

NIGERIA MARITIME UNIVERSITY

Okerenkoko, Warri South-West, Delta State

Department of Marine Geology

MGY 321

Engineering Geology

Lecture Note

Introduction to Engineering Geology · Soil Classification

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Course information

This note covers two parts of MGY 321: an introduction to engineering geology, and the description and classification of soils for engineering purposes.

Item	Detail
Course	MGY 321: Engineering Geology
Level	300 level, first semester, 2026/2027 session
Department	Marine Geology
Institution	Nigeria Maritime University, Okerenkoko, Warri South-West, Delta State
Lecturer	Dr. Daniel Tuoyo Amiwero
Part covered by this note	Introduction to engineering geology; soil classification

Learning outcomes

At the end of this part of the course, you should be able to:

1. Define engineering geology, explain how it differs from geotechnical engineering, and describe the role of the engineering geologist at each stage of a project.
2. Explain how rock type, structure, weathering, groundwater and natural hazards affect engineering works, using lessons from major dam and slope failures.
3. Describe the stages and main methods of a site investigation.
4. Use phase relationships to calculate water content, void ratio, porosity, degree of saturation and unit weight, and calculate total and effective stress.
5. Describe a soil in the field using a standard order of terms.
6. Determine and interpret particle size distribution, Atterberg limits, plasticity index, liquidity index, activity and relative density.
7. Classify soils using the Unified Soil Classification System, the AASHTO system and the British system.
8. Recognise problem soils in Nigeria, including lateritic soils, expansive clays and the soft organic clays of the Niger Delta.

Why engineering geology matters to a marine geologist

Ports, jetties, breakwaters, pipelines, offshore platforms, dredged channels and coastal defences are all built on or in the ground of the coast and the seabed. In the Niger Delta that ground is often soft clay, loose sand, silt or peat, with a high water table. Many of the graduates of this department will work on such projects or on the site investigations that come before them. They need to describe the ground correctly, classify its soils in a language engineers understand, and recognise the geological conditions that cause foundations, slopes and embankments to fail.

Section 1: Introduction to engineering geology

Every road, bridge, building, dam, tunnel, jetty and pipeline rests on or in the ground. Engineering geology is the branch of geology that makes sure the ground is understood before,

during and after such works are built. It applies the knowledge of rocks, soils, structures, groundwater and surface processes to the practical problems of construction and land use.

1.1 What is engineering geology?

The International Association for Engineering Geology and the Environment (IAEG) describes engineering geology as the science that investigates and solves the engineering and environmental problems that arise when geology and human activities interact. It also includes predicting geological hazards and developing measures to prevent or remedy them.

In practice, the engineering geologist answers questions such as:

- What materials lie beneath the site, how thick are they, and how do they vary?
- How strong and how compressible are they, and how will they behave when loaded, excavated or wetted?
- Where is the groundwater, and how will it affect the works?
- Which natural processes, such as landslides, erosion, flooding or subsidence, threaten the site?
- Where can suitable construction materials, such as aggregate, sand, laterite or clay, be found?

Engineering geology overlaps with several neighbouring disciplines:

Discipline	Main concern
Engineering geology	The geological conditions of a site and their effect on engineering works
Soil mechanics	The physical and mechanical behaviour of soils: strength, compressibility, seepage
Rock mechanics	The mechanical behaviour of intact rock and rock masses
Geotechnical engineering	The design of foundations, slopes, retaining walls, tunnels and earthworks using soil and rock mechanics
Hydrogeology	The occurrence and movement of groundwater

The engineering geologist provides the **ground model**: a description of what is in the ground and how it is arranged. The geotechnical engineer uses that model, with test results, to design the works. The two must work closely together, because a design is only as good as the ground model it is based on.

1.2 Lessons from failures

Many of the principles of engineering geology were learnt from failures. Four classic cases show how geology that was not understood led to disaster:

- **St Francis Dam, California (1928).** A concrete gravity dam failed on its first filling, killing more than 400 people. One abutment rested on a conglomerate that softened and lost strength when wet, and the other on schist with signs of old landslides. The failure led to new dam safety laws in California and a greater role for geologists in dam design.
- **Malpasset Dam, France (1959).** A thin concrete arch dam failed when water pressure built up beneath it along a fault and joints in the gneiss of the foundation, pushing out a wedge of rock. About 420 people died.
- **Vajont Dam, Italy (1963).** About 270 million cubic metres of rock slid from the side of the valley into the reservoir. The slide moved on thin clay layers in limestone beds that

dipped towards the valley, and filling the reservoir had raised the water pressure in the slope. The wave overtopped the dam and destroyed the town of Longarone; about 2,000 people died. The dam itself survived.

- **Teton Dam, Idaho (1976).** An earth dam failed on its first filling when water flowed through open joints in the volcanic rock of the abutment and eroded the core of the dam from inside (internal erosion, or piping).

In each case the structure was designed by competent engineers. What failed was the understanding of the ground. In Nigeria, failures are more often smaller but frequent: buildings that crack or settle on soft or expansive soils, roads that break up on clay-rich subgrades, and slopes, gully walls and riverbanks that collapse.

1.3 The engineering geologist in a project

The engineering geologist is involved at every stage of a project, not only at the start (Figure 1.1).

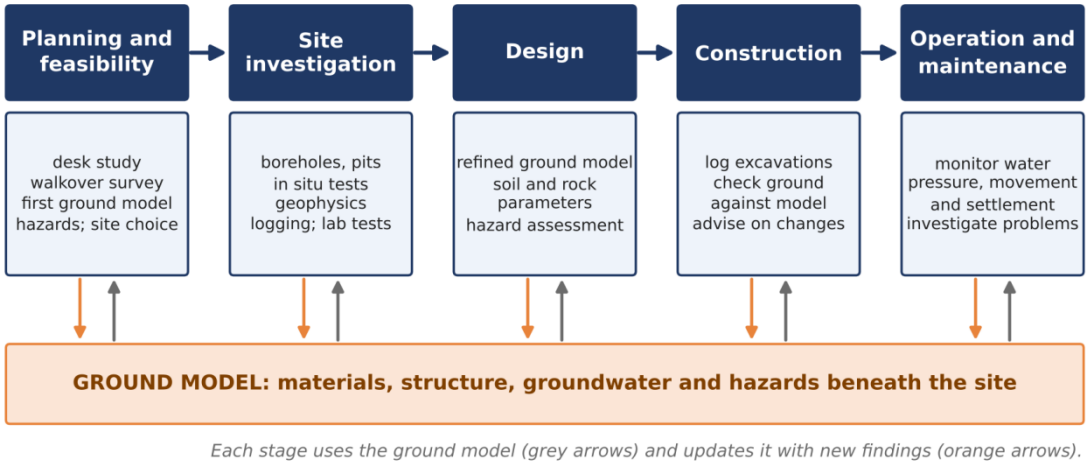


Figure 1.1. The stages of an engineering project and the main tasks of the engineering geologist at each stage. Findings at each stage feed back to the ground model.

Stage	Main tasks of the engineering geologist
Planning and feasibility	Desk study of geological maps, reports, satellite images and old borehole records; site walkover; first ground model; identify hazards and alternative sites
Site investigation	Plan and supervise boreholes, trial pits, in situ tests and geophysical surveys; log cores and samples; choose laboratory tests
Design	Refine the ground model; provide soil and rock parameters; assess hazards such as slope failure, settlement and flooding
Construction	Log excavations and foundations; check that the ground matches the model; advise on changes when it does not
Operation and maintenance	Monitor groundwater pressures, movement and settlement; investigate problems and failures

1.4 Geological factors that affect engineering works

Rock and soil type. The material determines strength, compressibility and permeability. A granite, a shale and a soft clay behave very differently under a foundation.

Discontinuities. Joints, faults, bedding planes and foliation are planes of weakness. They control the strength and permeability of a rock mass far more than the strength of the intact rock. Slopes and tunnels usually fail along discontinuities, as at Malpasset and Vajont.

Weathering. Weathering weakens rock and turns it into soil. In tropical Nigeria, chemical weathering of the basement complex has produced weathering profiles that can be tens of metres thick. Engineers describe the degree of weathering on a six-grade scale (Figure 1.2):

Grade	Term	Description
I	Fresh	No visible sign of weathering; perhaps slight discolouration on major joint surfaces
II	Slightly weathered	Discolouration of the rock and joint surfaces
III	Moderately weathered	Less than half of the rock is decomposed or broken down to soil
IV	Highly weathered	More than half of the rock is decomposed or broken down to soil
V	Completely weathered	All the rock is decomposed to soil, but the original structure of the rock mass is still visible
VI	Residual soil	All the rock is converted to soil; the rock structure and fabric are destroyed

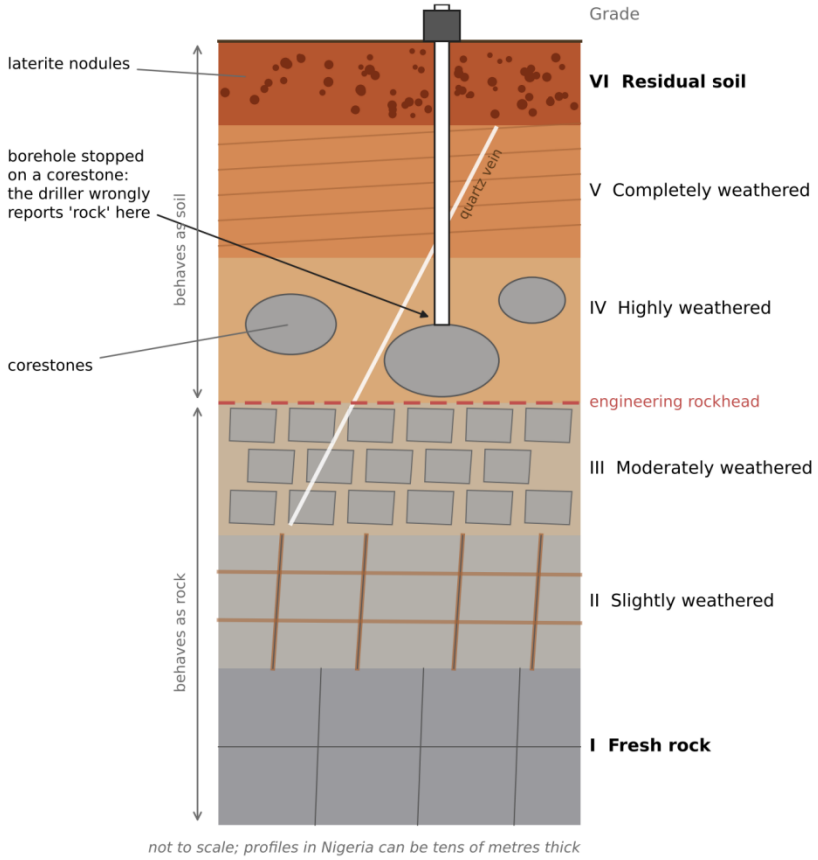


Figure 1.2. A tropical weathering profile on granite, showing the engineering grades of weathering. Corestones of fresher rock in grades IV and V can be mistaken for bedrock in a borehole.

