasticity, lean clay
		organic	OL	organic silt, organic clay
	silt and clay liquid limit > 50	inorganic	MH	silt of high plasticity, elastic silt
			CH	clay of high plasticity, fat clay
		organic	OH	organic clay, organic silt
Highly organic soils			Pt	peat

Table 4: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) - ASTM D2487 - 17

4. Site investigation

Site investigation is an activity throughout the infrastructure asset project lifespan

Field explorations and laboratory investigations are undertaken to collect, analyse, and report on information about the soil and ground conditions during site investigations. The design of all infrastructure asset requires an accurate understanding of the structure and properties of the natural ground materials on the proposed construction site.

MORE INFORMATION

AGS Guidelines for Good Practice in Site Investigation, Issue 2, March 2006

From Feasibility, Design Development, Construction, Operation and Maintenance stages, site investigations are designed to provide the level of information appropriate to the particular stage. Typically, initial site investigations will be general and will cover broader geographic areas. As the project development continues, geotechnical investigations become more detailed and cover smaller but more project specific areas.

Regardless of the type of project, the objectives of the site investigation are to:

- Establish the stratigraphy and the engineering properties of the soils and bedrock formations that will be affected by or will have an effect on the infrastructure; and
- Locate and determine the quality and approximate quantity of construction materials within an economical haul distance from the construction site.

There are minimum requirements for site investigations to be performed as part of the project stages. **Figure 3: Site investigation process (p. 21)** is a flowchart that summarises the process that is generally adopted for Site Investigations. It can be seen from the flowchart that the site investigation process involves a sequence of activities of increasing complexity, beginning with a preparatory phase and continuing through to analysis and interpretive phases. These phases are discussed in following section.

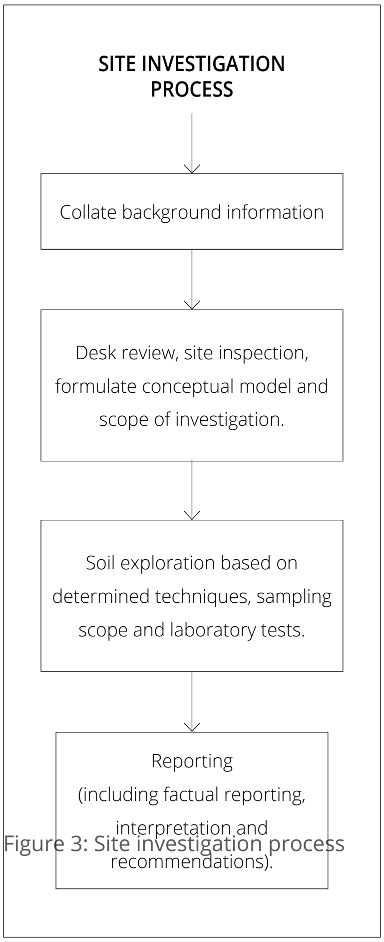


Figure 3: Site investigation process

4.1 Collate background information

As part of an initial assessment of a project, the first step is to form an understanding of the geology of the region where the site is located. Typically, this will entail the study of published geological maps of the area. These are generally available from local and international governmental agencies or university geology departments. Wherever possible Geological maps should be consulted prior to in situ investigation programme. For large-scale projects, it is possible to undertake remote sensing and geophysical studies to estimate the geology, which must be calibrated later with field investigation data.

Geological maps typically contain information mapped by lines, symbols, patterns and colours showing:

- Contours, topography and water bodies, rivers and streams; and
- Geological features such a rock types, formations, bedrock depth and geological age.

Knowledge of the regional and site specific geology is essential to preliminary planning and selection of sites and to interpretation of soil investigation data. A study of the geological data is used to estimate the following:

- Identify what rock and soil types are within the project area, and to estimate their age, characteristics and properties (particularly quality of material);
- Use estimated soil characteristics, properties and potential project geometry to identify possible geotechnical concerns, such as faults, sinkholes and potential seismic activity;
- Identify problematic soils, which are discussed in **Section 6. Geotechnical problems and solutions (p. 51)** and
- Identify potential construction material sources.

4.2 Site inspection and reconnaissance

The purpose of the site inspection is to evaluate the overall nature of the site and adjacent areas and to estimate the type of soils and rock occurring on site. It is preferable for the design engineer to visit the project site and complete the site inspection. It is advisable to carry out reconnaissance visit with the Clients Representative. The site inspection and assessment facilitates to define the scope of the investigation, planning of the extent of the site investigation programme and adjust the investigation approach to the site conditions and the proposed infrastructure asset.

The site inspection will include the following investigations:

- Identify relevant topographic features;
- Investigate existing open excavations and cuttings to evaluate soil profiles;
- Investigate existing structures (structural condition, foundations, settlement);
- Identify surface drainage patterns and groundwater conditions;
- Identify vegetation type and patterns;
- Identification of existing service utilities, such as sewer, water, electricity and communication lines;
- Identify potential construction material sources;
- Identify hazardous materials;
- Interact with local people and contractors to gain a history of the area;
- Learn local construction methods; and
- Learn local design standards and material applications.

An optimum site inspection will consist of a combination of as many of the above investigations as possible

KEY MESSAGE

4.1 and 4.2 are usually carried out (in technical terms) at the inception stage of geotechnical investigation as a part of design development. The information / data gathered is included in the inception report to inform the detailed planning and preferred approach.

4.3 Site investigation

This stage consists of undertaking a soil exploration at the site, by borings and excavations, in situ testing and visual inspection of the excavations, recovery of soil and rock samples from various depths of the excavations, and laboratory testing. There are various methods of soil exploration with varying complexity and cost, obtaining varying results. The method of soil exploration used is project specific and is dependent on budget, type of infrastructure, type of loading and the nature of in situ material.

No rigid rule exists for determining the scope of the site investigation; **Table 5 (p. 35), Table 6 (p. 37)** and **Table 7 (p. 38)** provide an indicative recommendation on the type, size and depths of borings, excavations to be made and samples to be collected. The uniformity or variability of the ground conditions at the project site will largely influence the complexity of the problems affecting the design and construction of the project. The site investigation must therefore be of sufficient extent to provide enough information to the design engineer to develop a sound understanding of the interaction of the structure with the supporting soil or rock. This understanding is critical for a safe and economical design to be undertaken. Laboratory testing is an important part of any soil investigation and it is important that the laboratory testing be conducted according to a standard.

None of the existing investigation techniques fits to study all possible geotechnical issues. The optimum solution relies on the combination of different techniques.

4.4 Supplementary investigation and construction control

A supplementary investigation should be conducted to analyse external factors that may influence the design, construction and operation of the infrastructure. The following supplementary investigation is made to give a full picture of the site investigation of soil as well as the structure.

- Any special feature such as the possibility of earthquakes or climatic factors like flooding, seasonal swelling and shrinkage, permafrost, or soil erosion;
- The availability and quality of local constructional materials such as concrete aggregates, building and road stone, and water for constructional purposes;
- For maritime or river structures information on normal spring and neap tide ranges, extreme high and low tidal ranges and river levels, seasonal river levels and discharges, velocity of the tidal and river currents and other hydro-graphic and meteorological data;
- Results of laboratory tests on soil and rock samples appropriate to the particular foundation design or construction problems;
- Results of chemical analysis on soil, fill materials, and ground water to determine possible deleterious effects on foundation structures; and
- Results of chemical and bacteriological analysis on contaminated soils, fill materials and emissions to determine health hazard risks.

By conducting supplementary investigations, one can eliminate many risks not highlighted in the soil investigation. This can reduce unexpected costs and assist in optimizing designs and construction methods and phasing.

4.5 Reporting

While the soil report content and format will vary by project type, size and client, there is essential information that should be included in all soil reports:

- Summary of all subsurface exploration data, including subsurface soil profile, exploration logs, laboratory or in situ test results, and ground water information;
- Interpretation and analysis of the subsurface data;
- Specific engineering recommendations for the foundation design;
- Discussion of conditions for solution of anticipated problems; and
- Recommended special geotechnical provisions.

The report should contain the information gained during the site inspection, site investigation, laboratory testing and the materials or geotechnical engineer's recommendations.

The report will contain technical information, which must be presented in an orderly, easily digested manner and written in clear, unambiguous language. Since most of the intended readers are mainly visually orientated, the use of photos, maps, soil profiles, borehole logs and other visual aids is to be recommended, as is the tabulation of test results and other information. The report is not a thesis nor a scientific treatise, but a factual report with comments, opinions and recommendations based on the interpretation of the facts from experience. The facts and opinions must be clearly separated. (Site Investigation Report, n.d.)

4.5.1 Reporting stages

Depending on the stage of the project, the reporting of the soil investigation required will differ and numerous types of reports can be produced through the investigation phase of a projects life. Some of the soil reports, which can be undertaken, are listed below with reference to the stage of the project that are conducted in;

- Desk Study or Initial Assessment Report (Feasibility Project Stage);
- Preliminary Materials Report (Preliminary Design Stage);
- Detailed Assessment and Design Report (Detail Design Stage);
- Materials Investigation and Utilisation Report (Dependent on project and client- recommended during Preliminary or Detail Design Stage);
- Construction Soil Reports (Construction Stage- generally specialist reporting due to problems during construction); and
- Operations or Maintenance Soils Reports (Operation & Maintenance- generally specialist reporting for guidance on maintenance or operation activities and if problems arise).

4.5.2 Sequence of report

Generally, the report should follow the normal sequence of items of engineering reports in having a title, contents list, synopsis, introduction, body of the report, conclusions and recommendations. Lengthy descriptions of tests and similar matters are best dealt with in appendices and the test results tabulated in the body of the report. The client tends to read the synopsis and recommendations; the main and sub-contractors concentrate on the body of the report and the design office on its conclusions and recommendations.

If the report imposed limitations on cost and time allocation for the investigation and the engineer or specialist was not able to carry out an adequate investigation, this should be tactfully pointed out. It should also be made clear in such cases that the engineer or specialist's conclusions and recommendations are qualified – this is necessary in the present construction claims environment.

