Chapter 1

Classification and Physical Properties of Soils

Learning objectives:

By the end of this chapter, you will have been introduced to:

- the formation of rocks and soils;
- clay soils and the field identification of soils;
- the classification of soils;
- various physical properties of soils and the relationships between them.

In the field of civil engineering, nearly all projects are built on to, or into, the ground. Whether the project is a structure, a roadway, a tunnel, or a bridge, the nature of the soil at that location is of great importance to the civil engineer. *Geotechnical engineering* is the term given to the branch of engineering that is concerned with aspects pertaining to the ground. *Soil mechanics* is the subject within this branch that looks at the behaviour of soils in civil engineering.

Geotechnical engineers are not the only professionals interested in the ground; soil physicists, agricultural engineers, farmers and gardeners all take an interest in the types of soil with which they are working. These workers, however, concern themselves mostly with the organic topsoils found at the soil surface. In contrast, geotechnical engineers are mainly interested in the engineering soils found beneath the topsoil. It is the engineering properties and behaviour of these soils, which are their concern.

1.1 Agricultural and engineering soil

If an excavation is made through previously undisturbed ground the following materials are usually encountered (Fig. 1.1).

Topsoil

A layer of organic soil, usually not more than 500 mm thick, in which humus (highly organic partly decomposed vegetable matter) is often found.

Smith's Elements of Soil Mechanics, 10th Edition. Ian Smith.

Companion website: www.wiley.com/go/smith/soilmechanics10e

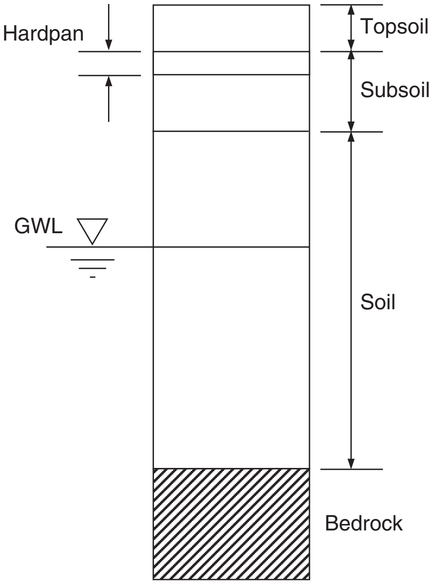

Fig. 1.1 Materials encountered during excavation.

Subsoil

The portion of the Earth's crust affected by current weathering and lying between the topsoil and the unweathered soil below.

Hardpan

In humid climates, humic acid can be formed by rainwater causing decomposition of humus. This acid leaches out iron and alumina oxides down into the lower layers where they act as cementation agents to form a hard, rock-like material. Hardpan is difficult to excavate and, as it does not soften when wet, has a high resistance to normal soil drilling methods. A hardpan layer is sometimes found at the junction of the topsoil and the subsoil.

Soil

The soft geological deposits extending from the subsoil to bedrock constitute soils. In some soils, there is a certain amount of cementation between the grains, which affects the physical properties of the soil. If this cementation is such that a rock-hard material has been produced, then the material must be described as rock. A rough rule is that if the material can be excavated by hand or hand tools, then it is a soil.

Bedrock

Beneath the soil, rock is encountered. This rock is often referred to as *bedrock* and the horizon at which the soil meets the rock is known as the *rockhead*.

Groundwater

A reservoir of underground water. The upper surface of this water may occur at any depth and is known as the *water table* or *groundwater level* (GWL).

1.2 The rock cycle

Rocks and soils are formed within a geological process known as the *rock cycle* (Fig. 1.2). The process is continuous and has lasted for millions of years.

1. Magma (molten rock) rises towards the surface, cooling and solidifying along the way.
2. The magma crystallises beneath or above the Earth's surface forming igneous rocks.
3. At the surface, rocks undergo physical and chemical weathering which break down the parent rock into particles.
4. The rock particles (sediments) are moved downslope and transported by glaciers, rivers and wind. The combined processes of weathering and transportation are referred to as *erosion*.
5. Eventually the sediments are deposited in oceans and floodplains, where they undergo *lithification*: the process where the particles are compressed under great pressure over time to form rock.
6. Sedimentary rocks are formed.
7. If the sedimentary rock is subjected to further great pressures and heat, it will react and change to a metamorphic rock.
8. Metamorphic rocks subjected to very high pressure or temperature, liquefy into magma that eventually crystallises into igneous rock, and the cycle starts again.

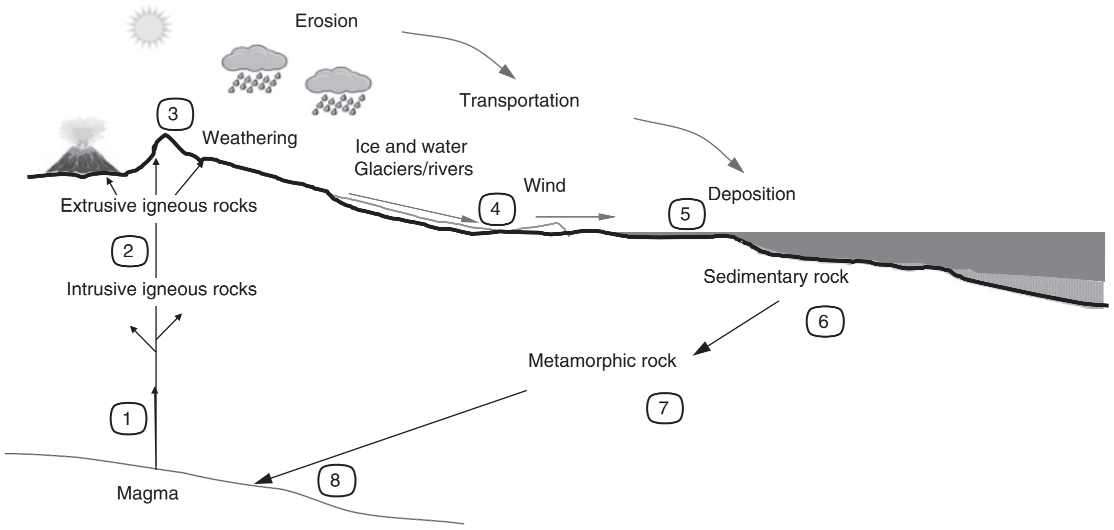

Fig. 1.2 The rock cycle.

1.2.1 Rock

Rocks are made from various types of minerals. Minerals are substances of crystalline form made up from a particular chemical combination. The main minerals found in rocks include quartz, feldspar, calcite and mica. We can classify all rocks into three basic groups: *igneous*, *sedimentary* and *metamorphic*. The position of each within the rock cycle is shown in Fig. 1.2.

Igneous rocks

These rocks have become solid from a melted liquid state. *Extrusive* igneous rocks are those that arrived on the surface of the Earth as molten lava and cooled. *Intrusive* igneous rocks are formed from magma that forced itself through cracks into the rock beds below the surface and solidified there.

Examples of igneous rocks: *granite, basalt, gabbro*.

Sedimentary rocks

Weathering reduces the rock mass into fragmented particles, which can be more easily transported by wind, water and ice. When dropped by the agents of weathering, they are termed *sediments*. These sediments are typically deposited in layers or beds called strata and when compacted and cemented together through lithification, they form sedimentary rocks.

Examples of sedimentary rocks: *shale, sandstone, chalk*.

Metamorphic rocks

Metamorphism through high temperatures and pressures acting on sedimentary or igneous rocks produces metamorphic rocks. The original rock undergoes both chemical and physical alterations.

Examples of metamorphic rocks: *slate, quartzite, marble*.