A practical consequence is that **rockhead** (the top of fresh rock) is irregular, and boulders of fresh rock called **corestones** float in the weathered zone. A borehole that hits a corestone may be stopped too early by a driller who thinks bedrock has been reached. Boreholes for important structures should therefore prove rock for several metres.

Groundwater. Water pressure in pores and joints reduces the strength of soil and rock (Section 1.5), pushes up on dams and basements, causes seepage into excavations, and drives piping. Changes in water level cause swelling, shrinkage and settlement.

Geomorphological processes and hazards. Landslides, gully erosion, river and coastal erosion, flooding and subsidence must be identified and allowed for. In the Niger Delta the ground is slowly subsiding as young sediments compact, adding to the flood risk.

Earthquakes. Nigeria lies far from plate boundaries and its seismic risk is low, but small earthquakes do occur and are considered in the design of critical structures such as large dams.

Construction materials. Engineering geologists locate and test sources of aggregate, sand, laterite for roads and clay for embankments and liners.

Describing rock for engineering. Rock cores and exposures are described in a standard order similar to that used for soils (Section 2.1): strength, weathering grade, colour, grain size, texture and structure, ROCK NAME, and the spacing and nature of the discontinuities. For example: "Strong, slightly weathered, pinkish grey, coarse-grained GRANITE with widely spaced joints". The strength of the intact rock is described by its uniaxial compressive strength (UCS):

Term	Uniaxial compressive strength (MPa)	Field guide
Very weak	1 to 5	Crumbles under firm blows of a geological hammer; can be peeled with a knife
Weak	5 to 25	Can be peeled with a knife with difficulty; shallow marks with the hammer point
Medium strong	25 to 50	Cannot be scraped with a knife; fractured by a single firm hammer blow
Strong	50 to 100	Needs more than one hammer blow to fracture
Very strong	100 to 250	Needs many hammer blows to fracture
Extremely strong	over 250	Can only be chipped with the hammer

Material weaker than about 1 MPa is described as extremely weak rock or treated as soil. The spacing of discontinuities is described with terms ranging from "extremely close" (less than 20 mm) through "close" (60 to 200 mm), "medium" (200 to 600 mm) and "wide" (600 mm to 2 m) to "extremely wide" (more than 6 m). Closely jointed rock behaves more like a soil, however strong the intact pieces are.

1.5 Basic engineering concepts: stress and effective stress

Engineers describe the load on the ground as **stress** (σ), the force per unit area. Its unit is the pascal (Pa); in practice the kilopascal (kPa, kN/m^2) is used. Stress causes **strain**, the change in length divided by the original length.

The **total vertical stress** at depth z is the weight of everything above a unit area. For layers of thickness z_i and unit weight γ_i:

$$\sigma_v = \sum \gamma_i z_i$$

Below the water table, water in the pores is under pressure. The **pore water pressure** (u) at a depth z_w below the water table is:

$$u = \gamma_w z_w$$

where γ_w is the unit weight of water, 9.81 kN/m^3.

Karl Terzaghi, the founder of soil mechanics, showed that the behaviour of soil is controlled not by the total stress but by the **effective stress** (σ'), the part of the stress carried by the contacts between grains:

$$\sigma' = \sigma - u$$

The **shear strength** of soil (τ_f) depends on effective stress through the Mohr–Coulomb criterion:

$$\tau_f = c' + \sigma' \tan\phi'$$

where c' is the cohesion and ϕ' the angle of shearing resistance. This explains why a rise in groundwater weakens a slope: it increases u, reduces σ' and so reduces the strength.

Worked example. At a site in the Niger Delta, the water table is 1.0 m below ground level. The soil has a unit weight of 17.0 kN/m^3 above the water table and a saturated unit weight of 18.5 kN/m^3 below it. Find the effective vertical stress at 6.0 m depth.

$$\sigma_v = (17.0 \times 1.0) + (18.5 \times 5.0) = 17.0 + 92.5 = 109.5 \text{ kPa}$$

$$u = 9.81 \times 5.0 = 49.1 \text{ kPa}$$

$$\sigma' = 109.5 - 49.1 = 60.4 \text{ kPa}$$

Only about 55% of the total stress is carried by the soil grains. If a flood raised the water table to the ground surface, the whole 6 m would be saturated: $\sigma_v = 18.5 \times 6.0 = 111.0$ kPa, $u = 9.81 \times 6.0 = 58.9$ kPa and $\sigma' = 52.1$ kPa. The effective stress would fall by about 14%, and the frictional part of the shear strength would fall by the same proportion.

1.6 Site investigation

A **site investigation** finds out the ground conditions at a site so that the works can be designed safely and economically. It usually follows these stages:

1. **Desk study:** collect geological, topographical and soil maps, satellite images and aerial photographs, records of old boreholes and wells, and reports of earlier works, floods or failures nearby.
2. **Site reconnaissance (walkover survey):** inspect the site for outcrops, springs, signs of slope movement, cracked buildings, erosion, flooding and access.
3. **Ground investigation:** explore the ground with boreholes, trial pits, in situ tests and geophysical surveys, and take samples for laboratory testing.
4. **Laboratory testing:** classification tests (Section 2), and strength, compressibility and permeability tests.
5. **Reporting:** a factual report of what was found, and an interpretative report with the ground model and design parameters.

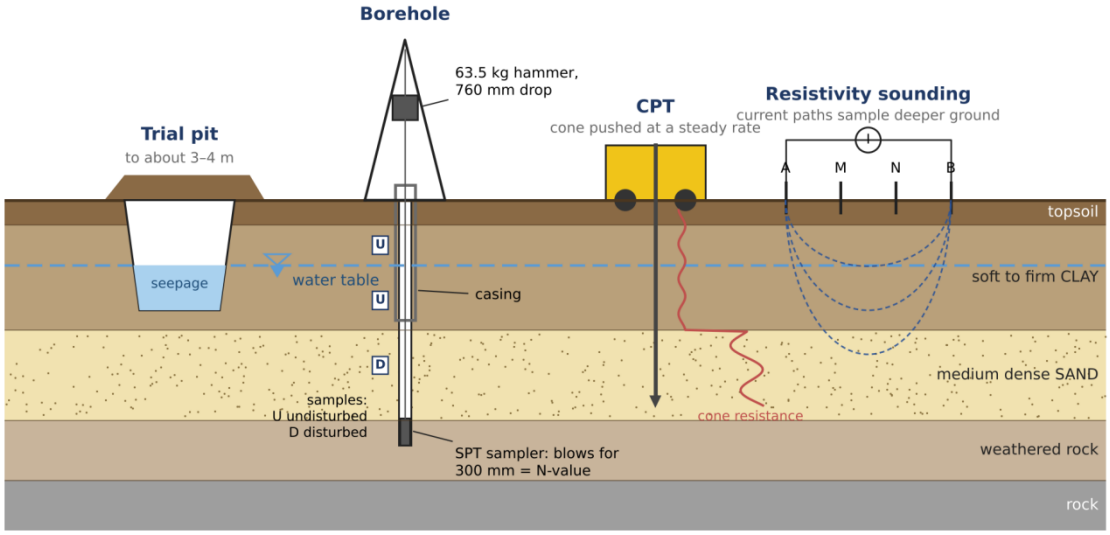


Figure 1.3. Common methods of ground investigation. Trial pits expose shallow soil; boreholes reach deeper soil and rock; the SPT and CPT test the ground in place; geophysical surveys fill in the ground between holes.

The main methods are (Figure 1.3):

- **Trial pits:** dug by hand or excavator to about 3 to 4 m. They show the soil layers clearly and allow block samples, but cannot go below the water table easily.
- **Hand auger:** a cheap way to sample shallow soft soils, widely used in the swamps of the Niger Delta.
- **Cable percussion boring:** a heavy tool is dropped repeatedly to advance a cased hole in soil. It is the most common method for building sites in Nigeria.
- **Rotary core drilling:** a rotating diamond or tungsten carbide bit cuts a continuous core of rock, which is logged for rock type, weathering grade and discontinuities.
- **Standard penetration test (SPT):** a split-barrel sampler is driven into the bottom of a borehole by a 63.5 kg hammer falling 760 mm. After a seating drive of 150 mm, the number of blows needed to drive it a further 300 mm is the **N-value**. It is used mainly to estimate the density of sands (Section 2.5).
- **Cone penetration test (CPT):** a cone with a 60° tip is pushed into the ground at a steady rate while the resistance on the tip and the friction on a sleeve are recorded. It gives a continuous profile and is well suited to the soft soils of the delta.
- **Vane shear test:** a four-bladed vane is pushed into soft clay and rotated; the torque gives the undrained shear strength.
- **Geophysical methods:** electrical resistivity (vertical electrical sounding is very widely used in Nigeria), seismic refraction and ground-penetrating radar give information between boreholes, such as depth to rock or the water table.

Samples are **disturbed** (bulk or bag samples, used for classification) or **undisturbed** (taken in tubes to keep the soil structure for strength and compressibility tests). Thin-walled tubes or piston samplers are needed in soft clays. Groundwater levels are recorded during boring and monitored afterwards in standpipes or piezometers.

Boreholes should be deep enough to pass through all the ground that will be stressed or affected by the works. For shallow foundations this is commonly 1.5 to 3 times the foundation width; for piles and dams, holes must reach and prove the bearing stratum or rock.

The results are presented on **borehole logs**, which record for each layer its depth, description (Section 2.1), samples, in situ test results and groundwater observations (Figure 1.4).