4.5.2.1. Site description

A small-scale plan showing site location, access and surrounding area is required. The proposed position of the buildings and access roads should be shown as well as all future construction interventions. The site plan should also show the general layout and surface features, note presence of existing buildings, old foundations and previous usage, services, vegetation, surface water, any subsidence or unstable slopes. The interaction of the proposed infrastructure and the overall site conditions should also be summarised.

A written description of the site exposure should be given together with details of ground conditions, previous use of site, present conditions, groundwater, drainage pattern and records of any flooding, erosion and other geographical, hydrographic and climatic information.

Geological maps and sections should, when they are necessary, be provided, noting mines, shafts, quarries, sinkholes and other geological features affecting design and construction.

Photographs taken on the site, preferably colour ones, can be very helpful and should be supplemented by aerial photographs if considered necessary. It is always good to have a reference object to understand the scale of the items photographed, such as a pen or geological pick.

4.5.2.2. The site investigation

The site investigation section of the report should cover three main points;

1. **Background study and location of exploration points**
   This should give a full account of the desktop study, examination of old records, information from local authorities, public utilities and the like, and the field survey. It should detail the position and depth of trial pits and boreholes, equipment used and in situ testing and information.
2. **Boreholes, trial pits and soil profiles**
   This section will be mainly a visual presentation of the logs and profiles together with colour photographs of the trial pits. **Figure 4: Typical test pit profile (p. 27)** and **Figure 5: Typical borehole profile (p. 28)** provide examples of a test pit and borehole profiles. Where possible, written information should be given in note form on the soil profiles and should include the coordinates of the profile in x, y, z format. Where possible the location of the water table should be given.
3. **Soil tests and Results**
   List the site and laboratory tests drawing attention to any unusual, unexpected or special results. The results of the tests should be tabulated, for ease of reference, and diagrams of such information as particle size distribution, pressure–void ratio curves and Mohr's circles should be given. If such form of presentation is not fully adequate, then test descriptions and results should be given in the appendix.

The tests must give adequate information to determine the soil's bearing capacity, settlement characteristics, behaviour during and after foundation construction and, where necessary, its chemical make-up and condition.

4.5.2.3. Recommendations

This includes both comment on facts and opinions based on experience; the difference should be made clear. Since the recommendations are a major part of the report, it should be broken down into sections for ease of reference and readability. The first section should briefly describe the proposed main and subsidiary structures and their loading, a description and assessment of the ground conditions and the types of appropriate foundations. The second section should advise on foundation depths, allowable bearing capacity, settlements, discuss alternatives giving advantages, disadvantages and possible problems keeping in mind cost and constructability considerations.

Typical main recommendations are:

- Allowable bearing capacities at various depths, estimates of total and differential settlement and time-span of settlement;
- Problems of excavation (fills, rock, water ingress, toxic and combustible material);
- Chemical attack on concrete and steel by sulphates and chlorides or acids within soil;
- Any protection to adjacent building and infrastructures, if there is risk of damage due to the future works on the site.
- Flotation effect on buoyant or submerged foundations;

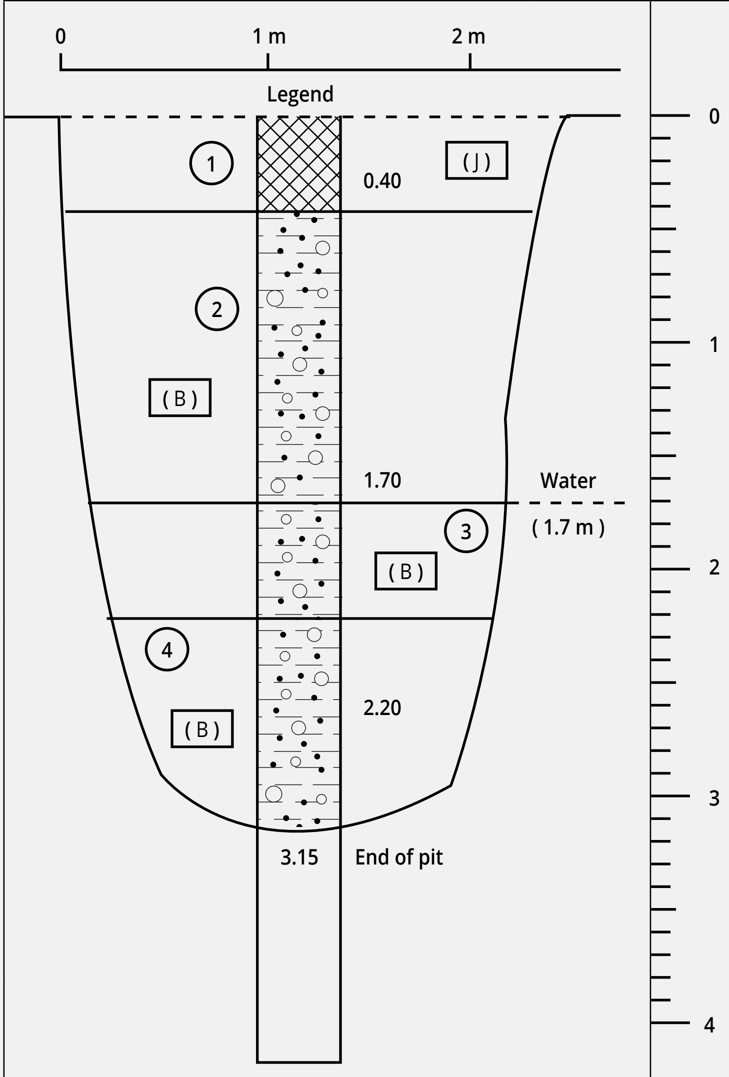
- Where the proposed structure will contain machinery and equipment which could vibrate or impact shock the soil, the effect on the soil must be assessed;
- Details of any necessary geotechnical processes to improve the soil's properties.
- Where piling is necessary, information must be given on founding level, possible negative skin friction, the piling group effect on the ultimate bearing capacity of obstructions, appropriate type and installation of piles and the effects of piling on adjacent constructions and existing buildings;
- Where a foundation is subject to lateral loading, the magnitude and position of the loading must be given together with the skin friction between the soil and the passive resistance of the soil;
- Where retaining walls are required, information is needed on active pressure, passive resistance, surcharge, factor of safety against slip circle failure, possible landslides or slips; and
- Where road construction is involved requiring CBR values.
- Others

The final section should give recommendations in the light of the results of the geotechnical investigation. The soil investigation gives recommendations on excavations, the type of foundation, and the allowable bearing capacity to use at the required depth. It also explains what other measures and precautions should be taken in laying of foundations, drainage and sewerage systems, for example; suggestions are shared on how to comply with the results of the tests in construction activities. In the end, the scope of the whole process and limitations of the results are also added here.

4.5.2.4. Appendices with graphs and detailed results

This is the section where all detailed results obtained are graphed and shared with the client. These graphs may include grain size distribution curve, results of the liquid limit, plasticity chart, borehole log, field tests (geophysics, SPT, DCP, CPT or any other) results for all types of soils encountered at the required depth at the site.

TRIAL PIT LOG	Job no.	Job name ....
Date	Co-ordinates	....
Weather	Logged by	....



DESCRIPTION OF FACE	
Black sandy topsoil	1
Medium dense, brown and black clayey fine sand with angular gravel and cobbles	2
Soft to firm mottled grey clay with traces of angular gravel	3
Soft to firm sandy clay with fine gravel and occasional cobbles	4

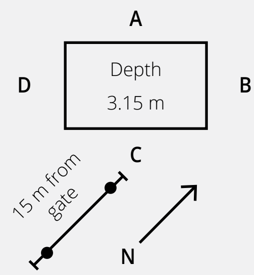
NOTES	KEY TO SAMPLE NUMBERS	PLAN OF PIT
Walls - generally stable Faces - B,C as A. Face D without CLAY Water - seepage for first 20 minutes Trial pit dug in centre of firm grass field Access for excavators is satisfactory	J -Jar sample B - Bulk sample	