Identification of rocks

The identification of rocks may, initially, be considered quite a tricky thing to get right. With practice and experience however, engineers and geologists can rapidly identify features, that enable the identification to be made swiftly. Features, which assist in the identification and description of the rock type, include colour, grain size, mineralogical composition, structure and void content. Guidance on the identification and description of rock types is given in BS EN ISO 14689 (BSI, 2018b) and in the *Code of practice for ground investigations*, BS 5930 (BSI, 2015).

1.2.2 Soil

The actions of frost, temperature, gravity, wind, rain and chemical weathering are continually forming rock particles that eventually become soils. There are three types of soil when considering modes of formation.

Transported soil (gravels, sands, silts and clays)

Many soils have been transported by water. As a stream or river loses its velocity, it tends to deposit some of the particles that it is carrying, dropping the larger, heavier particles first. Hence, on the higher reaches of a river, gravel and sand are found whilst on the lower or older parts, silts and clays predominate, especially where the river enters the sea or a lake and loses its velocity. Ice, in the form of huge slow-moving yet enormously powerful glaciers, is another important transportation agent, and large deposits of *boulder clay* and *moraine* are formed from *glaciation*.

In arid parts of the world, wind is continually forming sand deposits in the form of ridges. The sand particles in these ridges have been more or less rolled along and are invariably rounded and fairly uniform in size. Light brown, wind-blown deposits of silt-size particles, known as *loess*, are often encountered in thin layers, the particles having sometimes travelled considerable distances.

Residual soil (topsoil, laterites)

These soils are formed *in situ* by chemical weathering and may be found on level rock surfaces where the action of the elements has produced a soil with little tendency to move. Residual soils can also occur whenever the rate of break-up of the rock exceeds the rate of removal. If the parent rock is igneous or metamorphic the resulting soil sizes range from silt to gravel.

Laterites are formed by chemical weathering under warm, humid tropical conditions when the rainwater leaches out of the soluble rock material leaving behind the insoluble hydroxides of iron and aluminium, giving them their characteristic red-brown colour.

Organic soil

These soils contain large amounts of decomposed animal and vegetable matter. They are usually dark in colour and give off a distinctive odour. Deposits of organic silts and clays have usually been created from river or lake sediments. *Peat* is a special form of organic soil and is a dark brown spongy material, which almost entirely consists of lightly to fully decomposed vegetable matter. It exists in one of three forms:

- *Fibrous*: non-plastic with a firm structure only slightly altered by decay.
- *Pseudo-fibrous*: peat in this form still has a fibrous appearance but is much softer and more plastic than fibrous peat. The change is due more to prolonged submergence in airless water than to decomposition.
- *Amorphous*: with this type of peat, decomposition has destroyed the original fibrous vegetable structure so that it has virtually become an organic clay.

Peat deposits occur extensively throughout the world and can be extremely troublesome when encountered in civil engineering work.

1.2.3 Granular and cohesive soils

Geotechnical engineers classify soils as either *granular* or *cohesive*. Granular soils (sometimes referred to as *cohesionless* soils) are formed from loose particles without strong inter-particle forces, e.g. sands and gravels. Cohesive soils (e.g. clays, clayey silts) are made from particles bound together with clay minerals. The particles are flaky and sheet-like and retain a significant amount of adsorbed water on their surfaces. The ability of the sheet-like particles to slide relative to one another, gives a cohesive soil the property known as *plasticity*.

1.3 Clay soils

Rock fragments can be reduced by mechanical means to a limiting size of about 0.002 mm, so that a soil containing particles above this size has a mineral content similar to the parent rock from which it was created.

For the production of particles smaller than 0.002 mm, some form of chemical action is generally necessary before breakdown can be achieved. Such particles, although having a chemical content similar to the parent rock, have a different crystalline structure and are known as clay particles. An exception is rock flour, rock grains smaller than 0.002 mm, produced by the glacial action of rocks grinding against each other.

1.3.1 Classes of clay minerals

The minerals constituting a clay are invariably the result of the chemical weathering of rock particles and are hydrates of aluminium, iron or magnesium silicate generally combined in such a manner, as to create sheet-like structures only a few molecules thick. These sheets are built from two basic units, the tetrahedral unit of silica and the octahedral unit of the hydroxide of aluminium, iron or magnesium. The main dimension of a clay particle is usually less than 0.002 mm and the different types of minerals have been created from the manner in which these structures were stacked together.

The three main groups of clay minerals are as follows.

Kaolinite group

This mineral is the most dominant part of residual clay deposits and is made up from large stacks of alternating single tetrahedral sheets of silicate and octahedral sheets of aluminium. Kaolinites are very stable with a strong structure and absorb little water. They have low swelling and shrinkage responses to water content variation.

Illite group

Consists of a series of single octahedral sheets of aluminium sandwiched between two tetrahedral sheets of silicon. In the octahedral sheets, some of the aluminium is replaced by iron and magnesium; and in the tetrahedral sheets, there is a partial replacement of silicon by aluminium. Illites tend to absorb more water than kaolinites and have higher swelling and shrinkage characteristics.

Montmorillonite group

This mineral has a similar structure to the illite group but, in the tetrahedral sheets, some of the silicon is replaced by iron, magnesium and aluminium. Montmorillonites exhibit extremely high water absorption, swelling and shrinkage characteristics. Bentonite is a member of this mineral group and is usually formed from weathered volcanic ash. Because of its large expansive properties when it is mixed with water it is much in demand as a general grout in the plugging of leaks in reservoirs and tunnels. It is also used as a drilling mud for soil borings.

Readers interested in this subject of clay mineralogy are referred to the publication by Murray (2006).

1.3.2 Structure of a clay deposit

Macrostructure

The visible features of a clay deposit collectively form its macrostructure and include such features as fissures, root holes, bedding patterns, silt and sand seams or lenses and other discontinuities.

A study of the macrostructure is important as it usually has an effect on the behaviour of the soil mass. For example, the strength of an unfissured clay mass is much stronger than along a crack.

Microstructure

The structural arrangement of microscopic sized clay particles, or groups of particles, defines the microstructure of a clay deposit. Clay deposits have been laid down under water and were created by the settlement and deposition of clay particles out of suspension. Often during their deposition, the action of Van der Waals forces attracted clay particles together and created flocculant, or honeycombed, structures, which, although still microscopic, are of considerably greater volume than single clay particles. Such groups of clay particles are referred to as *clay flocs*.

1.4 Field identification of soil

Gravels, sands and peats are easily recognisable, but difficulty arises in deciding when a soil is a fine sand or a coarse silt or when it is a fine silt or a clay. The following rules may, however, help:

Fine sand	Silt	Clay
Individual particles visible	Some particles visible	No particles visible
Exhibits dilatancy	Exhibits dilatancy	No dilatancy
Easy to crumble and falls off hands when dry	Easy to crumble and can be dusted off hands when dry	Hard to crumble and sticks to hands when dry
Feels gritty	Feels rough	Feels smooth
No plasticity	Some plasticity	Exhibits plasticity

The dilatancy test involves moulding a small amount of soil in the palm of the hand; if water is seen to recede when the soil is pressed, then it is either a sand or a silt.

Organic silts and clays are invariably dark grey to blue-black in colour and give off a characteristic odour, particularly with fresh samples.

The condition of a clay very much depends upon its degree of *consolidation*. At one extreme, a soft normally consolidated clay can be moulded by the fingers whereas, at the other extreme, a hard overconsolidated clay cannot. Overconsolidation is defined in Section 4.4 and the subject of degree of consolidation is covered in Chapter 13. Guidance on the identification of soils may be found in the international standard for *Geotechnical investigation and testing*, BS EN IS0 14688-1 (BSI, 2018a) and in the *Code of practice for ground investigations*, BS 5930 (BSI, 2015).

Common types of soil

In the field, soils are usually found in the form of a mixture of components, e.g. silty clay, sandy silt, etc. Local names are sometimes used for soil types that occur within a particular region. e.g. London clay.