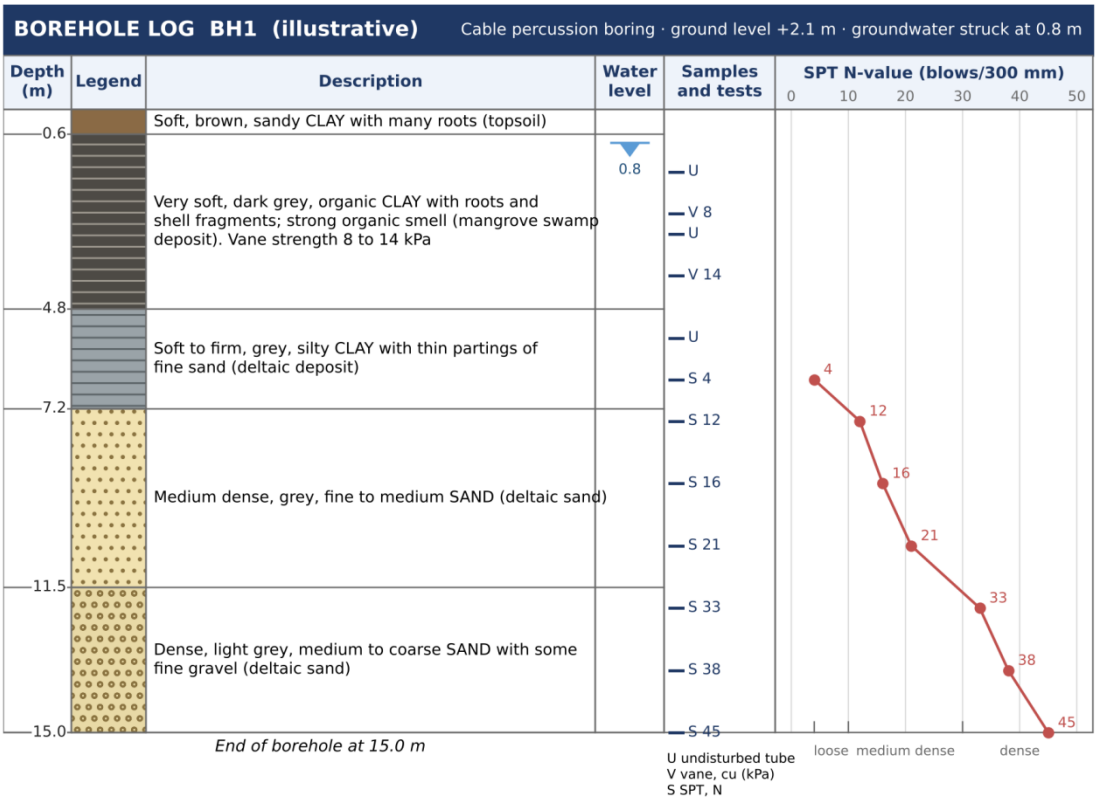


Figure 1.4. An illustrative borehole log of the kind produced for a site in the Niger Delta: soft organic clay over sands whose density increases with depth, shown by rising SPT N-values.

The log in Figure 1.4 shows a typical pattern for the delta. The soft clays near the surface would settle heavily under any significant load, so a jetty or building would be founded on piles driven into the dense sand below about 12 m.

1.7 Engineering geology in Nigeria

Ground condition	Where it occurs	Engineering problems
Soft organic clays and peat	Mangrove swamps and creeks of the Niger Delta, including the Okerenkoko and Warri areas; lagoon margins in Lagos	Very low strength; large and long-continued settlement; need for piles, sand filling or ground improvement
Loose saturated sands	Niger Delta, beach ridges and barrier islands	Scour around piers and jetties; boiling and collapse in excavations below the water table
Expansive clays (black cotton soils)	North-east, especially the Chad Basin around Maiduguri; parts of the Benue Trough	Seasonal swelling and shrinkage; cracked buildings, broken pavements
Lateritic soils	Widespread in the south and over the basement complex	Good road material when well graded; poor when clay-rich; properties change on drying
Deep weathering of the basement	South-west and north-central Nigeria	Irregular rockhead; corestones; variable foundations and excavations

Ground condition	Where it occurs	Engineering problems
Gully erosion	South-east (Agulu–Nanka in Anambra State, Imo, Abia) and Edo State	Loss of land, roads and houses; collapse of gully walls
Coastal erosion and flooding	Lagos, Ondo, Delta and Bayelsa coasts	Loss of land and coastal infrastructure; damage to jetties and roads
Land subsidence	Niger Delta	Higher flood risk; damage to pipelines and buildings

Many of these problems are first recognised by classifying the soils correctly, which is the subject of Section 2.

1.8 Key points of Section 1

- Engineering geology applies geology to the design, construction and maintenance of engineering works and to the management of geological hazards.
- The engineering geologist provides the ground model, which the geotechnical engineer uses for design. Many disasters were caused by an incomplete ground model.
- Rock and soil type, discontinuities, weathering, groundwater and natural processes all affect engineering works.
- Soil behaviour is controlled by effective stress, $\sigma' = \sigma - u$; a rise in groundwater lowers strength.
- A site investigation proceeds from desk study and walkover to boreholes, pits, in situ tests, geophysics, laboratory tests and reports.

Section 2: Soil classification

To an engineer, **soil** is any loose or weakly bonded natural deposit of mineral grains, with or without organic matter, that can be separated by gentle means such as shaking in water. Everything else is **rock**. Weak rocks and strong soils overlap, and a completely weathered rock (grade V) may be treated as either.

Soils vary enormously, from soft organic clay in a mangrove swamp to dense gravel in a river bed. **Soil classification** sorts them into groups with similar engineering behaviour, using simple tests that are cheap and quick to run. It does not replace strength or compressibility tests, but it:

- gives engineers and geologists a common language for describing soils;
- allows experience from one site to be applied to another with the same soil type;
- helps to plan the more expensive tests and to check their results;
- gives a first indication of suitability, for example as a foundation, a road subgrade or fill.

Classification uses two kinds of property: the **particle size distribution**, which controls the behaviour of coarse soils, and the **plasticity**, which controls the behaviour of fine soils.

The main classification tests and the standards that describe them are listed below. In Nigeria, laboratories commonly follow BS 1377 or the equivalent ASTM methods.

Test	What it measures	British standard	ASTM standard	Section

Test	What it measures	British standard	ASTM standard	Section
Water content	Mass of water per mass of dry soil	BS 1377-2	D2216	2.2
Specific gravity	Density of the soil grains	BS 1377-2	D854	2.2
Sieve analysis	Distribution of sand and gravel sizes	BS 1377-2	D6913	2.3
Sedimentation (hydrometer)	Distribution of silt and clay sizes	BS 1377-2	D7928	2.3
Liquid and plastic limits	Plasticity of the fine fraction	BS 1377-2	D4318	2.4
Organic matter content	Organic content	BS 1377-3	D2974	2.9

2.1 Describing soils in the field

Before any test is run, each soil is described from its appearance and feel. British practice (BS 5930) gives the description in a standard order:

1. **Consistency** of fine soils (for example soft, firm, stiff) or **density** of coarse soils (for example loose, dense) (Section 2.5).
2. **Structure**: fissured, laminated, bedded, homogeneous.
3. **Colour**: for example greyish brown, mottled red and yellow.
4. **Secondary constituents**: for example slightly sandy, gravelly, with shell fragments, with roots.
5. **Principal soil type**, written in capital letters: CLAY, SILT, SAND, GRAVEL, PEAT.
6. **Geological origin or formation**, in brackets where known.

Examples:

- Firm, fissured, greyish brown, slightly sandy CLAY (Imo Shale).
- Medium dense, light brown, clayey, fine to coarse SAND (Benin Formation).
- Very soft, dark grey, organic CLAY with roots and shell fragments (mangrove swamp deposit).

Simple field tests separate the main types. Sand grains can be seen and feel gritty. Silt feels slightly gritty between the teeth, dries quickly and dusts off the fingers; when a wet pat is shaken, water appears on its surface (**dilatancy**). Clay feels smooth and sticky, can be rolled into thin threads, dries slowly and is hard when dry.

2.2 Phase relationships

A soil is made of three **phases**: solid grains, water and air (Figure 2.1). Many engineering properties depend on the proportions of these phases, so a set of standard ratios is used.

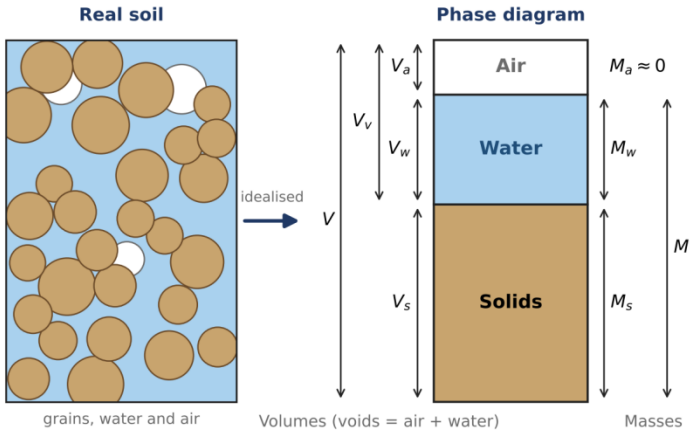


Figure 2.1. The phase diagram of a soil. The volumes of air, water and solids are shown on the left and their masses on the right. The voids are the spaces filled by air and water.

The **water content** (moisture content, w) is the mass of water divided by the mass of dry solids, expressed as a percentage. It is measured by weighing a sample, drying it in an oven at 105 to 110 °C, and weighing it again:

$$w = \frac{M_w}{M_s} \times 100$$

The **void ratio** (e) and **porosity** (n) describe how much of the soil is open space:

$$e = \frac{V_v}{V_s} \qquad n = \frac{V_v}{V}$$

They are related by:

$$n = \frac{e}{1+e} \qquad e = \frac{n}{1-n}$$

The **degree of saturation** (S) is the fraction of the voids filled with water. It is 0 for a dry soil and 1 (100%) for a saturated soil:

$$S = \frac{V_w}{V_v}$$

The **specific gravity of the solids** (G_s) is the density of the grains divided by the density of water. It is about 2.65 for quartz sands and 2.6 to 2.8 for most clays; lateritic soils rich in iron oxides may exceed 2.9. A very useful relationship links four of these quantities:

$$Se = wG_s$$

Bulk density (ρ) is the total mass divided by the total volume, and **dry density** (ρ_d) is the mass of solids divided by the total volume. The corresponding unit weights are found by multiplying by g (9.81 m/s^2):

$$\rho = \frac{M}{V} \qquad \rho_d = \frac{\rho}{1+w} = \frac{G_s \rho_w}{1+e}$$

$$\gamma = \rho g \qquad \gamma_{sat} = \frac{(G_s + e)\,\gamma_w}{1+e}$$

where ρ_w is the density of water (1.00 Mg/m^3) and γ_{sat} is the saturated unit weight. In the dry density formula, w is used as a decimal.