Figure 4: Typical test pit profile

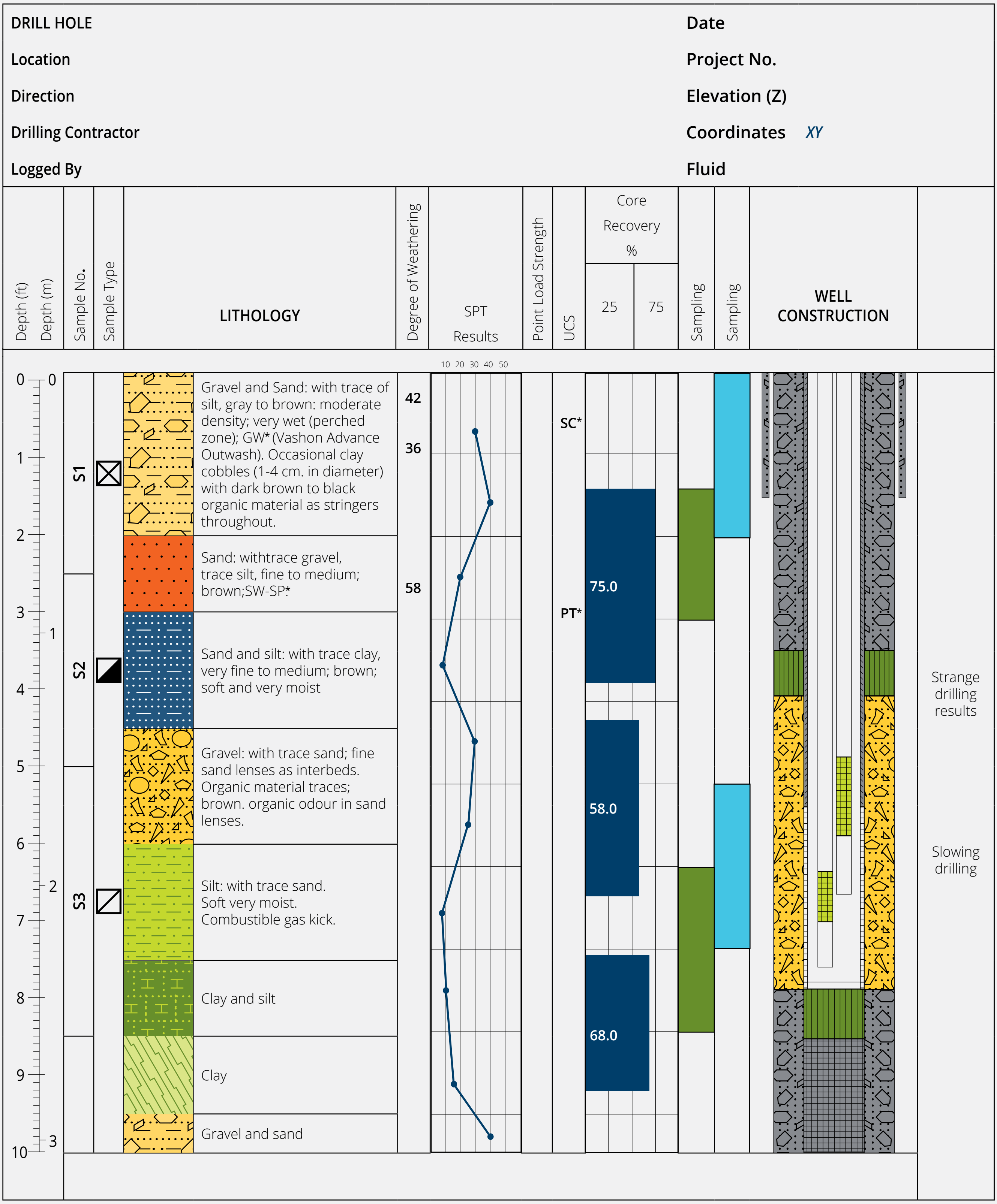


Figure 5: Typical borehole profile

* Refer to Table 4

5. Methods and extent of soil exploration

The methods of soil exploration that are commonly used are discussed in detail below.

5.1 Methods of soil exploration

5.1.1 Test pits

Test pits permit a direct inspection of the soil strata in place, and taking of adequate disturbed and undisturbed soil samples (the last one only on specific conditions). Test pits are the most satisfactory method of disclosing the in situ soil strata conditions. The cost of test pits increases rapidly with depth and number of test pits; they are typically uneconomical beyond a depth of 4m. They are impractical when groundwater is reached in the excavation.

5.1.2 Geophysical exploration methods

These methods have been used considerably in recent years for preliminary exploration of dam sites, aquifer characterization and for transport infrastructure such as roads, tunnels and railways. However these methods are not limited to these applications. Geophysical exploration methods are non-intrusive and can reduce the number of expensive time-consuming tests though could be costly. The two most common methods are the seismic method and the electrical method. Geophysical exploration methods are often used in conjunction with other exploration methods and provides the following information:

- The presence of rock;
- The approximate depth of the rock;
- The approximate density of the rock;
- Fracture zones or faulting in the rock;
- Material property changes; and
- Presence of subsurface cavities.
- Dynamic Properties of Soils.
- Location of the Water Table.

The seismic method is based on the principle that sound travels more rapidly through dense materials than through loose materials. Velocities as high as 6,000 m/s have been recorded in dense, solid rock and velocities as low as 180 m/s have been observed in loose sand. The electric resistance method consists of measuring changes in electric resistance of the soil. Dense rock has a very high electrical resistivity (resistance) and soft, saturated clay has a low resistivity (resistance).

There are various advantages and disadvantages associated with Geophysical Exploration methods that should be considered before applying this method.

Advantages:

- Geophysical testing is non-intrusive thus giving an accurate representation of the in situ material without cross contamination of samples when extruding;
- Geophysical testing covers a relatively large area; and
- Geophysical testing is relatively inexpensive.

Disadvantages

- Difficult to interpret between materials of similar physical properties;
- Results are generally interpreted qualitatively and thus the results are only as reliable as the person interpreting them; and
- Specialized equipment is required.

5.1.3 Boreholes

A Borehole is a narrow shaft bored in the ground either vertical or horizontal. They are used for soil investigation for buildings, roads, bridges, tunnels, dams, etc. For Boreholes, usually power-drilling rigs are used. The main principal type of equipment for making borings is the Rotary Drilling Rig.

A Rotary drill method uses rotation of the drill bit with the simultaneous application of pressure to advance the hole. This method is the most rapid method of advancing holes in the rock unless it is badly fissured; however, it can also be used for any other type of soil. If this is applied in soils when the sides of the hole tend to cave in, a drilling mud may be used. The drilling mud is usually a water solution of a thixotropic clay (Bentonite), with or without other admixtures, which is forced into the sides of the hole by the shaft rotary drill. This provides stability to keep the shaft open. The mud also tends to seal off the water flow into the shaft from the permeable water bearing strata.

Rotary core barrels, provided with commercial diamond-studded bits or a steel bit with shots, are also used for rotary drilling and simultaneously obtaining the rock cores or samples. The method is then also known as core boring or core drilling. Water is circulated down drill rods during boring.

Advantages

- Boreholes are a direct method for soil exploration, which means, there is no need to use any empirical interpretation that could be subject to uncertainties that involve high safety factors.
- Allow to obtain samples, undisturbed or disturbed, in the whole column or lithological profile, if they are executed by means of a continuous sampling technique.
- Can reach depths superior to those made with other techniques.
- Can serve as an installation point for auscultation elements, from piezometric pipes to elements for measuring of in situ stresses and strains.
- Make possible to carry out in situ tests at the desired depth, which are very important when it is not possible to obtain undisturbed samples.
- Allow to explore soils under the water table, as well as high resistance soil layers.
- Allow to assess the location of the water table.

Disadvantages

- Semi-invasive – the resultant hole might need to be re-filled or a mock-up be provided.
- Expensive.

5.1.4 Probing and sounding methods

These methods have been developed for determining the consistency of cohesive soils or relative density of cohesionless deposits. In this method, a rod (which may be encased in a sleeve) is forced into the soil and the resistance to penetration is recorded. By observing variations in the resistance, dissimilar soil layers are identified, and the quantification of the resistance value in layers can be calibrated to estimate physical properties of the layers.

MORE INFORMATION

http://uk-dcp.software.informer.com/3.1/

The following are examples of the available probing or sounding methods.

5.1.4.1. Dynamic penetrometer test

The simplest form of soils sounding consists of driving a rod (which may have a standard cone tip) into the ground by repeated blows of a hammer (constant weight and drop height). This method is commonly known as Dynamic Cone Penetrometer (DCP) testing. The typical apparatus is shown in **Figure 6: Dynamic penetration typical apparatus (p. 31).**

The penetration of the rod into the soil strata for a given number of blows is recorded. The penetration rate is used to infer the relative strength of the layers, and can be calibrated by empirical models to give standard information like in situ California Bearing Ratio (CBR). A DCP software tool is available to analyse DCP results (penetration depth vs no of blows) and to correlate with CBR and to analyse and interpret data collected using a DCP.

The soil friction acting on the rod is cumulative with depth and therefore, the penetration resistance does not directly represent the strength or density of the layer encountered.

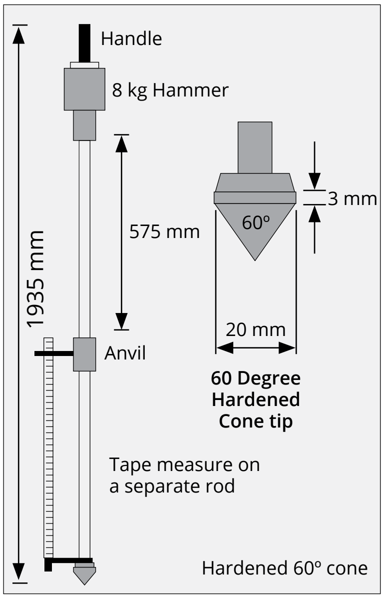


Figure 6: Dynamic penetration typical apparatus

Advantages

- Determines stiffness in mm/blow
- Layer changes can be inferred by slope changes
- Minimal surface disturbance
- Not 'rocket science' and not 'nuclear'
- Method of acceptance and verification
- Design and strength information via correlations
- Simple reliable, cost-effective tool for shallow pavement applications

Disadvantages

- Do not provide sample that can be used for soil identification
- Not for use on coarse gravel or soils with boulders, shell, asphalt, or concrete
- DCP can break under repetitive drops in very stiff material or with improper removal
- Does not measure moisture content or density (only measures stiffness)
- Should be used in combination with another exploration technique.
- Easy to abuse, seem as a 'short cut'.

5.1.4.2. Cone Penetrometer Test

A Cone Penetration Test (CPT) is performed using an instrumented probe with a conical tip, which is pushed into the soil hydraulically at a constant rate. A basic CPT instrument reports tip resistance and shear resistance along the cone friction sleeve. CPT data has been correlated empirically to soil properties and performance. **Figure 7: Cone Penetrometer Test apparatus (p. 32)** provides a graphic representation of a CPT set up.

Advantages

- Continuous data.
- Elimination of operator error.
- Reliable, repeatable test results.
- Measure of increase of water pressure and its dissipation.
- Can be used to undertake geophysical tests.

Disadvantages

- Inability to penetrate through gravels and cobbles.
- Newer technology = less populated database than Standard Penetration Test (SPT).
- Lack of sampling.