Boulder clay, also referred to as *glacial till*, is an unstratified and irregular mixture of boulders, cobbles, gravel, sand, silt and clay of glacial origin. In spite of its name, boulder clay is not a pure clay and contains more granular material than clay particles.

Moraines are gravel and sand deposits of glacial origin. Loam is a soft deposit consisting of a mixture of sand, silt and clay in approximately equal quantities.

Fill is soil excavated from a ‘borrow’ area, which is used for filling hollows or for the construction of earth-fill structures, such as dams or embankments. Fill will sometimes contain man-made materials such as crushed concrete or bricks from demolished buildings.

Soil classification (see Section 1.6) enables the engineer to assign a soil to one of a limited number of groups, based on the properties and characteristics of the soil. The classification groups are then used as a system of reference for soils. Soils can be classified in the field or in the laboratory. Field techniques are usually based upon visual recognition as described above. Laboratory techniques involve several specialised tests and, in Europe, these are described in different parts of BS EN ISO 17892: *Geotechnical investigation and testing – Laboratory testing of soil* (BSI, 2014–2019). In much of North America and some other nations, specification D2487-17, published by ASTM International, is used. The procedures are largely the same across all the testing standards.

1.5 Soil classification laboratory testing

1.5.1 Drying soils

Soils can be either oven or air dried. It is standard practice to oven dry soils at a temperature of 105 °C but it should be remembered that some soils can be damaged by such a temperature. Oven drying is necessary for water content, sieve analysis and a few other tests, but air drying can be used whenever a test does not require a fully dry sample, e.g. compaction tests, described in Chapter 15.

1.5.2 Determination of water content, w

The most common way of expressing the amount of water present in a soil is the *water content*. The water content, also called the *moisture content*, is given the symbol w and is the ratio of the amount of water to the amount of dry soil.

$$w = \frac{\text{Weight of water}}{\text{Weight of solids}} = \frac{W_w}{W_s} \quad \text{or} \quad w = \frac{\text{Mass of water}}{\text{Mass of solids}} = \frac{M_w}{M_s} \tag{1.1}$$

w is usually expressed as a percentage and should be quoted to two significant figures.

Example 1.1: Water content determination

A sample of soil was placed in a water content tin of mass 19.52 g. The combined mass of the soil and the tin was 48.27 g. After oven drying the soil and the tin had a mass of 42.31 g.

Determine the water content of the soil.

Solution:

$$w = \frac{M_w}{M_s} = \frac{48.27 - 42.31}{42.31 - 19.52} = \frac{5.96}{22.79} = 0.262 = 26\%$$

1.5.3 Granular soils – particle size distribution

A standardised system helps to ensure consistency between engineers in the classification of granular soils. The usual method is based on the determination of the *particle size distribution* (PSD) by shaking an oven dried sample of the soil (usually after washing the sample over a 63 µm sieve) through a set of sieves. The aperture size of each succeeding sieve is smaller than the one above. By weighing the mass of soil retained on each sieve, we can obtain the particle size distribution for the soil.

The particle size scale is based on the limits for each fraction listed in Table 1.1.

Table 1.1 Particle size limits for different soil fractions.

Particle size fractions and symbol	Upper size (mm)	Lower size (mm)
Gravel, Gr	60	2
Sand, Sa	2	0.06
Silt, Si	0.06	0.002
Clay, Cl	0.002	–

These fractions can be subdivided on the basis of the 6-2, 6-2 pattern:

e.g. gravel:

coarse, c: 60–20 mm
medium, m: 20–6 mm
fine, f: 6–2 mm.

Similar subdivisions can be made for sand and silt.

The symbols are combined to aid classification, e.g.

cGr – coarse gravel; fSa – fine sand; mSi – medium silt.

The particle size fractions listed above refer to the classification system adopted in Europe, see also BS EN ISO 14688-1:2018 (BSI, 2018a). ASTM International standard D2487-17 (2017) offers an alternative system (*United Soil Classification System, USCS*) which adopts different sizes as the boundaries between the particle size fractions.

The results of the sieve analysis are plotted with the particle sizes horizontal and the summation percentages vertical. As soil particles vary in size from molecular to boulder it is necessary to use a log scale for the horizontal plot so that the full range can be shown on the one sheet.

The smallest aperture generally used in soils work is that of the 0.063 mm size sieve. Below this size (i.e. silt and clay sizes) the distribution curve must be obtained by sedimentation (following either a pipette or hydrometer method of analysis). Unless a centrifuge is used, it is not possible to determine the range of clay sizes in a soil, and usually it is adequate to just obtain the total percentage of clay sizes present. The procedures for sieve, pipette and hydrometer analyses are given in BS EN ISO 17892-4:2016 (BSI, 2016).

Examples of particle size distribution, or *grading*, curves for different soil types are shown in Fig. 1.10. From these grading curves it is possible to determine for each soil, the total percentage of a particular size, and the percentage of particle sizes larger or smaller than any particular particle size.

The effective size of a distribution, D_{10}

An important particle size within a soil distribution is the *effective size*, which is the largest size of the smallest 10%. It is given the symbol D_{10}. Other particle sizes, such as D_{30} and D_{60}, are defined in the same manner.

Grading of a distribution

For a granular soil, the shape of its grading curve indicates the distribution of the soil particles within it.

If the shape of the curve is not too steep and is more or less constant over the full range of the soil's particle sizes, then the particle size distribution extends evenly over the range of the particle sizes within the soil and there is no deficiency or excess of any particular particle size. Such a soil is said to be *well graded*.

If the soil has any other form of distribution curve, then it is said to be *poorly graded*. According to their distribution curves, there are two types of poorly graded soil:

- if the major part of the curve is steep, then the soil has a particle size distribution extending over a limited range with most particles tending to be about the same size. The soil is said to be *closely graded* or, more commonly, *uniformly graded*;
- if a soil has large percentages of its bigger and smaller particles and only a small percentage of the intermediate sizes, then its grading curve will exhibit a significantly flat section or plateau. Such a soil is said to be *gap graded*.

The uniformity coefficient C_u and the coefficient of curvature, C_c

The grading of a soil is best determined by direct observation of its particle size distribution curve. This can be difficult for those studying the subject for the first time, but some guidance can be obtained by the use of a grading parameter known as the *uniformity coefficient* or by the *coefficient of curvature*.

$$C_u = \frac{D_{60}}{D_{10}} \tag{1.2}$$

$$C_c = \frac{(D_{30})^2}{(D_{60} \times D_{10})} \tag{1.3}$$

The shape of the grading of the soil can then be established through the guidance given in Table 1.2.

Other statistical data can also be obtained from the psd;

e.g. median – size at which 50% of sample is finer, $D_{50.}$

Table 1.2 Shape of grading curve.

Term	C_u	C_c
Uniformly graded	<3	<1
Poorly graded	3–6	<1
Medium graded	6–15	<1
Well graded	>15	1–3
Gap graded	>15	<0.5

Example 1.2: Particle size distribution

The results of a sieve analysis on a soil sample were:

Sieve size (mm)	Mass retained (g)
10	0
6.3	5.5
2	25.7
1	23.1
0.600	22.0
0.300	17.3
0.150	12.7
0.063	6.9

2.3 g passed through the 63 µm sieve.

Plot the particle size distribution curve and determine the uniformity coefficient of the soil.

Solution:

The aim is to determine the percentage of soil (by mass) passing through each sieve. To do this, the percentage retained on each sieve is determined and subtracted from the percentage passing through the previous sieve. This gives the percentage passing through the current sieve.

Calculations may be set out as follows:

Sieve size (mm)	Mass retained (g)	Percentage retained	Percentage passing
10	0	0	100
6.3	5.5	5	95
2	25.7	22	73
1	23.1	20	53
0.600	22.0	19	34
0.300	17.3	15	19
0.150	12.7	11	8
0.063	6.9	6	2
Pass 0.063	2.3	2	
	$\Sigma 115.5$ g		

e.g. 2 mm sieve:

$$\text{Percentage retained} = \frac{25.7}{115.5} \times 100 = 22\%$$

$$\text{Percentage passing} = 95 - 22 = 73\%$$

The particle size distribution curve is shown in Fig. 1.3. Using the vertical axis, we can easily see that the soil has approximate proportions of 30% gravel and 70% sand.