Worked example. A core cutter of volume 1.00×10^{-3} m^3 is driven into a clayey sand. The soil in it has a mass of 1.85 kg, and 1.60 kg after oven drying. $G_s = 2.68$. Find w, ρ, ρ_d, e, n and S.

$$w = \frac{1.85 - 1.60}{1.60} \times 100 = 15.6\%$$

$$\rho = \frac{1.85}{1.00 \times 10^{-3}} = 1850 \text{ kg/m}^3 = 1.85 \text{ Mg/m}^3 \qquad \rho_d = \frac{1.60}{1.00 \times 10^{-3}} = 1.60 \text{ Mg/m}^3$$

$$e = \frac{G_s \rho_w}{\rho_d} - 1 = \frac{2.68 \times 1.00}{1.60} - 1 = 0.675 \qquad n = \frac{0.675}{1.675} = 0.403$$

$$S = \frac{w G_s}{e} = \frac{0.156 \times 2.68}{0.675} = 0.62$$

The soil has a porosity of about 40% and its voids are 62% full of water. Its bulk unit weight is $1.85 \times 9.81 = 18.1$ kN/m^3.

2.3 Particle size distribution

Soil particles range from boulders more than a metre across to clay particles less than a thousandth of a millimetre. The size ranges are given names, but the boundaries differ slightly between standards:

Fraction	BS 5930 (mm)	USCS, ASTM D2487 (mm)	AASHTO (mm)
Boulders	over 200	over 300	—
Cobbles	63 to 200	75 to 300	over 75 (with boulders)
Gravel	2 to 63	4.75 to 75	2 to 75
Sand	0.063 to 2	0.075 to 4.75	0.075 to 2
Silt	0.002 to 0.063	Fines: below 0.075 (silt and clay separated by plasticity)	0.002 to 0.075
Clay	below 0.002		below 0.002

In BS 5930, sand and gravel are each divided into fine, medium and coarse. For sand the divisions are at 0.2 mm and 0.63 mm; for gravel at 6.3 mm and 20 mm.

Sieve analysis. The coarse fraction is measured by shaking a dried sample through a stack of sieves with decreasing openings and weighing the soil retained on each. If the soil contains fines, it is first washed through the 0.063 mm (or 0.075 mm) sieve. The result is plotted as the **percentage finer** (passing) against particle size on a logarithmic scale, giving the **particle size distribution curve** (grading curve, Figure 2.2).

Sedimentation (hydrometer or pipette) analysis. Particles finer than about 0.063 mm are too small to sieve. They are dispersed in water, and their size is found from the speed at which they settle. A small sphere settles at a terminal velocity given by **Stokes' law**:

$$v = \frac{(\rho_s - \rho_w)\, g\, D^2}{18\, \eta}$$

where D is the particle diameter, ρ_s and ρ_w are the densities of the particles and water, and η is the viscosity of water (about 1.0×10^{-3} Pa·s at 20 °C).

Worked example. How fast does a silt particle 0.01 mm in diameter, with $\rho_s = 2650$ kg/m^3, settle in water? How long does it take to fall 100 mm?

$$v = \frac{(2650 - 1000) \times 9.81 \times (1.0 \times 10^{-5})^2}{18 \times 1.0 \times 10^{-3}} = 9.0 \times 10^{-5} \text{ m/s} \approx 0.09 \text{ mm/s}$$

It falls 100 mm in about 1,100 s, or 18.5 minutes. Because v depends on D^2, a clay particle 0.002 mm across settles 25 times more slowly and takes nearly 8 hours to fall the same distance. This is why sedimentation tests take a day to complete.

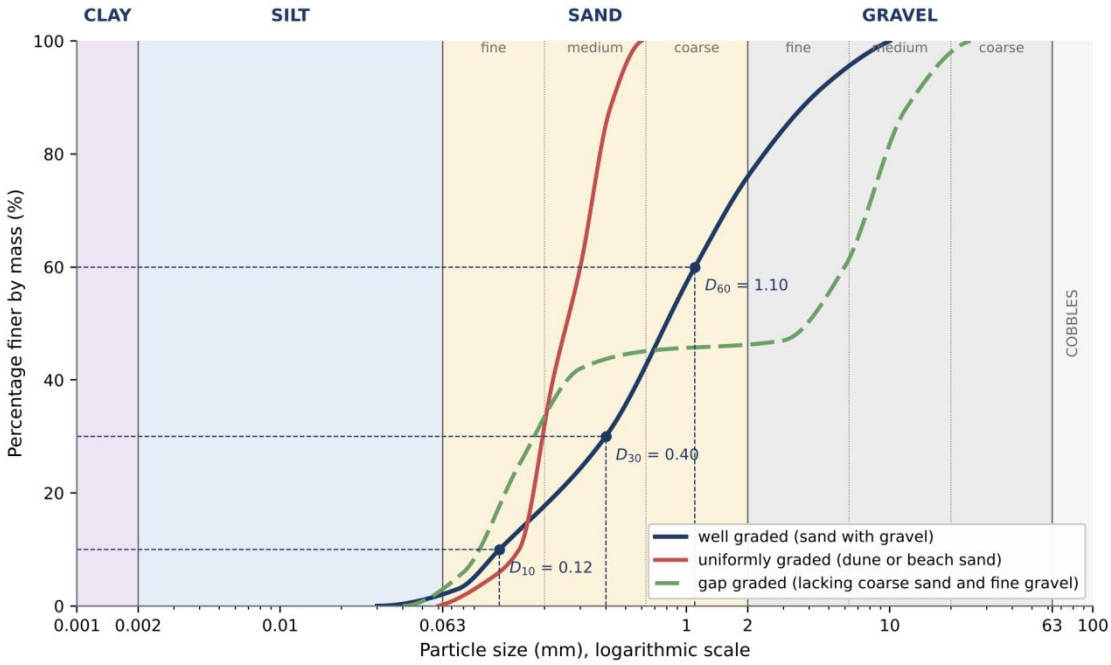


Figure 2.2. Particle size distribution curves. A well-graded soil has a wide range of sizes; a uniformly graded soil has most grains of about the same size; a gap-graded soil lacks a range of sizes. D10, D30 and D60 are marked for the well-graded soil.

Describing the grading. From the curve we read D_{10}, D_{30} and D_{60}, the particle sizes than which 10%, 30% and 60% of the soil by mass is finer. D_{10} is called the **effective size**. Two coefficients describe the shape of the curve:

$$C_u = \frac{D_{60}}{D_{10}} \qquad C_c = \frac{D_{30}^2}{D_{10} \times D_{60}}$$

C_u is the **coefficient of uniformity** and C_c the **coefficient of curvature** (or gradation). A soil is **well graded** if it has a wide range of sizes with no gaps or excess of any one size. In the Unified system a gravel is well graded if $C_u \geq 4$ and $1 \leq C_c \leq 3$; a sand is well graded if $C_u \geq 6$ and $1 \leq C_c \leq 3$. Otherwise it is **poorly graded**, which includes **uniformly graded** soils (low C_u) and **gap-graded** soils (C_c outside 1 to 3).

Grading matters because well-graded soils pack densely, are strong and compact well, which is why they make good road and fill materials. Uniform sands, such as many beach and river sands of the Niger Delta, are more permeable, harder to compact and more easily eroded.

Worked example. For a sand, $D_{10} = 0.12$ mm, $D_{30} = 0.40$ mm and $D_{60} = 1.10$ mm.

$$C_u = \frac{1.10}{0.12} = 9.2 \qquad C_c = \frac{0.40^2}{0.12 \times 1.10} = \frac{0.160}{0.132} = 1.21$$

Since $C_u \geq 6$ and C_c lies between 1 and 3, the sand is well graded.

2.4 Plasticity and the Atterberg limits

The behaviour of a fine soil depends strongly on its water content. A clay with very little water is hard and brittle; with more water it becomes plastic and can be moulded without cracking; with still more it flows like a thick liquid. In 1911 the Swedish scientist Albert Atterberg defined water contents that mark the boundaries between these states. They were adapted for engineering by Arthur Casagrande and are now called the **Atterberg limits** (Figure 2.3):

- The **liquid limit** (LL, w_L) is the water content above which the soil behaves as a liquid.
- The **plastic limit** (PL, w_P) is the water content below which the soil is no longer plastic and crumbles when moulded.
- The **shrinkage limit** (SL, w_S) is the water content below which further drying causes no further decrease in volume.

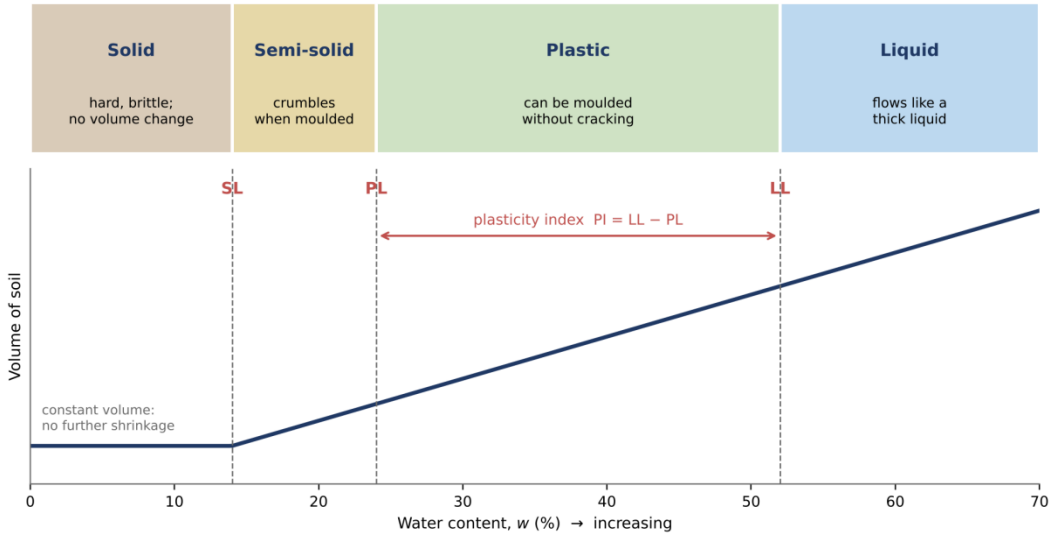


Figure 2.3. The states of consistency of a fine soil and the Atterberg limits. The lower graph shows how the volume of the soil changes as it dries.