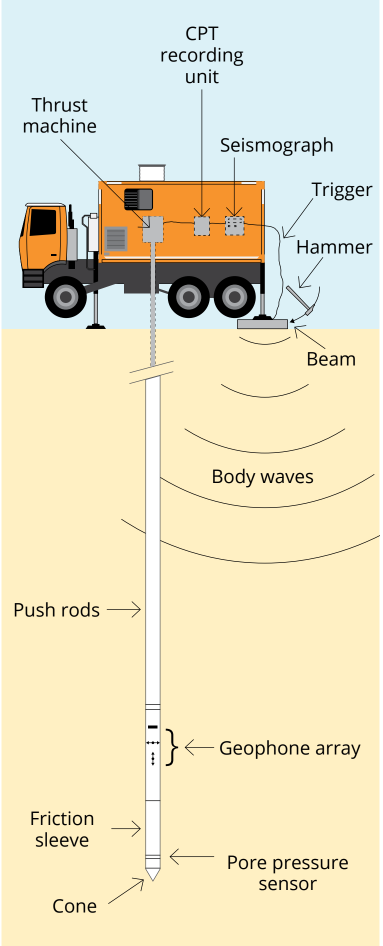


Figure 7: Cone Penetrometer Test apparatus

5.1.4.3. Standard Penetration Test

The Standard Penetration Test is an in situ dynamic penetration test designed to provide information on the geotechnical engineering properties of soil. The test procedure is described in ASTM D1586. The test uses a thick-walled sample tube, with an outside diameter of 50.8 mm and an inside diameter of 35 mm, and a length of around 650 mm. This is driven into the ground at the bottom of a borehole by blows from a slide hammer with a mass of 63.5 kg falling through a distance of 760 mm, please see **Figure 8: Standard Penetration Test (p. 33).** The sample tube is driven 150 mm into the ground and then the number of blows needed for the tube to penetrate each 150 mm up to a depth of 450 mm is recorded. The sum of the number of blows required for the second and third 150 mm of penetration is termed the "standard penetration resistance" or the "N-value". In cases where 50 blows are insufficient to advance it through a 150 mm interval, the penetration value '50 blows' is recorded. The blow count provides an indication of the density of the ground, and it is used in many empirical geotechnical engineering formulae, to estimate engineering performance of the soil.

Advantages

- Relatively quick and simple to perform.
- Provides a representative soil sample.
- Provides a useful index of relative strength and compressibility of the soil.
- Numerous case history of soil liquefaction during past earthquakes are available with SPT N-Values. The method based on this history can reflect actual soil behaviour during earthquakes, which cannot be simulated in the laboratory.
- The SPT is an in situ test that reflects soil density, soil fabric, stress and strain history effects, and horizontal effective stress, all of which are known to influence the liquefaction resistance but are difficult to obtain with undisturbed samples.
- The SPT equipment is rugged, and the test can be performed in a wide range of soil conditions.
- There are numerous correlations for predicting engineering properties with a good degree of confidence.

Disadvantages

- The SPT does not typically provide continuous data, therefore important data such as weak seams may be missed.
- Not recommended for soils containing, gravels, cobbles and boulders.
- Limited applicability in very soft cohesive soils.
- Somewhat slower than other sample methods due to sample retrieval.
- In addition to overburden pressure and relative density the SPT N-Value is also a function of soil type, particle size and age and stress history of the deposit.
    - Due to considerable differences in apparatus and procedure, significant variability of measured penetration resistance can occur; The basic

problems to consider are change in effective stress at the bottom of the borehole, dynamic energy reaching the sampler, sampler design, interval of impact, penetration resistance count.

- Samples that are obtained from the SPT are disturbed.
- The greatest disadvantage to SPTs is the lack of reproducibility of the test results.
- Lack of consistency on the effective energy transfer to the thick-walled sample tube during the test.
- Drilling, disturbance, mechanical variability, and operator variability all can cause significant variation in test results.
- Progress is slower than other in situ tests because of incremental drilling, testing, and sample retrieval, and SPTs may be more expensive than other in situ tests.

5.2 Extent and depth of soil investigations

When deciding on the extent and depth of soil investigations the following aspects should be taken into consideration:

- The variability of the ground conditions:
- Homogeneous: when the soil conditions are uniform across the entire site, less testing is required.

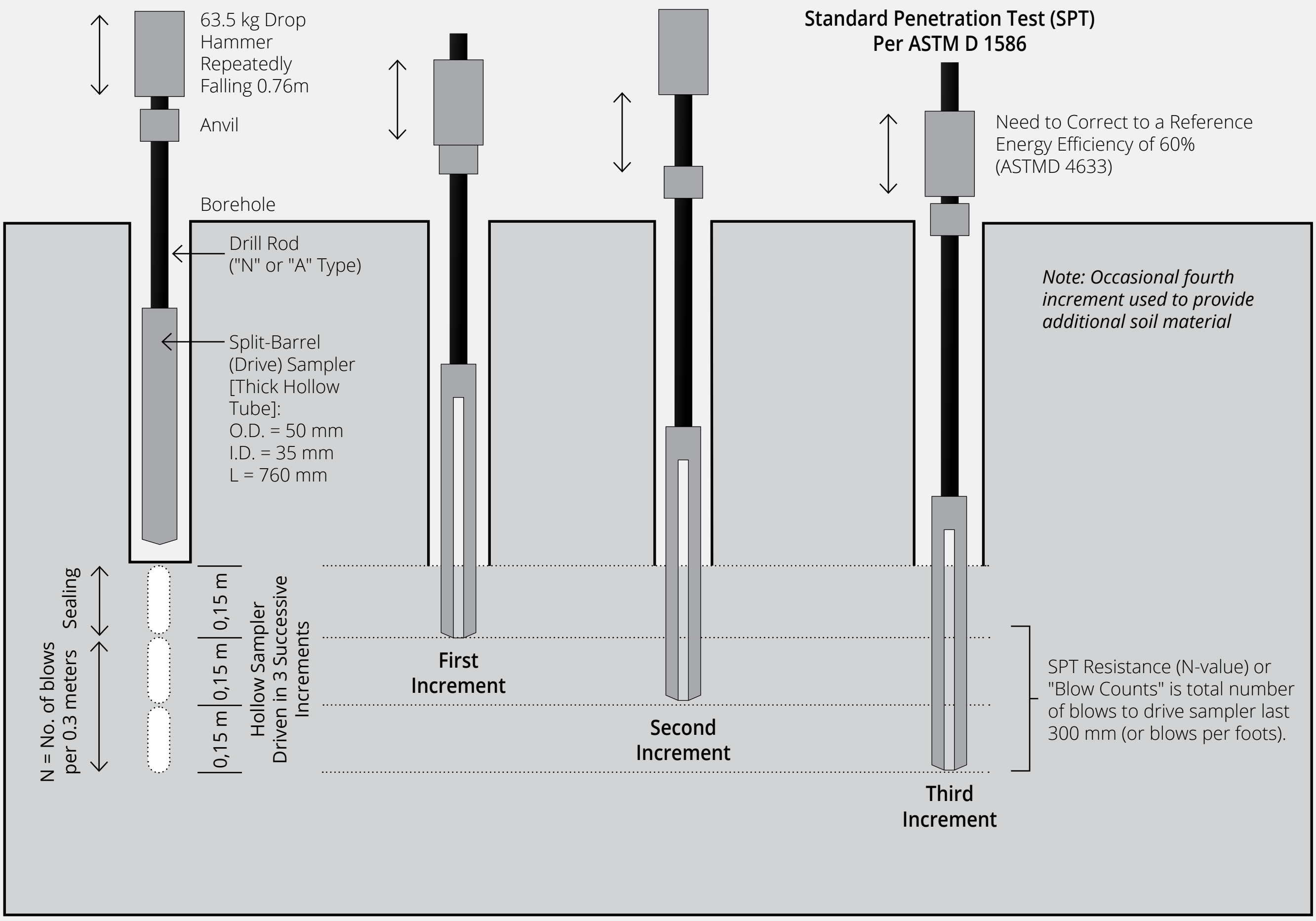


Figure 8: Standard Penetration Test

- Normal: when the soil conditions are not homogeneous, but there is not a lot of variability across the site. A normal ground condition can be considered when variability of the ground conditions and properties can be foreseen with 20m split boreholes.
- Heterogeneous soil conditions: are where there is high variability in the soil conditions and typical testing regimes would not be sufficient to obtain all the different soil conditions. In this case, test regimes should be adjusted to make provision for the variability.

• Foundation conditions:
  - Favourable: well known foundation behaviour, despite the soil properties
  - Normal: conventional foundation conditions based on previous experience that is not sensitive to the expected change in soil conditions
  - Adverse: Problematic soils that demand special foundation procedures
  - Type and extent of the project;
  - Cost of investigations.

Local standard specification and codes often stipulate the number of trial pits or borings that are required for structures, often based on area.

The following **tables: Table 5 (p. 35), Table 6 (p. 37) and Table 7 (p. 38)** summarise recommendations on the extent and depth of borings and excavations for various infrastructure types and typology of soils. These tables are to be used as a guideline only and judgment should be given based on the aspects as to the site specific extent and depth of borings mentioned above. This information is usually presented in project specification or design brief.

STRUCTURE	NUMBER OF BORINGS/SPACING	DEPTH OF BORINGS	REMARKS
Rigid Frame Structure	1 boring per 230m^2 of ground floor area	1.5 times the minimum dimension of the shallow footing below the base of the footing Pile footings - 1.5 times the minimum dimension of an imaginary footing located at 2/3 of the expected depth of piles.	**Cohesive Soils** continuous undisturbed samples for the first 3 meters Intermittent samples at 1.5 to 3m intervals thereafter sample at every change of soil type **Cohesionless Soils** obtain undisturbed samples (if possible) or conduct in situ soundings such as SPT
Continuous truss (girder) - type bridge	Minimum of 1 boring at every pier/footing	1.5 times the minimum dimension of the shallow footing below the base of the footing Pile footings - 1.5 times the minimum dimension of an imaginary footing located at 2/3 of the expected depth of piles	**Cohesive Soils** pier size <50 m^2 - continuous undisturbed samples at each pier pier size - 50 to 100 m^2 - 2 continuous undisturbed samples at each pier pier size - 100 to 250 m^2 - 4 continuous undisturbed samples at each pier pier size > 250 m^2 - minimum of 5 continuous undisturbed samples at each pier **Cohesionless Soils** Obtain undisturbed samples or soundings as for cohesive soils **Competent Rock** Trace formation at each pier - if in doubt of rock quality, drill at least 6 m into formation
Levees	Levee height = 3 to 6m,: space borings at 300m intervals	Depth of Boring - 6m	**Cohesive Soils** Continuous undisturbed samples
	Levee height = 6 to 12m,: space borings at 230m intervals	Depth at least equal to height of levee	**Cohesionless Soils** Continuous undisturbed samples or soundings
	Levee height = 12 to 18m,: space borings at 150m intervals	Depth at least equal to height of levee	Locate borings along centreline of proposed structure
Earth dams	See remarks column	Depth at least equal to height of dam or twice the maximum head, whichever is greater	**Preliminary investigation** Maximum stress occurs approximately at midpoint of slope between the centreline and toe of proposed structure. Establish a square grid pattern of borings located upstream and downstream of dam centreline near midpoint of slope in a direction with respect to dam centreline
		Trace the top of the impervious zone	**Primary investigation** Trace the limits of various strata, e.g. Sand Treat power plants, spillways and other control structures as rigid frame structures Obtain adequate subsurface data to define the character of the abutments Obtain in situ permeability and pore pressure measurements **Cohesive Soils** Continuous undisturbed samples **Cohesionless Soils** Continuous undisturbed samples or soundings
Borrow pits	Use a 60m grid spacing	Maximum depth to water table or working depth of equipment	Disturbed samples are satisfactory; may use augers to obtain samples