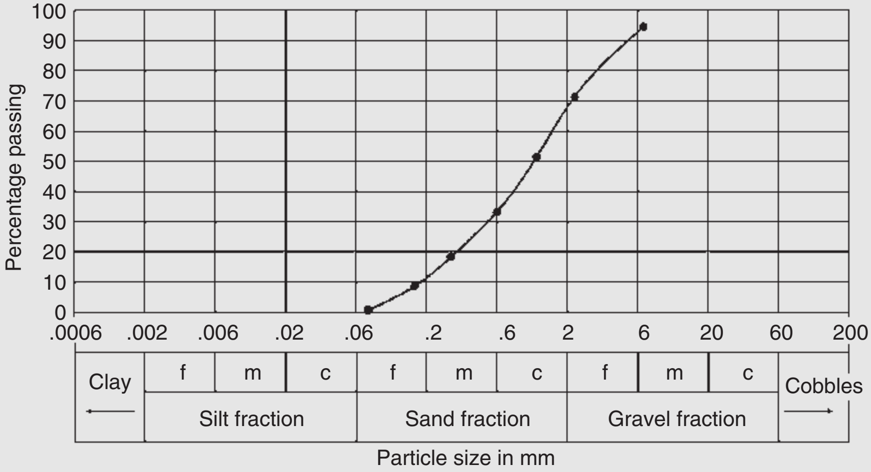

Fig. 1.3 Example 1.2.

$$D_{10} = 0.18\,\text{mm}; \quad D_{60} = 1.5\,\text{mm}; \quad C_u = \frac{D_{60}}{D_{10}} = \frac{1.5}{0.18} = 8.3$$

It is also seen that the grading curve has a regular slope and therefore contains roughly equal percentages of particle sizes. The soil is a medium graded, gravelly SAND.

1.5.4 Sedimentation analysis

The fraction of soil smaller than 0.06 mm cannot be separated by sieves, so a *sedimentation analysis* is used to establish the proportions of silt and clay fractions. The procedure is only considered necessary if more than 10% of the soil passes the 63 μm sieve. In the test, a sample of the dry soil passing the 63 μm sieve is placed into suspension with water in a sedimentation cylinder and allowed to settle over a period of time. Measurements of the percentage of particles remaining in suspension at set time intervals are established by either using a pipette or a hydrometer. Details of the test procedures are given in BE EN ISO 17892-4:2016 and Head (2006). The pipette procedure is described below.

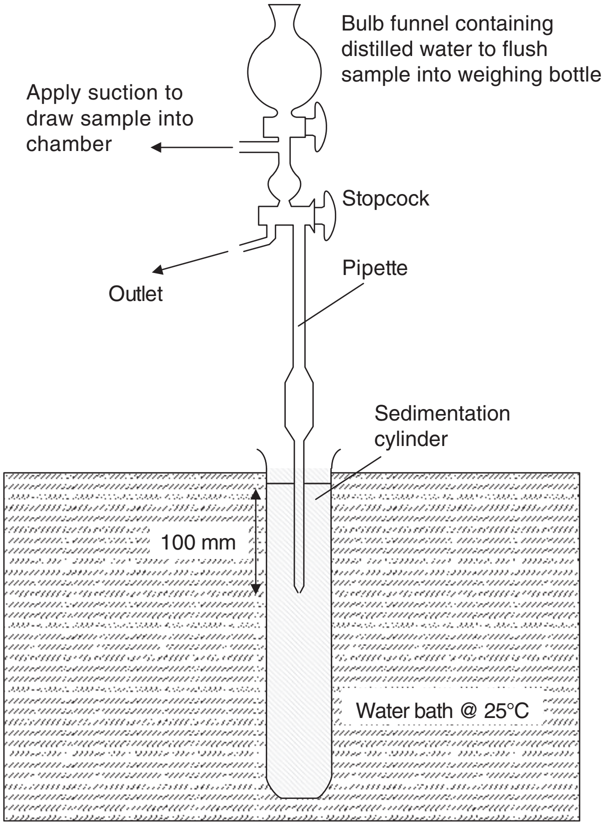

Fig. 1.4 Pipette analysis arrangement.

The dry soil of known mass is placed into a sedimentation cylinder of volume 500 ml and distilled water, containing a small amount of dispersing agent, is added. A dispersing procedure (e.g. end over end shaking) is adopted to separate all the particles in the suspension. The test begins by placing the upright cylinder into a water bath at 25 °C and a stopwatch is started. Three separate sampling dips are made at a depth of 100 mm using the pipette (Fig. 1.4) at pre-determined times. Different particle sizes will be captured in each sample, since the larger particles fall to the bottom of the cylinder before the smaller ones.

The pipette has a standard volume of 10 ml. This equals the volume of the solution sampled. That sample is flushed from the pipette into a small glass weighing bottle. By weighing the bottle before sampling and again after oven drying, the mass of the sampled soil is determined. By scaling the mass retained in the pipette sample (10 ml), less the mass of the dispersant, to that of the cylinder (500 ml), the mass of soil in suspension is determined. That, together with the determination of the particle size at the time of sampling, allows us to establish the percentage of particles passing that size.

The particle size, d (mm), sampled at depth, h (mm), at time, t (min) is established by:

$$d = 0.005531\sqrt{\frac{\eta \times h}{(\rho_s - 1) \times t}} \tag{1.4}$$

where

η is the dynamic viscosity of water (mPa s) (=0.89 at 25 °C)
ρ_s = particle density of the soil (Mg/m^3) – see Section 1.7.3.

If samples are taken at 4, 46 and 414 minutes for a soil with particle density of 2.65 Mg/m^3, the particle sizes in each sample will be 0.02, 0.006 and 0.002 mm respectively.

Example 1.3: Pipette analysis

The results of a standard pipette analysis, carried out on a sample of soil passing the 63 μm sieve of dry mass 27.25 g and particle density = 2.65 Mg/m^3, were:

	Sample 1	Sample 2	Sample 3
Time (min)	4	46	414
Mass of empty sample bottle (g)	5.1926	5.3710	5.2983
Mass of sample bottle plus dry soil (g)	5.6927	5.8052	5.6898

During a control test on the dispersant/water only solution (500 ml), it was established that the mass of dry dispersant in a sample of 10 ml was 0.0173 g.

Determine the percentages of fine silt and clay in the soil.

Solution:

Standard test, therefore:

Volume of cylinder = 500 ml;
Volume of pipette = 10 ml;
Water bath temperature = 25 °C;
Sampling depth = 100 mm

	Sample 1	Sample 2	Sample 3
Particle size, d (mm)	0.02	0.006	0.002
Mass of soil in sample (g)	0.5001	0.4342	0.3915
Equivalent mass in cylinder (g)	$= (0.5001 - 0.0173) \times \left(\frac{500}{10}\right) = 24.15$	8.0	5.5
Percentage passing d (%)	$= \frac{24.15}{27.25} \times 100 = 88.6$	76.5	68.7

From the results it is seen that the percentage of fine silt (0.006–0.002 mm) is 76.5 – 68.7 = 7.8% and the percentage of clay (<0.002 mm) is 68.7%.

1.5.5 Cohesive soils – liquid and plastic limit tests

The results of the grading tests described above can only classify a soil with regard to its particle size distribution. They do not indicate whether the fine grained particles will exhibit the plasticity generally associated with fine grained soils. Hence, although a particle size analysis will completely define a gravel and a sand, it is necessary to carry out plasticity tests in order to fully classify a clay or a fine silt.