Determining the liquid limit. In the **Casagrande cup** method, a pat of soil paste is placed in a brass cup and a groove is cut through it. The cup is dropped repeatedly through 10 mm onto a hard base, and the number of blows needed to close the groove over a length of about 13 mm is counted. The test is repeated at several water contents, and the results are plotted as water content against the number of blows on a logarithmic scale. This **flow curve** is a straight line, and the liquid limit is the water content at 25 blows (Figure 2.4). In the **cone penetrometer** method preferred in British practice, an 80 g cone with a 30° tip is allowed to sink into the soil for 5 seconds; the liquid limit is the water content at which it penetrates 20 mm.

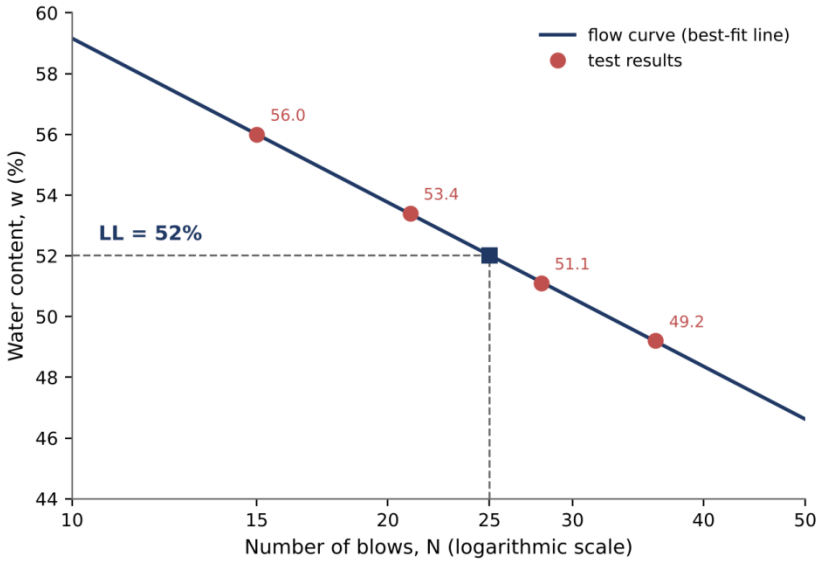


Figure 2.4. Flow curve from a Casagrande liquid limit test. The liquid limit is read at 25 blows.

Determining the plastic limit. A small ball of soil is rolled by hand on a glass plate into a thread. The plastic limit is the water content at which the thread just begins to crumble when it reaches 3 mm in diameter.

Plasticity and consistency indices. The range of water content over which the soil is plastic is the **plasticity index** (PI, I_P):

$$\text{PI} = \text{LL} - \text{PL}$$

A soil with no measurable plastic limit, such as a clean sand, is described as **non-plastic** (NP). The natural water content (w) of a soil can be compared with its limits through the **liquidity index** (LI) and the **consistency index** (CI):

$$\text{LI} = \frac{w - \text{PL}}{\text{PI}} \qquad \text{CI} = \frac{\text{LL} - w}{\text{PI}}$$

Liquidity index	State of the soil
Less than 0	Natural water content below the plastic limit: stiff to hard, brittle
0 to 1	Plastic: soft to stiff
Greater than 1	Natural water content above the liquid limit: very soft; may flow when disturbed

Many soft clays of the Niger Delta swamps have natural water contents close to or above their liquid limits, so their liquidity indices approach or exceed 1. Such soils lose much of their strength when disturbed by piling or excavation.

Activity. The plasticity of a soil depends on how much clay it contains and on which clay minerals are present. Skempton (1953) defined the **activity** (A) as:

$$A = \frac{\text{PI}}{\text{percentage of clay-size particles (finer than 0.002 mm)}}$$

Clays with activity below 0.75 are **inactive**, 0.75 to 1.25 **normal**, and above 1.25 **active** (Figure 2.5). Typical activities are about 0.4 for kaolinite, 0.9 for illite, 1.5 for calcium montmorillonite and 7 for sodium montmorillonite. Active clays, rich in smectite (montmorillonite), swell strongly when wetted and shrink when dried.

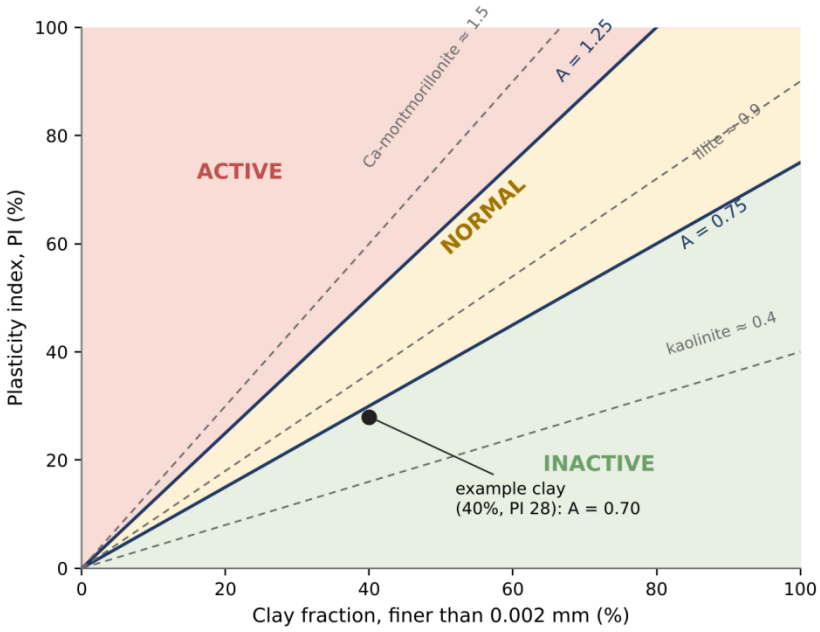


Figure 2.5. Activity chart. The plasticity index is plotted against the clay fraction; the lines A = 0.75 and A = 1.25 separate inactive, normal and active clays.

Worked example. A clay has LL = 52%, PL = 24% and a natural water content of 38%. It contains 40% clay-size particles.

$$\text{PI} = 52 - 24 = 28 \qquad \text{LI} = \frac{38 - 24}{28} = 0.50 \qquad \text{CI} = \frac{52 - 38}{28} = 0.50$$

$$A = \frac{28}{40} = 0.70$$

The clay is in the plastic state, about halfway between its plastic and liquid limits, and is inactive, suggesting that kaolinite or illite is the main clay mineral.

2.5 Density of coarse soils and consistency of fine soils

Relative density. The engineering behaviour of a sand or gravel depends mainly on how densely its grains are packed. This is expressed by the **relative density** (D_r), which compares the natural void ratio (e) with the void ratios of the soil in its loosest (e_{max}) and densest (e_{min}) states:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

Worked example. A sand has $e_{max} = 0.85$, $e_{min} = 0.45$ and a natural void ratio of 0.60.

$$D_r = \frac{0.85 - 0.60}{0.85 - 0.45} \times 100 = \frac{0.25}{0.40} \times 100 = 62.5\%$$

Because undisturbed samples of sand are hard to obtain, density in the field is usually estimated from the SPT N-value (Section 1.6):

Term	Relative density (%)	SPT N-value (blows per 300 mm)
Very loose	0 to 15	0 to 4
Loose	15 to 35	4 to 10

Term	Relative density (%)	SPT N-value (blows per 300 mm)
Medium dense	35 to 65	10 to 30
Dense	65 to 85	30 to 50
Very dense	85 to 100	over 50

The sand in the example, with $D_r = 62.5\%$, is medium dense.

Consistency of clays. The consistency of a fine soil is related to its **undrained shear strength** (c_u), which can be estimated in the field by hand or measured with a hand vane or pocket penetrometer. The terms long used in British practice (BS 5930:1999) are:

Consistency	Field test	Undrained shear strength c_u (kPa)
Very soft	Exudes between the fingers when squeezed	below 20
Soft	Moulded by light finger pressure	20 to 40
Firm	Moulded by strong finger pressure	40 to 75
Stiff	Cannot be moulded by fingers; indented by the thumb	75 to 150
Very stiff	Indented by the thumbnail	over 150

The 2015 revision of BS 5930 describes strength directly with terms ranging from "extremely low" to "extremely high", but the older terms remain widely used on Nigerian borehole logs.

2.6 The Unified Soil Classification System (USCS)

The Unified Soil Classification System grew out of a system developed by Arthur Casagrande in the 1940s for airfield construction. It is standardised as ASTM D2487 and is the most widely used system in engineering practice worldwide. Each soil is given a two-letter **group symbol** and a **group name**.

Letter	First letter: main soil type	Letter	Second letter: modifier
G	Gravel	W	Well graded
S	Sand	P	Poorly graded
M	Silt	M	With silty fines
C	Clay	C	With clayey fines
O	Organic soil	L	Low plasticity (LL below 50)
Pt	Peat	H	High plasticity (LL 50 or more)

The classification proceeds in steps (Figure 2.6):

Step 1: coarse or fine? If more than 50% of the soil is retained on the 0.075 mm sieve (No. 200), it is **coarse-grained**. If 50% or more passes, it is **fine-grained**. Highly organic soils, dark and fibrous with an organic smell, are classified as **peat** (Pt) by inspection.

Step 2 (coarse-grained soils): gravel or sand? If more than half of the coarse fraction is retained on the 4.75 mm sieve (No. 4), the soil is a **gravel** (G); otherwise it is a **sand** (S).

Step 3 (coarse-grained soils): the fines.

- Fines less than 5%: the soil is "clean", and the second letter depends on grading: GW or GP, SW or SP (Section 2.3).
- Fines more than 12%: the second letter depends on the plasticity of the fines: GM or GC, SM or SC. If the fines plot as silt (below the A-line or PI below 4) the symbol is M; if they plot as clay (above the A-line and PI above 7) it is C. Fines in the silty clay zone (PI from 4 to 7, above the A-line) give dual symbols such as SC-SM.
- Fines from 5% to 12%: borderline cases are given **dual symbols** that describe both grading and fines, such as SW-SM or GP-GC.

Step 4 (fine-grained soils): the plasticity chart. Fine soils are classified by plotting their liquid limit and plasticity index on Casagrande's **plasticity chart** (Figure 2.7). Two lines are drawn on it. The **A-line** separates clays (above) from silts and organic soils (below):

$$\mathrm{PI} = 0.73\,(\mathrm{LL} - 20)$$

The **U-line** marks the approximate upper limit of results for natural soils; points above it should be checked for errors:

$$\mathrm{PI} = 0.9\,(\mathrm{LL} - 8)$$

A vertical line at LL = 50 separates soils of low plasticity (L) from those of high plasticity (H). This gives the groups:

Group	Position on the plasticity chart	Group name
CL	LL below 50; PI above 7 and on or above the A-line	Lean clay
ML	LL below 50; PI below 4 or below the A-line	Silt
CL-ML	LL below 50; PI from 4 to 7 and on or above the A-line	Silty clay
CH	LL 50 or more; on or above the A-line	Fat clay
MH	LL 50 or more; below the A-line	Elastic silt
OL, OH	Below the A-line, organic	Organic silt or clay

A soil is **organic** if its liquid limit after oven drying is less than 0.75 times its liquid limit before drying, because drying changes the organic matter irreversibly.