STRUCTURE	NUMBER OF BORINGS/SPACING	DEPTH OF BORINGS	REMARKS
Roads	For 2 lane highways: 1 boring per 150m along centreline and at each major change of soil profile	For excavations and level terrain: 3m below level finished grade For compacted embankments: treat as for levees	**Cohesive Soils** Continuous undisturbed samples **Cohesionless Soils** Continuous undisturbed samples or soundings
	For multilane highways: 1 boring per 75m along centreline borings may be staggered	For rock: extend 0.75m into rock	
Airfields	See remarks column	See remarks column	**Preliminary investigation** Place borings at 300 m intervals in square grid patterns to a depth of 6 m. Samples may be disturbed. **Primary investigation** Runways - site two lines of borings in a square grid pattern at 30 m on either side of runway centreline to a depth of 6 m or 1.5 m into rock Taxiway - place borings at 60 to 75 m intervals along centreline to a depth of 6 m Apron - place boring in a 60 to 75 m square grid pattern to a depth of 6 m
Houses	1 boring per 8000 m2 in new subdivision	To unweathered rock or to 4.5m, whichever is lesser	Obtain samples at 1.5 m intervals using undisturbed sampling techniques for cohesive soils or undisturbed or sounding techniques for cohesionless soils
	1 boring per individual lot		

Table 6: Scope of site explorations based on type of structure

(Suggested Boring Programme for various Engineering Structures (after Dunlap 1980). Geotechnical Investigations, Engineering Manual 1110-1-1804, 1 January 2001)

MATERIALS AND MATERIAL SITES	SCOPE OF EXPLORATION/INVESTIGATION
Sand or Gravels Soils	SPT (split-spoon) samples should be taken at 1.5m (5ft) intervals or at significant changes in soil strata. Continuous SPT samples are recommended in the top 4.5 m (15 ft) of borings made at locations where spread footings may be placed in natural soils. SPT jar or bag samples should be sent to lab for classification testing and verification of field visual soil identification.
Silt or Clay Soils	SPT and 'undisturbed' thin wall tube samples should be taken at 1.5m (15 ft) intervals or at significant changes in strata. Take alternate SPT and tube samples in same boring or take tube samples in separate undisturbed boring. Tube samples should be sent to lab to allow consolidation testing (for settlement analysis) and strength testing (for slope stability and foundation bearing capacity Analysis). Field vane shear testing is also recommended to obtain in-place shear strength of soft clays, silts and well-rotted peat.
Rock	Continuous cores should be obtained in rock or shales using double or triple tube core barrels. In structural foundation investigations, core a minimum of 3m (10 ft) into rock to ensure it is bedrock and not a boulder. Core samples should be sent to the lab for possible strength testing (unconfined compression) if for foundation investigation. Percent core recovery and Rock Quality Designation (RQD) value should be determined in field or lab for each core run and recorded on boring log.
Groundwater	Water level encountered during drilling, and at 24 hours after completion of boring should be recorded on boring log. In low permeability soils such as silts and clays I, a false indication of the water level may be obtained when water is used for drilling fluid and adequate time is not permitted after boring completion for the water level to stabilize (more than one week may be required). In such soils, a plastic pipe water observation well should be installed to allow monitoring of the water level over a period of time. Seasonal fluctuations of water table should be determined where fluctuation will have significant impact on design or construction (e.g. borrow source, footing excavation, excavation at toe of landslide, etc.). Artesian pressure and seepage zones, if encountered, should also be noted on the boring log. In landslide investigations, slope inclinometer castings can also serve as water observational wells by using 'leaky' couplings (either normal aluminium couplings or Polyvinyl Chloride (PVC) couplings with small holes drilled through them) and pea gravel backfill. The top 0.3m (1ft) or so of the annular space between water observation well pipes and borehole wall should be backfilled with grout, bentonitem or sand-cement mixture to prevent surface water inflow, which can cause erroneous groundwater level readings.
Soil Borrow Sources	Exploration equipment that will allow direct observation and sampling of the subsurface soil layers is most desirable for material site investigations. Such equipment that can consist of backhoes, dozers, or large diameter augers, is preferred for exploration above the water table. Below the water table, SPT borings can be used. SPT samples should be taken at 1.5m (5ft) intervals or at significant changes in strata. Samples should be sent to the lab for classification testing to verify field visual identification. Groundwater level should be recorded. Observation wells should be installed to monitor water levels where significant seasonal fluctuation is anticipated.
Quarry Sites	Rock coring should be used to explore new quarry sites. Use of double or triple tube core barrels is recommended to maximize core recovery. For riprap source, spacing of fractures should be carefully measured to allow assessment of rock sizes that can be produced by blasting. For aggregate source, the amount and type of joint infilling should be carefully noted. If assessment is made on the basis of an existing quarry site face, it may be necessary to core or use geophysical techniques to verify that the nature of rock does not change behind the face or at depth. Core samples should be sent to lab for quality tests to determine suitability for riprap or aggregate.

Table 7: Scope of site explorations for different material and material sites

(Training Course in Geotechnical and Foundation Engineering: Subsurface Investigation, FHWA HI-97-021, November 1997)

5.3 Supplementary investigation and construction control

In addition to **Table 5 (p. 35), Table 6 (p. 37), Table 7 (p. 38)** supplementary investigation should be conducted to analyse external factors that may influence the design, construction and operation of the infrastructure. The following supplementary investigation is made to give a full picture of the site investigation of soil as well as the structure.

- Any special features such as the possibility of earthquakes or climatic factors such as flooding, seasonal swelling and shrinkage, permafrost, or soil erosion;
- The availability and quality of local constructional materials such as concrete aggregates, building and road stone, and water for constructional purposes;
- For maritime or river structures information on normal spring and neap tide ranges, extreme high and low tidal ranges and river levels, seasonal river levels and discharges, velocity of the tidal and river currents and other hydro-graphic and meteorological data;
- Results of laboratory tests on soil and rock samples appropriate to the particular foundation design or construction problems;
- Results of chemical analysis on soil, fill materials, and ground water to determine possible deleterious effects on foundation structures; and
- Results of chemical and bacteriological analysis on contaminated soils, fill materials and emissions to determine health hazard risks.
- By conducting supplementary investigations, one can eliminate many risks not highlighted in the soil investigation. This can reduce unexpected costs and assist in optimizing designs and construction methods and phasing

5.4 Sampling for laboratory testing

Typically, soil tests for classification and determining the engineering properties are performed in a laboratory, which require samples to be recovered and transported off-site.

Intrusive ground investigations by drilling boreholes, SPT sampling, or trial pitting, are used to recover samples (disturbed and undisturbed) of the soil and rock. Samples should be representative of the strata encountered, and sufficient quantity of samples and tests are needed to identify the typical range of material characteristics for each strata type and locations.

The cost of sampling is normally relatively low, so it is preferable to collect more samples rather than end up with not enough samples to conduct meaningful testing.

The size of the samples taken will be influenced by:

- Method of recovering the sample;
- The soil or rock type being sampled; and
- The type and number of tests expected to be carried out on the sample.

A guide to minimum sample sizes for typical types of soil tests are given in BS1377 (British Standard Methods of test for Soils for Vicil Engineering Purposes, BS 1377:1990 Parts 1 - 9, 1990) which is summarised in the Table 8. It can be seen that sample sizes can typically range between 25kg to 80kg for detailed testing of fine to coarse soils.

	BASED ON BS1377, PT1, TABLE 5: MINIMUM DRY MASS FOR TESTS		BASED ON BS1377, PT1, TABLE 5: MINIMUM DRY MASS FOR TESTS	
Test types	Fine soils <2mm	Coarse soils >20mm	More than 10%>2mm	0.15kg
Description	500g	4kg	More than 10%>20mm	2kg
Compaction	25kg	80kg	More than 10%>37.5mm	15kg
Organic & Sulphate	150g	3.5kg	More than 10%>100mm	220kg

Table 8: Summary of minimum sample sizes according to BS1377

5.4.1 Handling, storage and transportation of samples

Samples should be well labelled, packaged correctly in order to ensure all parties in the chain of custody from the sampling team to the transportation company to the laboratory conducting the testing are aware of all the details of the sample. Samples should be labelled with the following:

- A unique number assigned by the sampling team to correspond with information on a sampling sheet;
- A label that is weatherproof. It is good practice to place a label both inside the packaging and attached securely to the exterior of the packaged sample;
- The top and the bottom of the sample should be well indicated on the case of the sample.
- Identification details of the sample should be recorded on the sample sheet with the following details:

- Project number/name;
- Sample number; and
- Sampling date and latest testing date
- Test type.

Containers/packaging of the samples should be:

- Appropriate size for the sample;
- Weatherproof;
- Durable enough to endure handling; and
- Storage friendly.

It is essential that samples that require moisture content testing be airtight to ensure no moisture is lost during handling/transportation.

In transporting samples from the point of origin to the testing or storage facility, it is essential that the samples be handled carefully so that the sample containers are not damaged and the labelling remains intact. The samples should be protected in adverse weather conditions.