These tests were evolved by Atterberg (1911) and determine the various values of water content at which changes in a soil's strength characteristics occur. As an introduction to these tests, let us consider the volume of a soil as the amount of water within it is varied (Fig. 1.5).

As the water is added to the dry clay, there is no immediate increase in volume. However, as the amount of water is gradually increased, the volume increases too. Also, as the water content changes, the soil behaves differently: when dry, the soil is brittle but when extremely wet, the soil is a liquid (referred to as a *slurry*). There is a stage in between the brittle and liquid states and the soil in this range of water contents behaves as a plastic material.

The boundaries to the four states in which a soil may exist are defined:

liquid limit, w_L: the boundary between the liquid and the plastic state;
plastic limit, w_P: the boundary between the plastic and the semi-solid state;
shrinkage limit, w_S: the boundary between the semi-solid and the solid state.

The limits are defined as the water contents of the soil at each boundary, as indicated in Fig. 1.5.

Liquid limit (w_L) and plastic limit (w_P)

The water content at which the soil stops acting as a liquid and starts acting as a plastic solid is known as the *liquid limit* (w_L). If the soil is dried from the liquid limit, it passes through the plastic state. When plastic, the soil can be moulded in the fingers akin to working with modelling clay. But as further water is driven from the soil, the soil no longer behaves as a plastic material and instead acts as a brittle solid. The limit at which plastic behaviour changes to brittle failure is known as the *plastic limit* (w_P).

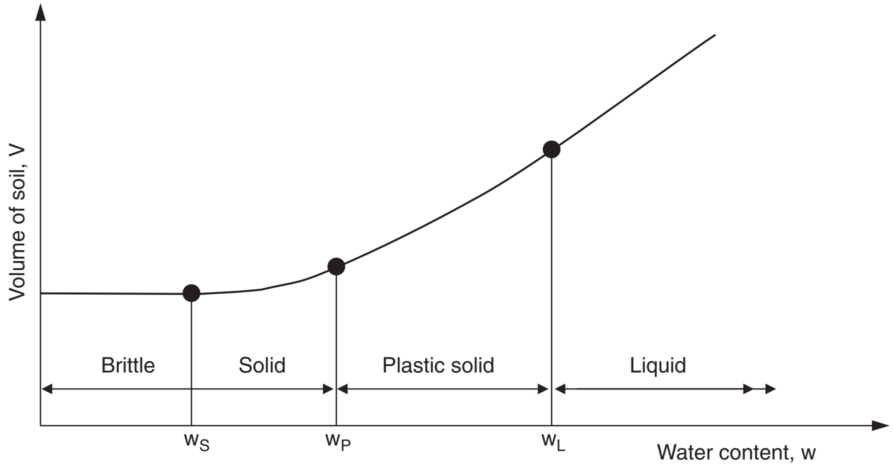

Fig. 1.5 Changes in volume against water content.

Plasticity index (I_P)

The *plasticity index* is the range of water content within which a soil is plastic; the finer the soil the greater its plasticity index.

Plasticity index = Liquid limit − Plastic limit

$$I_P = w_L - w_P \qquad (1.5)$$

Liquidity index

The *liquidity index* enables a comparison to be made of a soil's plasticity with its natural water content (w).

$$I_L = \frac{w - w_p}{I_p} \qquad (1.6)$$

If $I_L = 1.0$ the soil is at its liquid limit. If $I_L = 0$ the soil is at its plastic limit.

Shrinkage limit (w_S)

If the drying process is prolonged after the plastic limit has been reached, the soil will continue to decrease in volume until a certain value of water content is reached. This value is known as the *shrinkage limit* and at values of water content below this level the soil is partially saturated. In other words, below the shrinkage limit the volume of the soil remains constant with further drying, but the weight of the soil decreases until the soil is fully dried.

Determination of liquid and plastic limits

The test procedures are given in BS EN ISO 17892-12 (BSI, 2018).

Liquid limit test

BS EN ISO 17892-12 specifies two methods for determining the liquid limit of soil.

(1) Fall cone method (preferred method)

This is typically referred to as the *cone penetrometer test*. Details of the apparatus are shown in Fig. 1.6. The soil to be tested is air dried and thoroughly mixed. At least 200 g of the soil is sieved through a 425 μm sieve and placed on a glass plate. The soil is then mixed with distilled water into a paste.

A metal cup, approximately 55 mm in diameter and 40 mm deep, is filled with the paste and the surface struck level. The cone, of mass 80 g, is next placed at the centre of the smoothed soil surface and level with it. The cone is released so that it penetrates into the soil and the amount of penetration, over a time period of five seconds, is measured.

The test is now repeated by lifting the cone clear, cleaning it and filling up the depression in the surface of the soil by adding a little more of the wet soil.

If the difference between the two measured penetrations is less than 0.5 mm then the tests are considered valid, else a third penetration test is done. The average penetration is noted, and a water content determination is carried out on the soil.

The procedure is repeated at least four times with increasing water contents. The amount of water used throughout should be such that the penetrations obtained lie within a range of 15–25 mm.

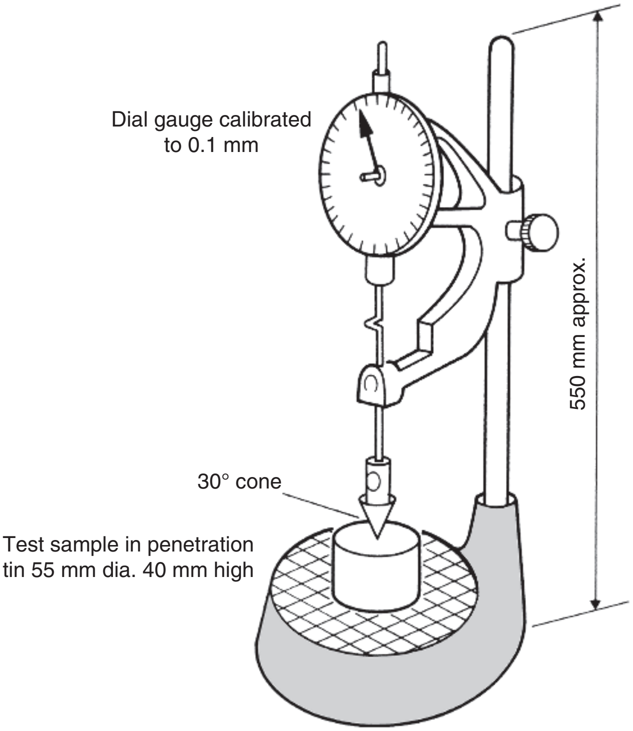

Fig. 1.6 Fall cone apparatus.

To obtain the liquid limit, the variation of cone penetration is plotted against water content and the best straight line is drawn through the experimental points. The liquid limit is taken to be the water content corresponding to a cone penetration of 20 mm, expressed as a whole number.

(2) *Casagrande apparatus*

Although still used worldwide, the Casagrande test has now been largely superseded by the fall cone method because the latter achieves more repeatable results. In the UK, the fall cone test is adopted as the first-choice test method.

Plastic limit test

About 20 g of soil prepared as in the liquid limit test is used. The soil is mixed on the glass plate with just enough water to make it sufficiently plastic for rolling into a ball, which is then rolled out between the hand and the glass to form a thread. The soil is judged to be at its plastic limit when it just begins to crack at a thread diameter of 3 mm. At this stage, several pieces of the thread are taken for water content determination. The test is repeated until two water content tins contain an adequate mass of soil threads – approximately 10–15 g in each tin.

It is interesting to note that in some countries, the fall cone penetrometer is used to determine both w_L and w_P. The apparatus uses a 30° angle cone of mass 76 g. The procedure is the same as the fall cone described above, only this time w_L is taken at a penetration of 17 mm and w_P is taken as the water content at a penetration of 2 mm.