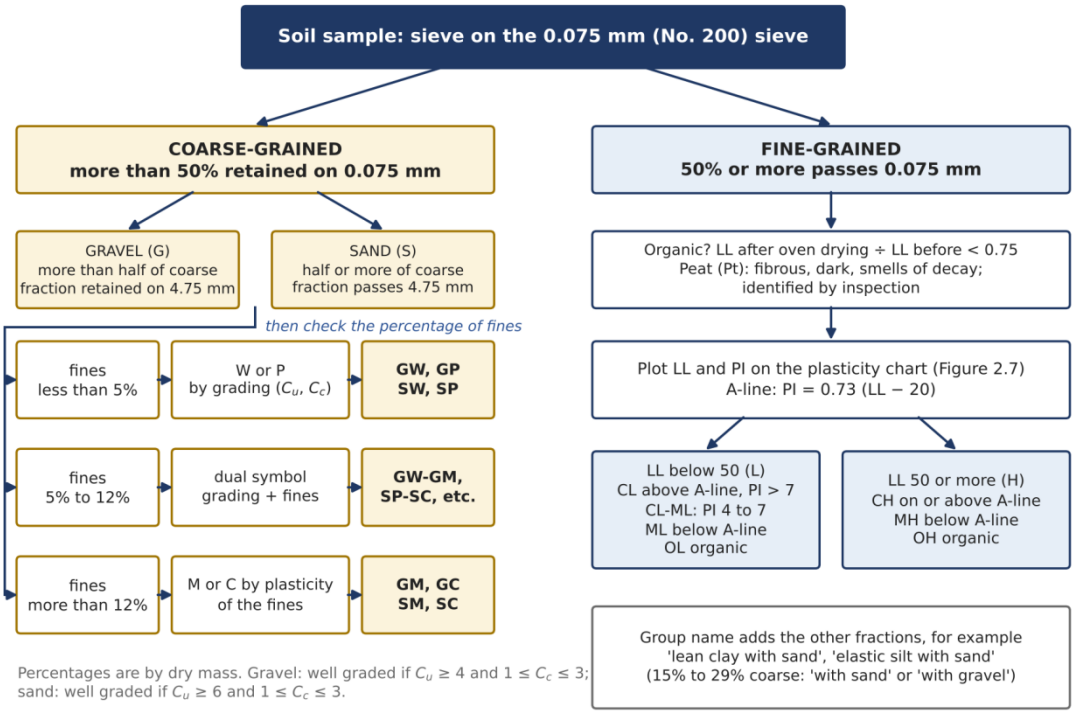


Figure 2.6. Simplified flow chart for the Unified Soil Classification System. Percentages are by dry mass.

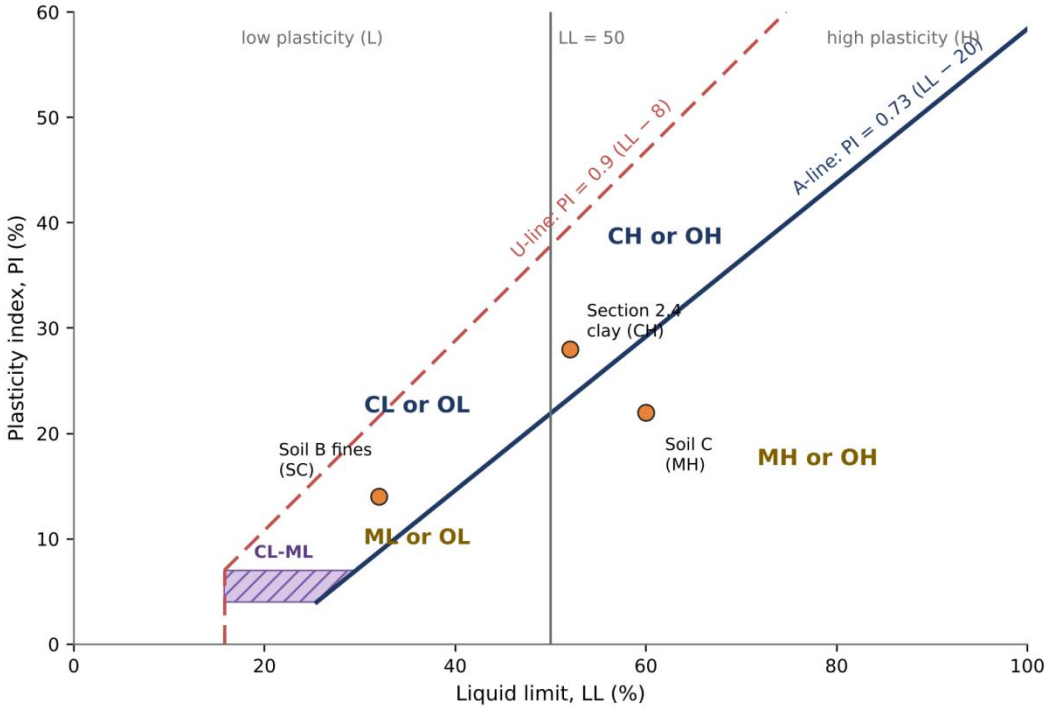


Figure 2.7. Casagrande's plasticity chart, with the A-line, the U-line and the fields of the main USCS groups. The three fine soils used as examples in this section are plotted.

The group name is completed with terms that describe the other fractions, for example "well-graded sand with gravel", "clayey sand" or "elastic silt with sand". In USCS, a fine soil with 15% to 29% retained on the 0.075 mm sieve is described as "with sand" or "with gravel", depending on which is more abundant.

2.7 The AASHTO classification

The American Association of State Highway and Transportation Officials (AASHTO) system (AASHTO M 145) was developed to judge the suitability of soils as **subgrade** and other road materials. It is widely used by highway engineers, including in Nigeria. Soils are placed in seven main groups, A-1 to A-7, using the percentages passing the 2.0 mm (No. 10), 0.425 mm (No. 40) and 0.075 mm (No. 200) sieves, and the liquid limit and plasticity index of the fraction finer than 0.425 mm.

Group	Passing 2.0 mm (%)	Passing 0.425 mm (%)	Passing 0.075 mm (%)	LL (%)	PI (%)	Typical material
A-1-a	50 max	30 max	15 max	—	6 max	Stone fragments, gravel and sand
A-1-b	—	50 max	25 max	—	6 max	Gravelly sand
A-3	—	51 min	10 max	—	NP	Fine sand
A-2-4	—	—	35 max	40 max	10 max	Silty or clayey gravel and sand
A-2-5	—	—	35 max	41 min	10 max	Silty or clayey gravel and sand
A-2-6	—	—	35 max	40 max	11 min	Silty or clayey gravel and sand
A-2-7	—	—	35 max	41 min	11 min	Silty or clayey gravel and sand
A-4	—	—	36 min	40 max	10 max	Silty soils
A-5	—	—	36 min	41 min	10 max	Silty soils
A-6	—	—	36 min	40 max	11 min	Clayey soils
A-7-5, A-7-6	—	—	36 min	41 min	11 min	Clayey soils

Soils with 35% or less passing the 0.075 mm sieve are **granular materials** (A-1, A-3 and A-2); those with more than 35% are **silt–clay materials** (A-4 to A-7). The table is read from left to right (in the order A-1-a, A-1-b, A-3, A-2, A-4 to A-7), and the soil is placed in the first group whose limits it satisfies. Group A-7 is divided into A-7-5, where $PI \leq LL - 30$, and A-7-6, where $PI > LL - 30$. The limits for the fine soils are easiest to apply on a chart of PI against LL (Figure 2.8).

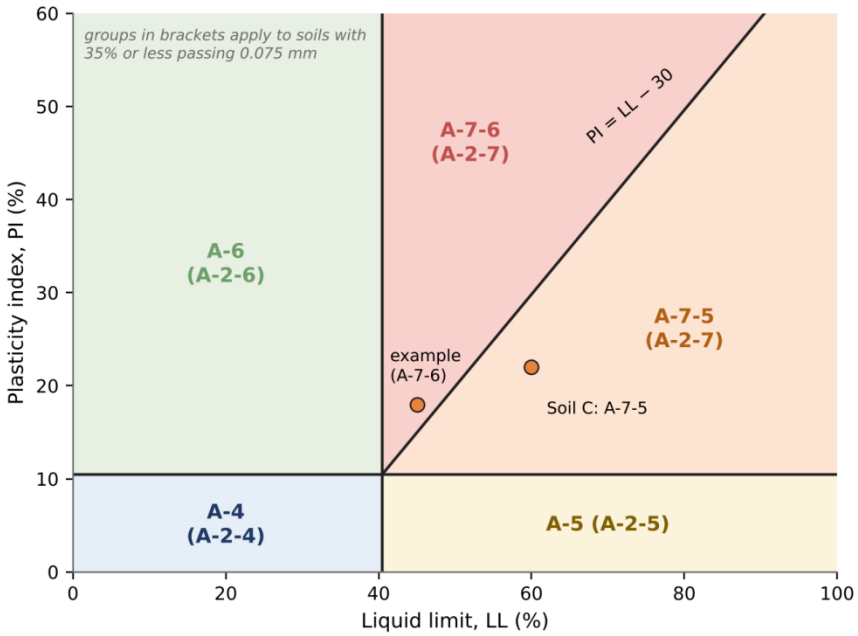


Figure 2.8. Chart for the AASHTO classification of fine soils (and of the fines in A-2 soils), using the liquid limit and plasticity index.

As subgrade, groups A-1, A-3 and A-2 are generally rated excellent to good, and groups A-4 to A-7 fair to poor.

Group index. To compare soils within a group, AASHTO calculates a **group index** (GI):

$$\mathrm{GI} = (F - 35)\,[0.2 + 0.005\,(\mathrm{LL} - 40)] + 0.01\,(F - 15)\,(\mathrm{PI} - 10)$$

where F is the percentage passing the 0.075 mm sieve. The GI is rounded to the nearest whole number and written in brackets after the group, for example A-6(7). A negative GI is reported as 0. For groups A-2-6 and A-2-7 only the second term is used. Groups A-1-a, A-1-b, A-2-4, A-2-5 and A-3 always have a GI of 0. The higher the GI, the poorer the soil as a subgrade: a GI of 0 indicates a good subgrade and a GI of 20 or more a very poor one.