Transporting of samples is sometimes carried out by subcontracted hauliers. In these cases, it is essential that the samples are appropriately packaged and labelled, to ensure their undamaged delivery. The transporting agency must be briefed on the handling and protection of the samples, for example, what actions to take in the event of damages to samples, to never drop sample containers, and to never overturn core boxes.

5.5 Field (in situ) testing

In situ tests are often the best means for determining meaningful in situ engineering properties of the ground materials, due to the disturbance of the natural soil state during sampling and transportation.

Typically, the following in situ tests can be undertaken:

5.5.1 Field classification tests

One can classify a material quite simply purely based on the look and feel of the soil. Although this method is subjective, it provides meaningful information about the soil simply and timeously.

A. Grain size, grain shape, and gradation of coarse-grained, cohesionless soils
Fine sand particles are the smallest soil individual grain that can be seen with the naked eye. Fine grained soils, which are silts and clays, cannot be seen individually without a magnifying glass.

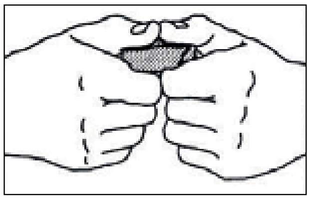
In order to get a sense of the size of the soil particles, close visual examination of a soil sample is required. The sizes of the various soil particles are noted as well as noting if the particles are too small to see. Since the four basic soil components are gravel, sand, silt and clay, one can determine if the soil is mostly gravel or sand or a clay/silt just by looking at it.

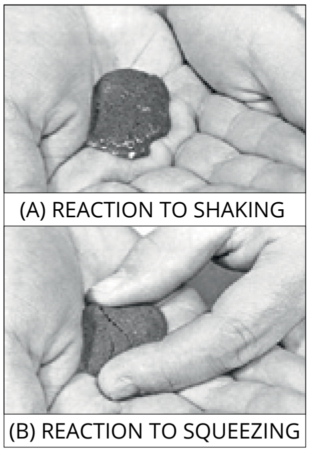
The next important soil classification regards cohesion. A cohesive soil sticks together, it has strong bonds between the individual soil particles. Clays tend to be cohesive soils. A simple field test for cohesion involves grabbing a small handful of the soil and rolling it between two hands, trying to create a long, thin thread (think about a worm or a small snake). If the soil sample rolls into a narrow thread approximately 100mm (4”) long and 3mm (1/8”) thick it has a high degree of cohesion and is probably mostly clay. If the sample just breaks apart as it begins to roll into the thread, it has much less cohesion and is mostly silt.

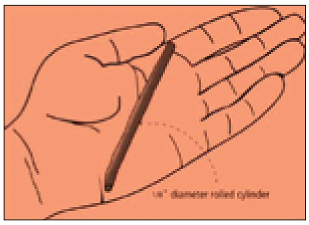
In soils the concept of cohesive and non-cohesive is very important. In cohesive soils particles stick together (cohesive literally means mutual attraction between particles)

These soils, clays and silts, can generally be squeezed in one's hand to form a ball. Conversely if one squeezes a handful of sand or gravel, there will be no cohesion. Clays may be distinguished from silts by using the following simple tests as shown in Figure 9.

1. Dry Strength Test: Mould a small block of soil and allow it air dry. Break the brick and place a small (3-4 mm) fragment between thumb and finger. A silt fragment will break easily whereas clay will not.
2. Dilatancy Test: Mix a small sample with water to form a thick slurry. When the sample is squeezed, water will flow back into a silty sample quickly. The return rate will be much lower for clay. This slurry is placed in the open palm of the hand and shaken, or vibrated horizontally. This is most effectively done by tapping the hand holding the soil, with the other hand. With a silt, “quick” behaviour appears (water will appear on the surface, giving it a shiny appearance), and will then disappear if the sample is squeezed or manipulated. During vibration, the sample tends to collapse and water runs to the surface. When it is manipulated the sample tends to dilate and draw water back into it. With a clay, these characteristics are not present.
3. Plasticity Test: Roll a moist soil sample into a thin (3-4mm) thread. As the thread dries, silt will be weak and friable, but clay will be tough.
4. Dispersion Test: Dispense a sample of soil in water. Measure the time for the particles to settle. Gravel will settle immediately, sand will settle in 30 to 60 seconds. Silt will settle in 15 to 60 minutes, while clay will remain in suspension for a long time.

1.


2.


3.


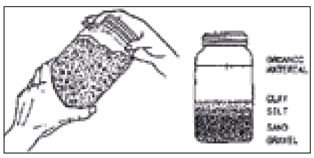
4.


Figure 9: Field tests

B. Texture and colour of fine-grained soils

Organic soils are distinguished by their coarse, fibrous texture and dark colour.

C. Feel tests

A simple flowchart to help assess sample types by feel is shown in **Figure 10: Flowchart to identify a soil type by feel/touch.(p. 42)**

D. Moisture content description

Such as, dry, moist, or wet recognises that tests need consideration of test location, weather conditions and immediacy of test.

5.5.2 Field shear testing

Various tests can be undertaken on site and on the in situ material to determine the shearing properties. These methods are discussed below.

5.5.2.1. Field vane shear test

The vane shear test apparatus consists of four stainless steel blades fixed at right angle to each other and firmly attached to a high tensile steel rod. The length of the vane is usually kept equal to twice its overall width. The diameters and length of the stainless steel rod were limited to 2.5mm and 60mm respectively. The test starts by pushing the vane and the rod vertically into the soft soil. The vane is then rotated at a slow rate of 6° to 12° per minute. The torque is measured at regular time intervals and the test continues until a maximum torque is reached and the vane rotates rapidly for several revolutions.

Advantages

- The test is simple and quick.
- It is ideally suited for the determination of the undrained shear strength of non-fissured fully saturated clay.
- The test can be conveniently used to determine the sensitivity of the soil.
- The test can be conducted in soft clays situated at a great depth, samples of which are difficult to obtain.

IS THE MOIST SOIL PREDOMINANTLY ROUGH AND GRITTY?

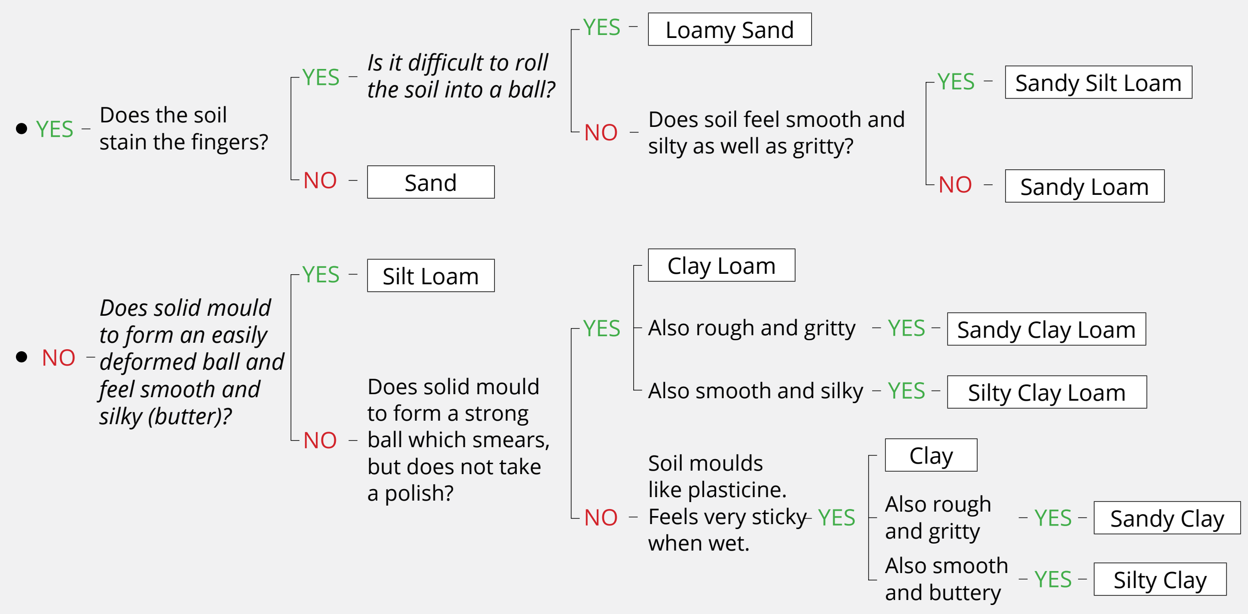


Figure 10: Flowchart to identify a soil type by feel/touch

Disadvantages

- The test cannot be conducted on the clay containing sand or silt laminations or the fissured clay.
- The test does not give accurate results when the failure envelope is not horizontal.

5.5.2.2. Dynamic Cone Penetrometer (DCP)

As discussed in **5.1.4.1. Dynamic penetrometer test (p. 31)**, Dynamic Cone Penetrometer Testing (DCP) is a cost effective, simple test to give an indication of the in situ CBR. This CBR is purely indicative and should not be used to extrapolate other properties.

Figure 11: CBR determined in-situ by DCP for roadworks project (p. 43) describes a method to identify if in situ soils will be suitable for use in roadworks (CBR determined in situ by DCP).

5.5.2.3. Cone Penetrometer Tests (CPT)

As discussed in **5.1.4.2. Cone Penetrometer Test (p. 31)**

5.5.2.4. Standard Penetration Test (SPT)

As discussed in **5.1.4.3. Standard Penetration Test (p. 32)**

5.5.2.5. Plate bearing tests

The Plate Bearing Test (or Plate Loading Test) is an in situ site investigation field test used for determining the ultimate bearing capacity of the ground and the likely settlement under a given load. It consists of loading a steel plate of known diameter and recording the settlements corresponding to each load increment. The test load is gradually increased until the plate starts to settle at a rapid rate.