Example 1.4: Consistency limits tests

A cone penetrometer test was carried out on a sample of the clay from Example 1.3, with the following results:

Cone penetration (mm)	16.1	17.6	19.3	21.3	22.6
Water content (%)	50.0	52.1	54.1	57.0	58.2

The results from the plastic limit test were:

Test no.	Mass of tin (g)	Mass of wet soil + tin (g)	Mass of dry soil + tin (g)
1	8.1	20.7	18.7
2	8.4	19.6	17.8

Determine the liquid limit, plastic limit and the plasticity index of the soil.

Solution:

The plot of cone penetration to water content is shown in Fig. 1.7. The liquid limit is the water content corresponding to 20 mm penetration, i.e. w_L = 55%.

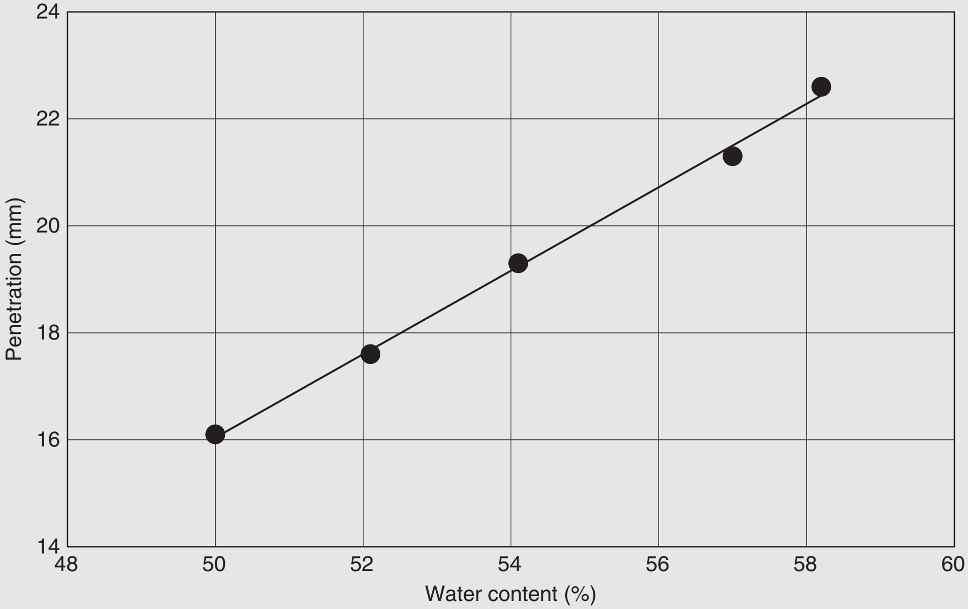

Fig. 1.7 Example 1.4.

The plastic limit is determined thus:

$$w_P(1) = \frac{20.7 - 18.7}{18.7 - 8.1} \times 100 = 18.9\%$$

$$w_P(2) = \frac{19.6 - 17.8}{17.8 - 8.4} \times 100 = 19.1\%$$

Average $w_P = 19\%$

The plasticity index is the difference between w_L and w_P i.e.

$$I_P = 55 - 19 = 36\%$$

1.5.6 Activity of a clay

In addition to their use in soil classification, the w_L and w_P values of a plastic soil also give an indication of the types and amount of the clay minerals present in the soil.

It has been found that, for a given soil, the plasticity index increases in proportion to the percentage of clay particles in the soil. Indeed, if a group of soils is examined and their I_P values are plotted against their clay percentages, a straight line, passing through the origin, is obtained.

If a soil sample is taken and its clay percentage artificially varied, a relationship between I_P and clay percentage can be obtained. Each soil will have its own straight line because, although in two differing soils the percentages of clay may be the same, they will contain different minerals.

The relationship between montmorillonite, illite, kaolinite and the plasticity index is shown in Fig. 1.8. The plot of London clay is also shown on the figure and, from its position, it is seen that the mineral content of this

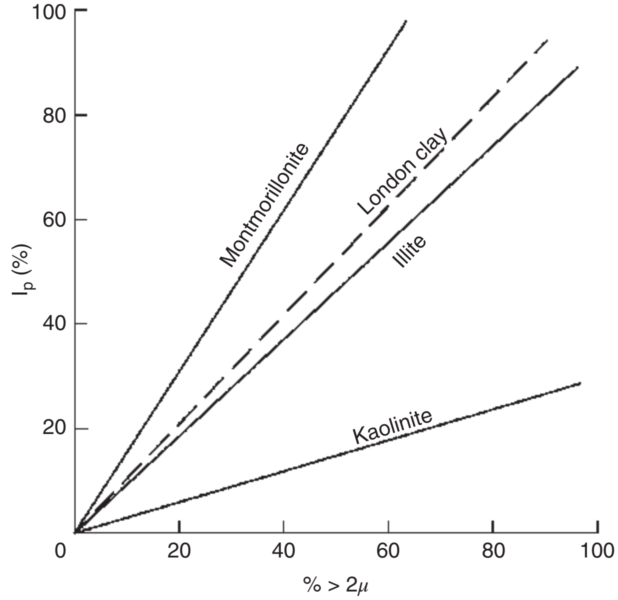

Fig. 1.8 Relationship between I_P and clay percentage. Modified from Skempton (1953).

soil is predominantly illite. London Clay has a clay fraction of about 46% and consists of illite (70%), kaolinite (20%) and montmorillonite (10%). The remaining fraction of 54% consists of silt (quartz, feldspar and mica: 44%) and sand (quartz and feldspar: 10%). In Fig. 1.8, the slope of the line is the ratio:

$$\frac{I_P}{\%\text{clay}}$$

Skempton (1953) defined this ratio as the *activity* of the clay. Clays with large activities are called active clays and exhibit plastic properties over a wide range of water content values.

1.6 Soil classification and description

1.6.1 Soil classification

Soil classification systems have been in use for a very long time with the first recorded use being in China over 4000 years ago. In 1896 a soil classification system was proposed by the Bureau of Soils, United States Department of Agriculture in which the various soil types were classified purely on particle size and it is interesting to note that the limiting sizes used are more or less the same as those in use today. Further improved systems allowed for the plasticity characteristics of soil, and a modified form of the system proposed by Casagrande in 1947 was the basis of the soil classification system used in the UK for many years. With the widespread adoption of BS EN ISO 14688:2018 (BSI, 2018a,c), the classification of soils across Europe now follows a standardised approach.

In order to classify soils, the system considers natural soils as falling into one of the following categories: *very coarse*, *coarse*, *fine* and *organic*. The majority of soils are inorganic, and particle sizes and plasticity characteristics of these soils are used to identify the *primary soil fraction*. Developing the notion of fraction sizes listed in Table 1.1, BS EN ISO 14688-2:2018 (BSI, 2018c) offers the principles of classification listed in Table 1.3.

Since soils are usually composite (i.e. contain various amounts of different particle sizes) it will be the case that secondary and tertiary fractions will also exist in the soil. In soil classification and description, these additional fractions are used as adjectives and the primary fraction is the noun. The primary fraction is written in capitals: e.g. sandy, silty CLAY; gravelly, coarse SAND; clayey SILT.

For fine soils, the results of the liquid and plastic limits tests are used to classify these soils. Classification is done through the use of a plasticity chart (Fig. 1.9). To use the plasticity chart, a point is plotted whose coordinates are the liquid limit and the plasticity index of the soil. The soil is then classified by observing the position of the point relative to the sloping straight line drawn across the diagram. This line, known as the *A-line*, is

Table 1.3 Principles of soil classification.