Worked example. A soil has 58% passing the 0.075 mm sieve, LL = 45% and PI = 18%.

Since more than 35% passes 0.075 mm, it is a silt–clay material. LL is above 40 and PI above 10, so it is in group A-7. LL − 30 = 15, and PI (18) is greater than 15, so it is **A-7-6**.

$$\mathrm{GI} = (58 - 35)\,[0.2 + 0.005\,(45 - 40)] + 0.01\,(58 - 15)\,(18 - 10)$$

$$\mathrm{GI} = 23 \times 0.225 + 0.01 \times 43 \times 8 = 5.18 + 3.44 = 8.6 \approx 9$$

The soil is classified as A-7-6(9), a clayey soil that would make a poor subgrade.

2.8 The British Soil Classification System

The British Soil Classification System (BS 5930) uses symbols similar to the USCS, with two main differences:

- A soil is classified as **fine** if more than **35%** of it is finer than 0.063 mm, compared with 50% in the USCS. This reflects the observation that a soil with more than about 35% fines already behaves as a fine soil.
- Plasticity is divided into five classes instead of two:

Symbol	Plasticity	Liquid limit (%)

Symbol	Plasticity	Liquid limit (%)
L	Low	below 35
I	Intermediate	35 to 50
H	High	50 to 70
V	Very high	70 to 90
E	Extremely high	over 90

For example, a clay with LL = 60% plotting above the A-line is CH, and one with LL = 80% is CV. Coarse soils are classified as gravel (G) or sand (S) with grading and fines terms, as in the USCS.

2.9 Problem soils in Nigeria

Classification tests are the first warning that a soil may cause problems. Three groups are especially important in Nigeria.

Lateritic soils. Laterites are reddish, iron- and aluminium-rich residual soils formed by intense chemical weathering under a hot, wet tropical climate. Their formation is covered in the other part of this course. They are the most important road construction material in Nigeria. A chemical index often used to distinguish them is the **silica–sesquioxide ratio**:

$$\frac{\mathrm{SiO_2}}{\mathrm{Al_2O_3} + \mathrm{Fe_2O_3}}$$

calculated from the molecular proportions. Values below 1.33 indicate a true laterite, values from 1.33 to 2.0 a lateritic soil, and values above 2.0 a non-lateritic tropical soil.

Lateritic soils need care in testing. Their grains are often weak concretions that break down during sieving and compaction, and oven drying can change their Atterberg limits and grading irreversibly. Tests should be run on samples air-dried or at natural water content, and the method should be reported. For road subbase and base courses, the Nigerian *General Specifications for Roads and Bridges* (Federal Ministry of Works and Housing, 1997) limit the liquid limit to 35% and the plasticity index to 12%, together with minimum California bearing ratio (CBR) values, which are covered with compaction in the other part of the course.

Expansive clays. Clays rich in smectite, such as the dark “black cotton” soils of the Chad Basin around Maiduguri and parts of the Benue Trough, swell when wet and shrink and crack when dry. Light buildings, pavements and pipes on them crack as the ground heaves and settles with the seasons. They are recognised by a high liquid limit and plasticity index, high activity, and plotting high above the A-line. Chen (1975) related the swelling potential to the plasticity index:

Swelling potential	Plasticity index (%)
Low	0 to 15
Medium	10 to 35
High	20 to 55
Very high	35 and above

The ranges overlap because the plasticity index alone does not decide swelling; the clay mineral, the density and the initial water content also matter.

Soft organic clays and peat. The mangrove swamps and creeks of the Niger Delta, including the Okerenkoko area, are underlain by very soft grey to black clays and silts with roots, shells and decaying plant matter, locally passing into peat. They have very high water contents, often near or above the liquid limit (LI close to or above 1), low unit weights and very low undrained shear strength. Under load they settle by large amounts and for many years. They classify as OH, CH, MH or Pt and are identified by their dark colour, smell, the oven-drying test for organic soils (Section 2.6) and the **loss on ignition**, the loss in mass when a dry sample is heated to burn off its organic matter. Structures on them are usually founded on piles driven to the underlying sands.

2.10 Classifying three soils: worked examples

The results of classification tests on three soils are given below. Classify each soil in the USCS and the AASHTO system.

Test result	Soil A	Soil B	Soil C
Passing 4.75 mm (%)	92	85	100
Passing 2.0 mm (%)	76	78	98
Passing 0.425 mm (%)	32	52	90
Passing 0.075 mm (%)	3	18	72
D_{10}, D_{30}, D_{60} (mm)	0.12, 0.40, 1.10	—	—
Liquid limit (%)	NP	32	60
Plastic limit (%)	NP	18	38
Organic test (LL after oven drying ÷ LL before)	—	—	0.95

Soil A.

- *USCS.* Only 3% passes 0.075 mm, so the soil is coarse-grained. The coarse fraction is 97%; the gravel fraction (retained on 4.75 mm) is 8%, much less than half of 97%, so it is a sand. Fines are below 5%, so grading decides: $C_u = 9.2$ and $C_c = 1.21$ (Section 2.3), so the sand is well graded. **SW: well-graded sand.**
- *AASHTO.* With 3% passing 0.075 mm it is granular. It fails A-1-a because 76% passes 2.0 mm (more than 50). It meets A-1-b: 32% passing 0.425 mm (50 max), 3% passing 0.075 mm (25 max), non-plastic. **A-1-b(0)**: an excellent subgrade and fill material.

Soil B.

- *USCS.* With 18% fines the soil is coarse-grained. The gravel fraction is 15%, much less than half of the coarse fraction (82%), so it is a sand. Fines exceed 12%, so their plasticity decides. PI = 32 − 18 = 14. On the A-line at LL = 32, $\text{PI} = 0.73 \times (32 - 20) = 8.8$. The fines plot above the A-line with PI above 7, so they are clay. **SC: clayey sand.**
- *AASHTO.* With 18% passing 0.075 mm it is granular. PI (14) exceeds 6, so it is not A-1, and it is not A-3. In the A-2 groups, LL = 32 (40 max) and PI = 14 (11 min) give **A-2-6**. Only the second term of the group index is used:

$$\text{GI} = 0.01 \times (18 - 15) \times (14 - 10) = 0.12 \approx 0$$

The soil is **A-2-6(0)**, a good subgrade, though its plastic fines make it sensitive to water.

Soil C.

- *USCS.* With 72% passing 0.075 mm it is fine-grained. The organic test ratio (0.95) is above 0.75, so it is not organic. PI = 60 − 38 = 22. LL is above 50, so the soil has high plasticity. On the A-line at LL = 60, PI $= 0.73 \times (60 - 20) = 29.2$; the soil plots below it, so it is a silt. 28% is retained on the 0.075 mm sieve, all of it sand. **MH: elastic silt with sand.**
- *AASHTO.* With 72% passing 0.075 mm it is a silt–clay material. LL (60) exceeds 40 and PI (22) exceeds 10, so it is A-7. LL $- 30 = 30$ and PI (22) is less than this, so it is **A-7-5**.

$$\text{GI} = (72 - 35)\,[0.2 + 0.005\,(60 - 40)] + 0.01\,(72 - 15)\,(22 - 10)$$

$$\text{GI} = 37 \times 0.30 + 0.01 \times 57 \times 12 = 11.1 + 6.8 = 17.9 \approx 18$$

The soil is **A-7-5(18)**, a very poor subgrade. Soils like this are common in deeply weathered profiles and need to be removed, stabilised or covered by a thick pavement.

The three soils, together with the clay of the worked example in Section 2.4 (LL = 52%, PI = 28%, which plots above the A-line as **CH**), are plotted on the plasticity chart in Figure 2.7.

2.11 Key points of Section 2

- Soils are classified by particle size distribution (for coarse soils) and plasticity (for fine soils), using cheap, standard tests.
- Phase relationships link water content, void ratio, porosity, saturation and density; $Se = wG_s$ is the key link.
- Grading is described by C_u and C_c; Atterberg limits define the plastic range, and the liquidity index and activity indicate the state and the clay minerals.
- The USCS uses the 0.075 mm sieve, grading and the plasticity chart with its A-line; AASHTO groups A-1 to A-7 and the group index rate soils as road subgrades; the British system uses 35% fines and five plasticity classes.
- Lateritic soils, expansive clays and the soft organic clays of the Niger Delta are the main problem soils in Nigeria, and are first recognised through classification.

Summary, review questions and glossary

Summary

Topic	Main ideas	Nigerian examples
Engineering geology	Definition; ground model; links with soil and rock mechanics and geotechnical engineering	Foundations, roads, jetties and coastal works
Lessons from failures	Dams and slopes failed through weak foundations, water pressure on discontinuities and piping	Cracked buildings, failed roads, gully and riverbank collapse
Geological factors	Rock and soil type; discontinuities; weathering grades I to VI; groundwater; hazards; materials	Deep weathering of the basement; corestones; delta subsidence
Stress	Total stress, pore pressure, effective stress, Mohr–Coulomb strength	High water table in the Niger Delta
Site investigation	Desk study, walkover, pits, boreholes, SPT, CPT, vane, geophysics, sampling, logs	Cable percussion boring; resistivity sounding

Topic	Main ideas	Nigerian examples
Phase relationships	w, e, n, S, G_s, densities and unit weights; $Se = wG_s$	—
Particle size	Sieve and sedimentation analysis; Stokes' law; C_u and C_c	Uniform delta sands; well-graded laterites
Plasticity	LL, PL, SL; PI, LI, CI; activity	Soft swamp clays with LI near 1
Density and consistency	Relative density; SPT N; consistency and c_u	Loose delta sands; soft clays
Classification systems	USCS (plasticity chart, A-line); AASHTO (A-1 to A-7, group index); British (35% fines, five plasticity classes)	Road subgrades and subbases
Problem soils	Laterite; expansive clays; soft organic clays and peat	Laterite roads; black cotton soils of the north-east; Niger Delta swamps