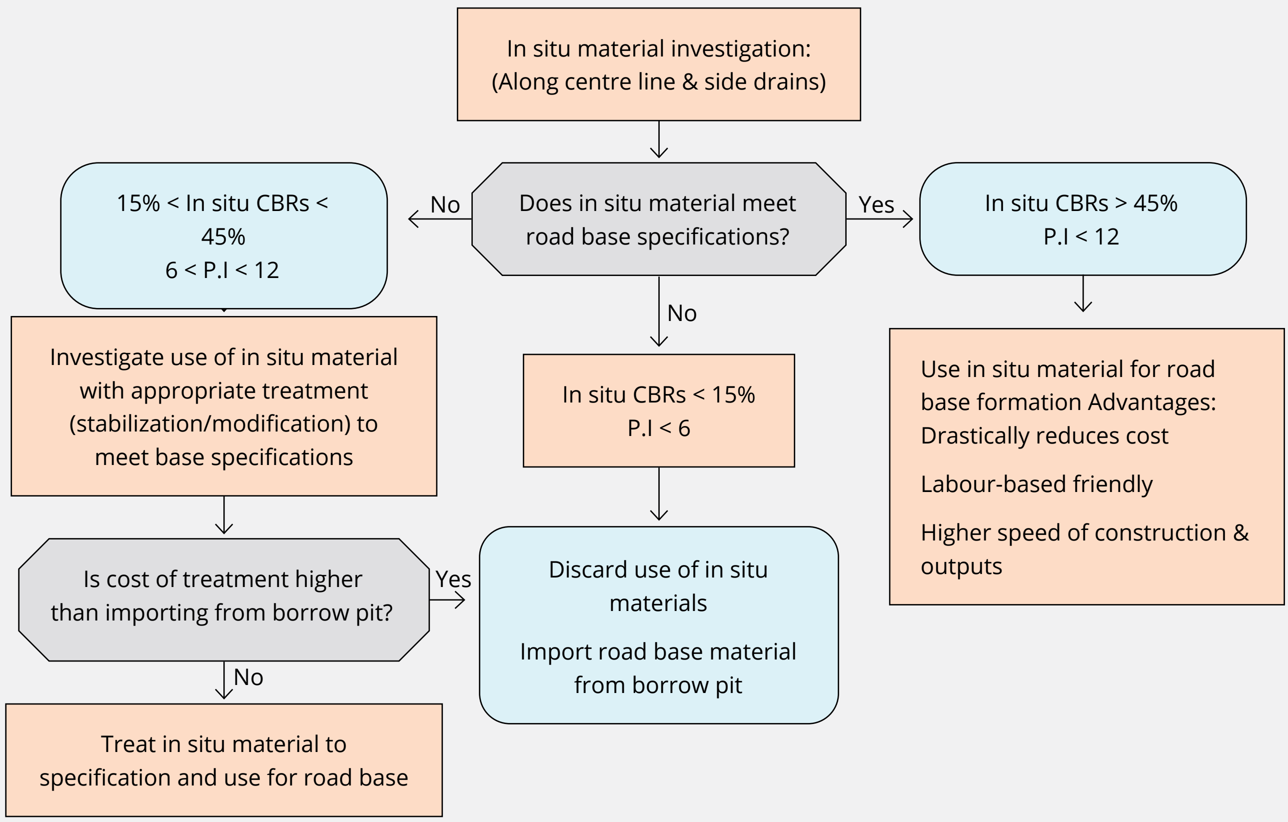


Figure 11: CBR determined in-situ by DCP for roadworks project

The total value of load on the plate divided by the area of the steel plate gives the value of the ultimate bearing capacity of soil. A factor of safety is applied to give the allowable bearing capacity of soil (serviceability settlement should also be verified).

Advantages

- Gain understanding of foundation behaviour which will enable the evaluation of foundation bearing capacity and settlement under loading condition

Disadvantages

- The settlement influence zone is much larger for the real foundation than that for the test plate, which may lead to misinterpretation of the expected settlement for proposed foundation.
- Settlements in loose sands are usually much larger than what is predicted by the plate bearing test
- Plate bearing test is relatively short duration and gives mostly the immediate settlement
- In the case of granular soils, the immediate settlement is close to the total settlement. In cohesive soils, due to the consolidation settlement the plate bearing test becomes irrelevant.

5.6 Laboratory testing

Laboratory testing is an important part of any soil investigation and it is imperative that the laboratory testing be conducted according to a standard.

There are two main international standards namely the American Society for Testing and Materials (ASTM) and the British Standard (BS). The testing methods set out in these standards are not open source but are available on the following websites:

- ASTM – www.astm.org
- BS – www.bsigroup.com

5.6.1 Soil description and classification tests

The first series of tests conducted in a laboratory comprises the grading analyses and the Atterberg indices, which are classified as the indicator tests. These tests are used in the design of the infrastructure, but also provide the designer and technicians with valuable information regarding the nature and characteristics of the material to aid in its identification and classification in accordance with standard methods.

A Visual classification

The first step in testing a soil sample should be to look at the material and to compare if what is observed corresponds with the description of the material as given in the trial pit logs. This step aids the development of a feeling for soil behaviour and may aid in the interpretation of the test results that are to be obtained. Simply looking at the material for verification may also detect possible mistakes on the trial pit logs or perhaps the sample numbering.

B Grading analysis

One factor, upon which soil behaviour always depends to some degree, is the size and distribution of the individual particles. The grain-size distribution of a soil is also vital data required for the proper design of filters in embankment dams and other structures. The determination of the fines (particles passing of 0.075mm (#200) sieve) in a soil is of particular importance for design.

MORE INFORMATION

ASTM D6913-04(2009)e1, Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, ASTM International, West Conshohocken, PA, 2009, , www.astm.org

ASTM D7928-16, Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis, ASTM International, West Conshohocken, PA, 2016, www.astm.org

The grain-size distribution of a material must, however, never be viewed in isolation, but seen together with the other characteristics of the soil, and serve to provide complete information with regard to its properties and possible uses. Grain-size analyses are performed as routine tests on all soil samples submitted to a materials laboratory. The grading analysis is also vital to the classification of the soil.

C Atterberg limits

Depending on the amount of water present (moisture content), a fine-grained soil can exist in any of several states. When water is added to a dry soil, each particle is covered by a film of absorbed water. If more water is added, the thickness of the water film around the particle increases, and this acts as a lubricant that permits the particles to slide past one another more easily. The behaviour of the soil is therefore related to its moisture content. The Atterberg Limits defines the boundaries in terms of "limits" as follows:

- Liquid Limit: The boundary between the liquid and plastic state of the soil is defined as "that water content, expressed as a percentage of the mass of oven-dried soil, at which two halves of a pat of soil, separated by a groove of standard dimensions, will close at the bottom of the groove along a distance of 10 mm under the impact of 25 blows given in 12.5 seconds in a standard liquid-limit device."
- Plastic Limit: The boundary between the semi-solid and solid states is defined as "that water content, expressed as a percentage of the mass of oven-dried soil, at which the soil begins to crumble when rolled into a thread 3 mm in diameter." The amount of water that must be added to change a soil from its plastic limit to its liquid limit is an indication of the plasticity of the material. The plasticity is measured by the "plasticity index," which is equal to the liquid limit minus the plastic limit.

The Atterberg properties are of an empirical nature, but by performing these tests routinely on all soil samples submitted, a relative ranking can be gained for the character of the soil. Over time, the Atterberg limits have been empirically linked to performance of soils. The measured properties are also required for the classification of the soil.

A final test related to moisture behaviour of fine-grained soils is the test for the linear shrinkage. The results of this test are usually grouped with the Atterberg indices. The linear shrinkage of a soil is defined as "the percentage decrease in one dimension of the original dimension of the soil mass, when the moisture content is reduced from the liquid limit to an oven-dry state."

MORE INFORMATION

ASTM D4318-10e1, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA, 2010, www.astm.org

D Moisture content

For many materials, the water content is one of the most significant index properties used in establishing a correlation between soil behaviour and its index properties. The water content of a soil is used in expressing the phase relationships of air, water, and solids in a given volume of material. In fine-grained (and cohesive) soils, the consistency of a given soil type depends on its water content.

MORE INFORMATION

ASTM D2216-10, Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, ASTM International, West Conshohocken, PA, 2010,

www.astm.org

5.6.2 Tests for mechanical properties

The second series of tests comprises the following: compaction tests, determination of specific gravity, permeability, quickshear, triaxial tests, among others. These tests provide the data that are to be used for the design of the infrastructure and for the specification of how the materials must be placed during construction.

E Unit weight (density)

Dry density measurements, are useful for determining degree of soil compaction, and when specific gravity is known, dry density can be used to calculate porosity and void ratio of the soil.

The Bulk density of soils generally varies depending on the moisture content since soil volume changes; hence, moisture content should also be measured when determining the bulk density

MORE INFORMATION

ASTM D7263-09, Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens, ASTM International, West Conshohocken, PA, 2009,

www.astm.org

F Specific gravity

The specific gravity of soils is defined as the ratio between the weight per unit volume of the soil at a stated temperature (usually 20 degrees Celsius) and the weight per unit volume of water. The specific gravity of soil solids is used in calculating the phase relationships of soils, such as void ratio and degree of saturation. It is also used to calculate the density of the soil solids, by multiplying its specific gravity by the density of water (at the standard temperature).

MORE INFORMATION

ASTM D854-14, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, ASTM International, West Conshohocken, PA, 2014,

www.astm.org

G Moisture-density relationship (compaction)

Soil placed as engineering fill and under foundations is compacted to a dense state to obtain satisfactory engineering properties such as, shear strength, compressibility, or permeability. Laboratory compaction tests provide the basis for determining the percent compaction and water content needed to achieve the required engineering properties, and for controlling construction to assure that the required compaction and water contents are achieved.

The Proctor compaction test is a laboratory method of experimentally determining the optimal moisture content at which a given soil type will achieve its maximum dry density. The dry density of a soil for a given compaction effort is dependent on the amount of water the soil contains during soil compaction. The original test is most commonly referred to as the standard Proctor compaction test, which was updated to create the modified Proctor compaction test, in which the compaction effort was increased.

MORE INFORMATION

ASTM D698-12e2, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)), ASTM International, West Conshohocken, PA, 2012, www.astm.org

ASTM D1557-12e1, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)), ASTM International, West Conshohocken, PA, 2012, www.astm.org

H CBR test

This test method is used to evaluate the potential strength of subgrade, subbase, and base course materials, including recycled materials for use in the design of road and airfield pavements. The CBR value obtained in this test forms an integral part of several flexible pavement design methods.