Soil group	Primary function	Criteria
Very coarse	Boulders (Bo)	50% of particles >200 mm in size
	Cobbles (Co)	200 mm > 50% > 63 mm
Coarse	Gravel (Gr)	63 mm > 50% > 2 mm
	Sand (Sa)	2 mm > 50% > 0.06 mm
Fine	Silt (Si)	Low plasticity or non-plastic
	Clay (Cl)	Plastic

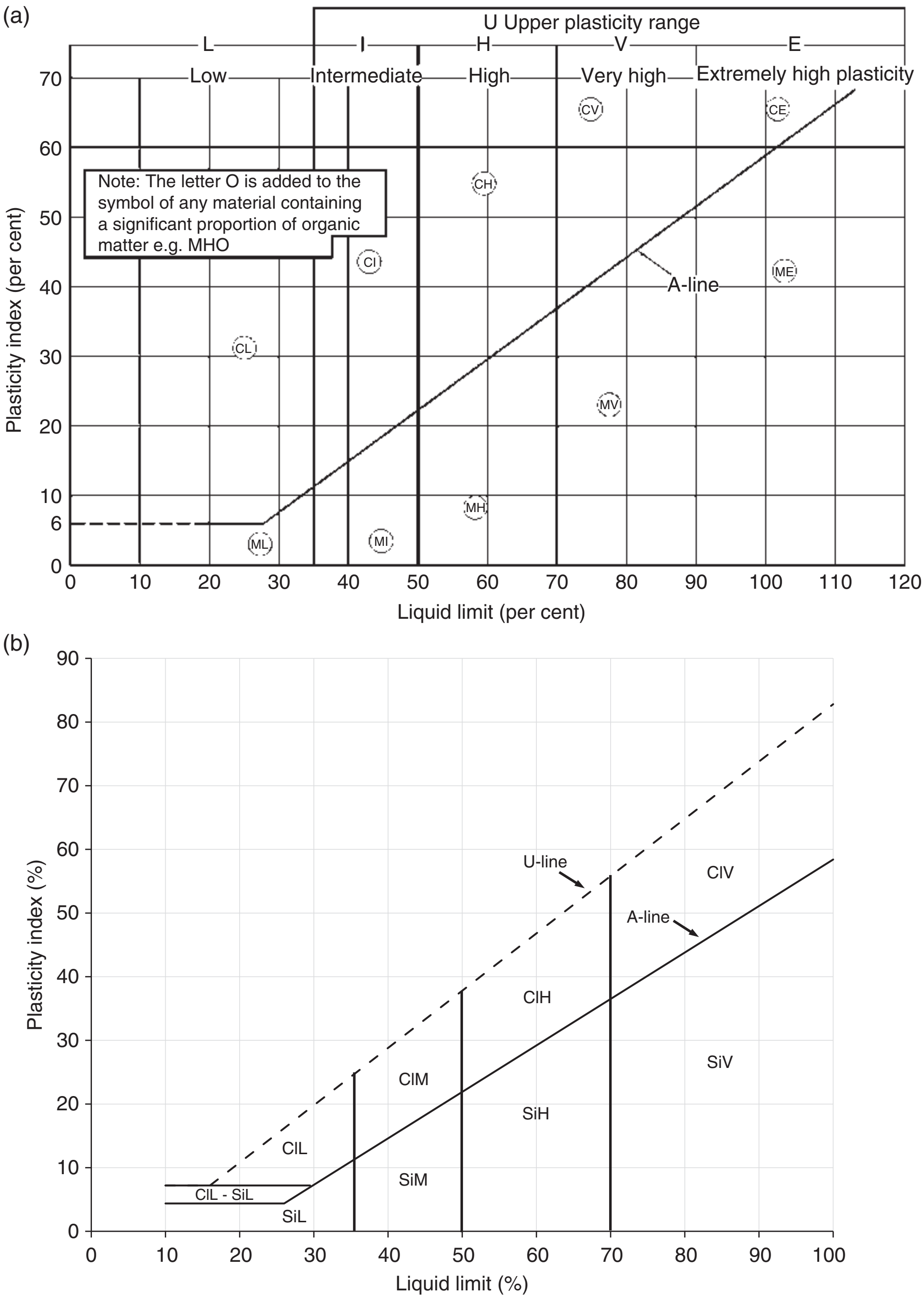

Fig. 1.9 (a) Plasticity chart based on BS 5030 (BSI, 2015) (b) Plasticity chart based on BS EN ISO 14688-2 (BSI, 2018c).

an empirical boundary between inorganic clays, whose points lie above the line, and organic silts and clays whose points lie below. The A-line goes through the base line at ($w_L = 20\%$, $I_P = 0$) so that its equation is:

$$I_P = 0.73(w_L - 20\%)$$

Two versions of the plasticity chart exist (BS 5930 and BS EN ISO 14688-2) and either may be used: the former in the UK, the latter elsewhere in Europe. The boundaries between the degrees of plasticity are the same from both charts. It is only the symbols used to indicate the plasticity group that differ between the two.

The U-line in Fig. 1.9b indicates the approximate upper limit for natural soils and has equation,

$$I_P = 0.9(w_L - 8\%)$$

Example 1.5: Soil classification (i)

(a) Classify the soil of Example 1.2 whose particle size distribution curve is shown in Fig. 1.3.

(b) If the soil tested in Example 1.3 experienced 100% passing the 63 mm sieve, 96% passing the 2 mm sieve and 85% passing the 63 μm sieve, classify the soil.

Solution:

(a) $C_u = \dfrac{D_{60}}{D_{10}} = \dfrac{1.5}{0.18} = 8.3;$

$$C_c = \frac{(D_{30})^2}{(D_{60} \times D_{10})} = \frac{0.51^2}{1.5 \times 0.18} = 0.96$$

Using Tables 1.2 and 1.3, the soil is classified a medium graded gravelly SAND.

(b) The PSD may be plotted to visualise the results (see spreadsheet example_1.3_and_1.5b.xls) or the classification may be made by reviewing the data directly:

Particle fractions:

Gravel: 100 – 96 = 4%
Sand: 96 – 85 = 11%
Silt: 85 – 58* = 27%
Clay: 58*%

*In the pipette analysis, 68.7% of the sample was found to be clay. That test was performed only on the fraction passing the 63 μm sieve. To establish the percentage of clay in the whole soil, we must consider the proportion passing the 63 μm sieve as a fraction of the whole soil sample.

i.e. $\%\text{clay} = 0.687 \times 85 = 58\%$

Based on the percentages of each fraction, the soil may therefore be classified as a slightly sandy, silty CLAY.

Since it is a clay, it must also be classified in terms of its plasticity. To do this we use the results of Example 1.4 together with the plasticity chart (Fig. 1.9). It is seen that the soil therefore is a slightly sandy, silty CLAY of high plasticity.

Example 1.6: Soil classification (ii)

A set of particle size distribution analyses on three soils, A, B and C, gave the following results:

	Percentage passing		
Sieve size (mm)	Soil A	Soil B	Soil C
20	90	–	–
10	56	–	–
6.3	47	–	–
2	43	–	–
0.6	39	93	–
0.425	–	78	–
0.300	28	16	–
0.212	–	5	–
0.150	–	–	100
0.063	5	2	92

Soil C: Since more than 10% passed the 63 μm sieve, a pipette analysis was performed. The results were:

Particle size (mm)	Percentage passing
0.04	79
0.02	62
0.006	47
0.002	40

Soil C was found to have a liquid limit of 48% and a plastic limit of 29%. Plot the particle size distribution curves and classify each soil.

Solution:

The particle size distribution curves for the three soils are shown in Fig. 1.10. The curves can be used to obtain the following particle sizes for soils A and B.

Soil	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)
A	0.1	0.31	12.0
B	0.26	0.36	0.38

Soil A: From the grading curve it is seen that this soil consists of 57% gravel and 43% sand and is therefore predominantly gravel. The curve has a horizontal portion indicating that the soil has only a small percentage of soil particles within this range. It is therefore gap graded. Also, $C_u = 120$.

The soil is a gap graded sandy GRAVEL.