Summary of key equations

Quantity	Equation	Section
Total vertical stress	$\sigma_v = \sum \gamma_i z_i$	1.5
Pore water pressure	$u = \gamma_w z_w$	1.5
Effective stress	$\sigma' = \sigma - u$	1.5
Mohr–Coulomb shear strength	$\tau_f = c' + \sigma' \tan\phi'$	1.5
Water content	$w = \frac{M_w}{M_s} \times 100$	2.2
Void ratio and porosity	$e = \frac{V_v}{V_s}, n = \frac{V_v}{V} = \frac{e}{1+e}$	2.2
Degree of saturation	$S = \frac{V_w}{V_v}, Se = wG_s$	2.2
Dry density	$\rho_d = \frac{\rho}{1+w} = \frac{G_s \rho_w}{1+e}$	2.2
Saturated unit weight	$\gamma_{sat} = \frac{(G_s + e)\,\gamma_w}{1+e}$	2.2
Stokes' law	$v = \frac{(\rho_s - \rho_w)\, g\, D^2}{18\,\eta}$	2.3
Coefficient of uniformity	$C_u = \frac{D_{60}}{D_{10}}$	2.3
Coefficient of curvature	$C_c = \frac{D_{30}^2}{D_{10} \times D_{60}}$	2.3
Plasticity index	$\mathrm{PI} = \mathrm{LL} - \mathrm{PL}$	2.4

Quantity	Equation	Section
Liquidity and consistency indices	$\mathrm{LI} = \frac{w - \mathrm{PL}}{\mathrm{PI}}, \mathrm{CI} = \frac{\mathrm{LL} - w}{\mathrm{PI}}$	2.4
Activity	$A = \frac{\mathrm{PI}}{\%\ \mathrm{clay}}$	2.4
Relative density	$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$	2.5
A-line and U-line	$\mathrm{PI} = 0.73\,(\mathrm{LL} - 20), \mathrm{PI} = 0.9\,(\mathrm{LL} - 8)$	2.6
AASHTO group index	$\mathrm{GI} = (F - 35)[0.2 + 0.005(\mathrm{LL} - 40)] + 0.01(F - 15)(\mathrm{PI} - 10)$	2.7

Review questions

Part A: Short answers

1. Define engineering geology and explain how it differs from geotechnical engineering.
2. What is a ground model, and why is it important?
3. For one of the St Francis, Malpasset, Vajont or Teton dam failures, describe the geological cause and the lesson learnt.
4. List the tasks of an engineering geologist at each stage of a project.
5. Describe the six grades of rock weathering. Why are corestones a problem in site investigation?
6. Explain the principle of effective stress and why a rise in the water table can trigger a landslide.
7. List the stages of a site investigation and the purpose of a desk study.
8. Describe the standard penetration test and the cone penetration test, and state one advantage of each.
9. Distinguish between disturbed and undisturbed samples, and state what each is used for.
10. Write a full field description of a soil you have seen, in the standard order of terms.
11. Draw and label the phase diagram of a partly saturated soil.
12. Why is the sedimentation test needed, and on what law is it based?
13. What do C_u and C_c tell us about a soil? Distinguish between well-graded, uniformly graded and gap-graded soils.
14. Define the liquid, plastic and shrinkage limits, and describe how the liquid limit is measured by the Casagrande cup.
15. What does a liquidity index greater than 1 indicate, and why is it important in the Niger Delta?
16. Define activity and explain how it relates to clay mineralogy.
17. What is the A-line, and how is it used in the USCS?
18. Explain the differences between the USCS and the British Soil Classification System.
19. What is the purpose of the AASHTO group index?
20. Why must lateritic soils be tested with care? What is the silica–sesquioxide ratio?

Part B: Calculations

21. At a site, 3.0 m of sand overlies clay. The water table is 1.5 m below the surface. The sand has a unit weight of 18.0 kN/m^3 above the water table and 19.5 kN/m^3 below it; the clay has a saturated unit weight of 17.5 kN/m^3. Calculate the total stress, pore water pressure and effective stress at a depth of 8.0 m.
22. A saturated clay has a water content of 48% and $G_s = 2.70$. Calculate its void ratio, porosity and saturated unit weight.
23. A moist soil of mass 2.10 kg fills a mould of volume 1.00×10^{-3} m^3. Its water content is 12% and $G_s = 2.65$. Calculate its bulk density, dry density, void ratio and degree of saturation.
24. A beach sand has $D_{10} = 0.08$ mm, $D_{30} = 0.15$ mm and $D_{60} = 0.20$ mm. Calculate C_u and C_c, describe its grading and give its USCS symbol if it has 2% fines.
25. Using Stokes' law, calculate how long a particle 0.005 mm in diameter ($\rho_s = 2650$ kg/m^3) takes to settle 80 mm in water at 20 °C.
26. In a Casagrande test the following results were obtained: 12 blows at 49.8%, 19 blows at 46.8%, 27 blows at 44.5% and 38 blows at 42.3% water content. The plastic limit is 21%, the natural water content 30% and the clay fraction 25%. Plot the flow curve, find the liquid limit, and calculate the plasticity index, liquidity index and activity. Classify the soil on the plasticity chart.
27. A sand has $e_{max} = 0.92$, $e_{min} = 0.55$ and a natural void ratio of 0.80. Calculate its relative density and describe its state.
28. A soil has 90% passing 4.75 mm, 45% passing 0.075 mm, LL = 38% and PI = 15%. Classify it in the USCS and in the AASHTO system, including the group index.
29. A lateritic soil contains 28% SiO_2, 22% Al_2O_3 and 30% Fe_2O_3 by mass. Using molar masses of 60.1, 102.0 and 159.7 g/mol, calculate its silica–sesquioxide ratio and classify it.

Part C: Essay questions

30. Discuss the role of the engineering geologist in the planning, investigation, design and construction of a jetty in the Niger Delta.
31. Using examples, explain how discontinuities, weathering and groundwater have caused the failure of dams and slopes.
32. Describe how you would plan and carry out a site investigation for a three-storey building on the deeply weathered basement complex of south-western Nigeria.
33. Describe the tests used to classify a fine-grained soil, and explain how the results are used in the USCS and AASHTO systems.
34. Discuss the identification, classification and engineering problems of lateritic soils, expansive clays and soft organic clays in Nigeria.

Glossary

Term	Meaning
A-line	The line $\mathrm{PI} = 0.73(\mathrm{LL} - 20)$ on the plasticity chart that separates clays from silts
Activity	The plasticity index divided by the percentage of clay-size particles
Atterberg limits	The liquid, plastic and shrinkage limits of a fine soil

Term	Meaning
Cone penetration test (CPT)	An in situ test in which a cone is pushed into the ground and its resistance recorded continuously
Consistency	The firmness of a fine soil, related to its undrained shear strength
Corestone	A rounded block of fresher rock within a weathered profile
Degree of saturation	The proportion of the voids filled with water
Desk study	The collection and review of existing information about a site
Discontinuity	A plane of weakness in a rock mass, such as a joint, fault or bedding plane
Effective stress	The part of the total stress carried by the contacts between soil grains
Engineering geology	Geology applied to engineering works and to the management of geological hazards
Expansive clay	A clay that swells when wetted and shrinks when dried, usually rich in smectite
Fines	Particles finer than 0.075 mm (USCS) or 0.063 mm (BS): silt and clay
Ground model	A description of the materials, structure and groundwater beneath a site
Group index	A number used in the AASHTO system to rate a soil as a road subgrade
Laterite	A reddish, iron- and aluminium-rich residual soil of tropical regions
Liquid limit	The water content above which a soil behaves as a liquid
Liquidity index	The position of the natural water content relative to the plastic and liquid limits
Peat	A soil made mainly of plant remains
Phase diagram	A diagram showing the volumes and masses of solids, water and air in a soil
Piping	Internal erosion of soil by water seeping through it
Plastic limit	The water content below which a soil is no longer plastic
Plasticity index	The range of water content over which a soil is plastic, $\mathrm{LL} - \mathrm{PL}$
Pore water pressure	The pressure of the water in the voids of a soil or rock
Relative density	The density of a coarse soil compared with its loosest and densest states
Residual soil	Soil formed in place by the weathering of the underlying rock
Rockhead	The surface of fresh or slightly weathered rock beneath soil or weathered rock
Shrinkage limit	The water content below which further drying causes no further decrease in volume
Site investigation	The process of finding out the ground conditions at a site
Standard penetration test (SPT)	An in situ test in which the blows to drive a sampler 300 mm are counted
Subgrade	The natural or compacted soil on which a road pavement is built
Void ratio	The volume of voids divided by the volume of solids
Water content	The mass of water divided by the mass of dry solids

Term	Meaning
Well graded	Having a wide and even range of particle sizes

References and further reading

Engineering geology

- Bell, F. G. (2007). *Engineering Geology* (2nd ed.). Butterworth-Heinemann, Oxford.
- Kiersch, G. A. (1964). Vaiont reservoir disaster. *Civil Engineering*, 34(3), 32–39.
- Price, D. G. (2009). *Engineering Geology: Principles and Practice* (M. H. de Freitas, Ed.). Springer, Berlin.
- Waltham, T. (2009). *Foundations of Engineering Geology* (3rd ed.). Spon Press, London.

Soil mechanics and classification

- Casagrande, A. (1948). Classification and identification of soils. *Transactions of the American Society of Civil Engineers*, 113, 901–930.
- Das, B. M. and Sobhan, K. (2014). *Principles of Geotechnical Engineering* (8th ed.). Cengage Learning, Stamford, Connecticut.
- Knappett, J. A. and Craig, R. F. (2012). *Craig's Soil Mechanics* (8th ed.). Spon Press, Abingdon.
- Skempton, A. W. (1953). The colloidal activity of clays. *Proceedings of the 3rd International Conference on Soil Mechanics and Foundation Engineering*, Zurich, 1, 57–61.
- Terzaghi, K., Peck, R. B. and Mesri, G. (1996). *Soil Mechanics in Engineering Practice* (3rd ed.). John Wiley and Sons, New York.

Standards and specifications

- AASHTO M 145. *Standard Specification for Classification of Soils and Soil–Aggregate Mixtures for Highway Construction Purposes*. American Association of State Highway and Transportation Officials, Washington, DC.
- ASTM D2487. *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*. ASTM International, West Conshohocken, Pennsylvania.
- BS 1377-2:1990. *Methods of Test for Soils for Civil Engineering Purposes. Part 2: Classification Tests*. British Standards Institution, London.
- BS 5930:2015. *Code of Practice for Ground Investigations*. British Standards Institution, London.
- Federal Ministry of Works and Housing (1997). *General Specifications for Roads and Bridges*, Volume II. Federal Ministry of Works and Housing, Lagos.

Tropical and problem soils

- Chen, F. H. (1975). *Foundations on Expansive Soils*. Elsevier, Amsterdam.
- Gidigasu, M. D. (1976). *Laterite Soil Engineering: Pedogenesis and Engineering Principles*. Elsevier, Amsterdam.
- Winterkorn, H. F. and Chandrasekharan, E. C. (1951). Laterite soils and their stabilization. *Highway Research Board Bulletin*, 44, 10–29.