MORE INFORMATION

ASTM D1883-16, Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils, ASTM International, West Conshohocken, PA, 2016, www.astm.org

I Hydraulic conductivity (constant head method)

This test allows for the determination of the coefficient of permeability for the laminar flow of water through granular soils that may occur in natural deposits as placed in embankments, or when used as base courses under pavements. In order to limit consolidation influences, the test is limited to disturbed granular soils containing less than 10 % passing the 75-micron (No. 200) sieve.

MORE INFORMATION

ASTM D2434-68(2006), Standard Test Method for Permeability of Granular Soils (Constant Head) (Withdrawn 2015), ASTM International, West Conshohocken, PA, 2006, www.astm.org

J Consolidation test

The data from the consolidation test are used to estimate the magnitude and rate of both differential and total settlement of a structure or fill. The test is sensitive to sample disturbance and therefore careful selection and preparation of test specimens is required to reduce the potential of disturbance effects.

MORE INFORMATION

ASTM D2435 / D2435M-11, Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading, ASTM International, West Conshohocken, PA, 2011, www.astm.org

K Shear strength

The direct shear test is used to determine the consolidated drained shear strength of a soil material in direct shear. The test is performed by deforming a specimen at a controlled strain rate on or near a single shear plane. Generally, three or more specimens are tested, each under a different normal load, to determine the effects upon shear resistance and displacement. The strength properties such as Mohr strength envelopes, cohesion and peak friction angle are determined.

MORE INFORMATION

ASTM D3080 / D3080M-11, Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, ASTM International, West Conshohocken, PA, 2011, www.astm.org

L Unconfined Compression Test

The Unconfined Compression Test (UCT) is used to assess the mechanical properties of rocks and fine-grained soils that possess sufficient cohesion to permit testing in the unconfined state. It provides a measure of the undrained strength and the stress-strain characteristics of the rock or soil. The test can be conducted on rock samples or on undisturbed, reconstituted cohesive soil samples.

MORE INFORMATION

ASTM D2166 / D2166M-16, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, ASTM International, West Conshohocken, PA, 2016, , www.astm.org

M Triaxial Tests: shear strength (UU/CU/CD)

Conventional triaxial test is a common laboratory testing method widely used for obtaining shear strength parameters for a variety of soil types under drained or undrained condition.

Conventional triaxial test involves subjecting a cylindrical soil sample (100 mm diameter and 200 mm height, enclosed within a thin rubber membrane) to a confining pressure applied by water inside a pressure chamber. Soil samples can be either undisturbed or remoulded.

The sample is placed between two rigid plates, which can move vertically and apply vertical stresses to the specimen. The axial strain/stress of the sample is controlled through the movement of this vertical axis. The volume change of the sample is controlled and measured by the volume of the confining water.

Depending on the combination of loading and drainage condition, three main types of triaxial tests can be carried out:

- Consolidated – Drained (CD)
- Consolidated – Undrained (CU)
- Unconsolidated - Undrained (UU)

From the triaxial test results, it is possible to deduce the shear strength parameters, namely friction angle, cohesion, dilatancy angle and the other dependent parameters. The soil stiffness can be also determined.

MORE INFORMATION

ASTM D4767-11, Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils, ASTM International, West Conshohocken, PA, 2011, www.astm.org
ASTM D2850-15, Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils, ASTM International, West Conshohocken, PA, 2015, www.astm.org

N Swell

The potential of a material (clay) to swell is determined by the One-Dimensional Swell or Collapse of Soils test. The wetting-induced swell/collapse strains measured from the test method can be used to develop estimates of heave or settlement of a confined soil profile. They can also be used to estimate the magnitudes of the swell pressure and the free swell strain. The load-induced strains after wetting can be used to estimate stress-induced settlement following wetting-induced heave or settlement. Selection of test method, loading, and inundation sequences should, as closely as possible, simulate field conditions because relatively small variations in density and water content, or sequence of loading and wetting can significantly alter the test results.

MORE INFORMATION

ASTM D4546-14, Standard Test Methods for One-Dimensional Swell or Collapse of Soils, ASTM International, West Conshohocken, PA, 2014, www.astm.org

O Dynamic test

The dynamic properties of soils are required when designing infrastructure that will be subject to dynamic loading. Examples of structures subject to dynamic loading are foundations for machinery and structures that may be subject to earthquakes. The following tests can be done to determine the dynamic properties of soil:

- Resonant column technique
- Geophysics
- Correlation with SPT
- Dynamic triaxial test

Dynamic soil testing is a highly specialized field and thus when dynamic testing is required, a specialist should be consulted.

MORE INFORMATION

ASTM D4015-15, Standard Test Methods for Modulus and Damping of Soils by Fixed-Base Resonant Column Devices, ASTM International, West Conshohocken, PA, 2015, www.astm.org

ASTM D5311 / D5311M-13, Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil, ASTM International, West Conshohocken, PA, 2013, www.astm.org

6. Geotechnical problems and solutions

The failure to identify problem soils during the site investigation can lead to stability risks for built infrastructure.

Problems in soils can result in geotechnical issues such as inadequate bearing capacity, unacceptable settlements and instability of slopes.

Sometimes extreme weather conditions or geological events can lead to rapid unexpected changes in soil bearing capacity or volume.

This section of the guideline identifies common problem soils, together with their geotechnical risks and methods to identify and mitigate against the risks. If problematic soils are expected, a specialist should be consulted.

6.1 Expansive soils

Expansive soil refers to soils that undergo volumetric changes (shrinking or swelling) under changing moisture conditions. Expansive soils pose a hazard to foundations for light structures.

The expansive nature is due to the swelling of clay minerals (smectites) present in expansive soils. When exposed to water, the clay minerals absorb the water molecules, expand, and under dry conditions the clay minerals shrink resulting in voids in the soil. The volume changes in the soil induces stresses in the foundations leading to cracking and damage to the structure. Seasonal wetting and drying cycles compound the problem.

The origin and formation mechanism of expansive soils are well known, and generally, geological knowledge can be used to identify the occurrence of these soils. Generally, expansive soils originate from either basic (alkali) igneous rocks or argillaceous (clay containing) sedimentary rocks.

Countermeasures to the presence of expansive soils include the design of special foundation measures such as raft foundations and piled foundations, and drainage and protection measures to prevent cyclic drying or wetting of the material. Foundation levels can be designed to mitigate the effect of expansive soils by raising the foundation high enough with quality material that reflective cracking does not occur.

6.2 Collapsible soils

Collapsible soils are typically comprised of poorly graded, clayey fine sand and silt mixtures with a porous texture. They are derived from residual, aeolian or hill-wash geological processes. The fine sand particles are interconnected by clay bridges. When subjected a trigger mechanism such as wetting under load, stress changes, dynamic loading or earth tremors, the clay collapses, leading to a sudden and irreversible decrease in the soil volume. The volumetric decrease can be up to 20%. The collapse generally occurs in local pockets under the structure, resulting in localized damage to structures.

Collapsible soils are typically identified from geological maps, since the occurrence of a collapsible soil fabric is a result of very specific geological conditions, which lead to the formation of silty sand or sandy silt with a low percentage of clay-sized particles. A collapsible soil fabric generally occurs in wind deposited sands (loess); old, highly weathered and leached granite soils; or residually weathered sandstones, but in some instances also in soils which have been deposited by sheet wash, gulley wash, wave action, or termite activity.

If a collapsible soil is identified prior to construction, preventative measures can simply be proper densification or compaction of the soil to ensure the soil collapses prior to construction.

6.3 Compressible soils (soft clays)

Soft clays are soils of low shear strength (less than 40kPa) and high moisture content, which consolidate over an extended time span (typically over months and years) after a structure has been placed on them.

The clayey soil is generally normally consolidated and of recent geological origin. Due to the low permeability of clay materials, the soil takes a long time to consolidate under load, by expelling water many years may pass before the soil moisture can be sufficiently expelled to complete the consolidation process, and the rate of consolidation may vary across the horizon leading to differential consolidation and differential settlement in structures.

These materials often lead to slope instability and structural damage when underlying road embankments, dams or other fixed structures, and may undergo sudden shear failure upon load application.

Mitigation measures can include provision of drainage structures to accelerate consolidation, soil improvement such as stabilisation or special foundation treatment to bridge the problem soil horizons.

6.4 Acidic soils

Acid soils can be found as:

- Naturally occurring acidic soils in high rainfall areas;
- Acid sulphate soils of coastal areas; and
- Soils polluted by sulphide rich industrial waste or acidic leachate.

The pH of acid soils can reach levels below three and such soils can become very corrosive to concrete and metal infrastructure and underground services, apart from the environmental and ecological hazards.

Mitigation measures can include treatment of the acids soils with lime (for thin layers); removal of the acid soils prior to construction; the use high corrosion resistant materials; protective coatings and cathodic protection.

6.5 Dispersive soils

Dispersive soils are soils that are highly susceptible to erosion by flowing surface water. Dispersion occurs in clays with a high sodium content (sodic soils). The sodium in the soil allows the particles to break down and be transported easily.

The simplest mitigation of dispersion is burial and revegetation of dispersive soils, however dispersive soils can be treated with gypsum or lime if burial and revegetation is not possible.

6.6 Soils at risk of liquefaction

Liquefaction is the temporary loss of strength in saturated, cohesionless soils due to the increased pore pressures caused by dynamic loading. Seismic forces such as earthquakes are the most common causes of liquefaction; the shaking causes the water pressure in the soil to increase allowing particles to move freely.

The risk of liquefaction can be mitigated with compaction techniques such as vibro compaction, dynamic compaction and vibro stone columns. Drains may also be used to dissipate pore pressures before reaching critical levels. If this is not possible, the soil may be improved using compaction grouting to prevent liquefaction. Robust structures that can withstand liquefaction can be designed, however this would have a considerable cost implication.

6.7 Other Geotechnical Problems

For other geotechnical problems as landslides, karst, scour, among others. Please seek for guidance with a geotechnical expert.

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