Soil B: From the grading curve, it is immediately seen that this soil is a sand with most of its particles about the same size. Also, $C_u = 1.5$.

The soil is a uniformly graded SAND.

Soil C: From the grading curve, it is seen that the soil is a mixture of 10% sand, 50% silt and 40% clay so it is a slightly sandy, very clayey SILT. The liquid limit of the soil = 48% and the plasticity index, $(w_L - w_P) = 19\%$. Using Fig. 1.9, it is seen that the soil is a silt with the group symbol MI (BS 5930) or SiM (BS EN ISO 14688-2).

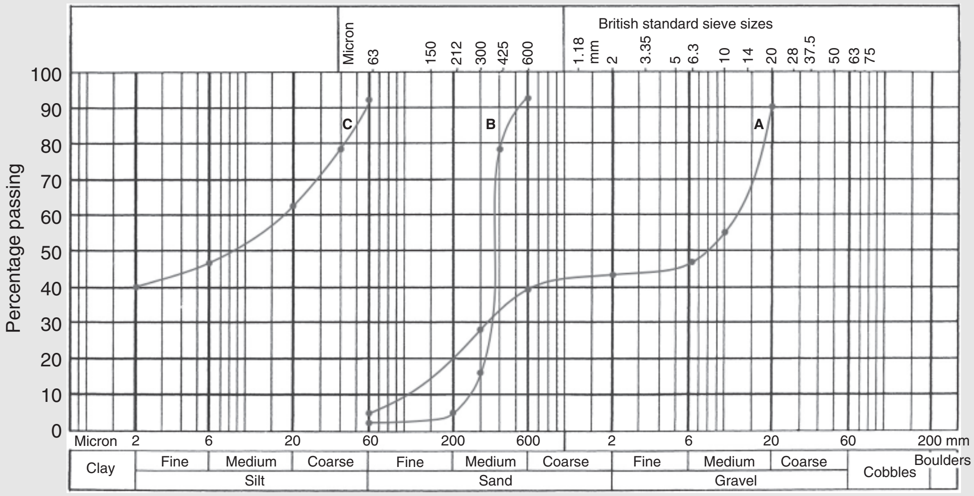

Fig. 1.10 Example 1.6.

1.6.2 Description of soils

Classifying and describing a soil are two operations, which are not necessarily the same. An operator who has not even visited the site from which a soil came can classify the soil from the information obtained from grading and plasticity tests carried out on disturbed samples. Such tests are necessary if the soil is being considered as a possible construction material and the information obtained from them must be included in any description of the soil.

Further information regarding the colour of a soil, the texture of its particles, etc., can be obtained in the laboratory from disturbed soil samples but a full description of a soil must include its *in situ*, as well as its laboratory, characteristics. Some of this latter information can be found in the laboratory from undisturbed samples of the soil collected for other purposes, such as strength or permeability tests, but usually not until after the tests have taken place and the samples can then be split open for proper examination. Other relevant information such as bedding details, gravel particle shapes (e.g. angular, rounded, elongated), clay consistency (e.g. soft, firm, stiff) and site observations can also be included in the soil's description.

1.7 Soil properties

From the foregoing it is seen that soil consists of a mass of solid particles separated by spaces, or *voids*. A cross-section through a granular soil may have an appearance similar to that shown in Fig. 1.11a.

In order to study the properties of such a soil mass, it is advantageous to adopt an idealised form of the diagram as shown in Fig. 1.11b. The soil mass has a total volume V and a volume of solid particles equal to V_s. The volume of the voids, V_v is obviously equal to $V - V_s$.

1.7.1 Void ratio and porosity

From a study of Fig. 1.11, the following may be defined:

Void ratio, e

$$e = \frac{\text{Volume of voids}}{\text{Volume of solids}} = \frac{V_v}{V_s} \tag{1.7}$$

Porosity, n

$$n = \frac{\text{Volume of voids}}{\text{Total volume}}$$

$$n = \frac{V_v}{V} = \frac{V_v}{V_s + V_v} = \frac{e}{1 + e} \tag{1.8}$$

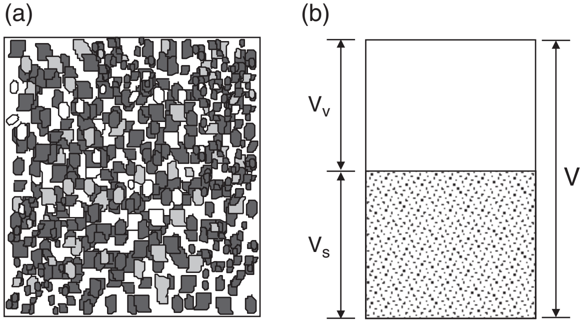

Fig. 1.11 Cross-section through a granular soil. (a) Actual form. (b) Idealised form.

1.7.2 Degree of saturation, S_r

The voids of a soil may be filled with air or water or both. If only air is present the soil is dry, whereas if only water is present the soil is *saturated*. When both air and water are present the soil is said to be partially saturated. These three conditions are represented in Fig. 1.12a–c.

The degree of saturation is simply:

$$S_r = \frac{\text{Volume of water}}{\text{Volume of voids}} = \frac{V_w}{V_v} \tag{1.9}$$

(usually expressed as a percentage)

For a dry soil, $S_r = 0$

For a saturated soil, $S_r = 1.0$

1.7.3 Particle density, ρ_s and specific gravity, G_s

The specific gravity of a material is the ratio of the weight or mass of a volume of the material to the weight or mass of an equal volume of water. In soil mechanics the most important specific gravity is that of the actual soil grains and is given the symbol G_s.

From the above definition it is seen that for a soil sample with volume of solids, V_s, mass of solids, M_s and weight of solids, W_s,

$$G_s = \frac{M_s}{V_s \rho_w} = \frac{W_s}{V_s \gamma_w} \tag{1.10}$$

where ρ_w is the density of water (=1.0 Mg/m^3 at 20 °C) and γ_w is the unit weight of water (=9.81 kN/m^3).

The density of the particles ρ_s is defined as:

$$\rho_s = \frac{M_s}{V_s}$$

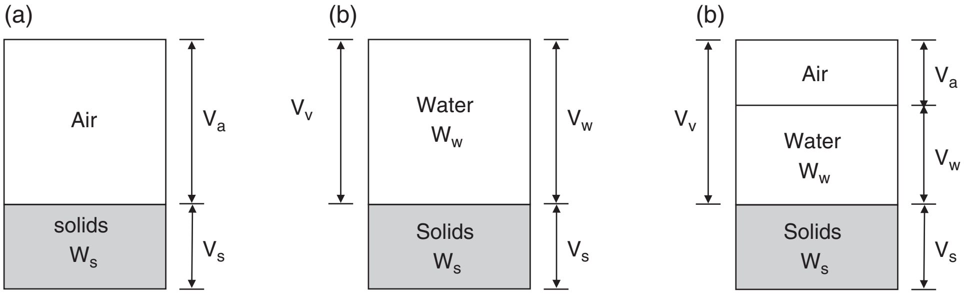

Fig. 1.12 Water and air contents in a soil. (a) Dry soil. (b) Saturated soil. (c) Partially saturated soil.

therefore,

$$G_s = \frac{\rho_s}{\rho_w}$$

If ρ_s is measured in units of Mg/m^3 and the water temperature is assumed to be 20 °C, it follows that ρ_s and G_s are numerically equal. G_s, however is dimensionless whereas ρ_s has the units of density, Mg/m^3.

Particle density is determined in the laboratory through a well-established and reliable testing procedure (described in BS EN ISO 17892-3:2015, BSI, 2015). A mass of dry soil is mixed with distilled water in a standard glass vessel known as a *pycnometer* to separate all the particles and to enable all the air to be removed from the soil. In the test the difference in the volumes of water required to fill the pycnometer, both with and without the soil present, is determined. The particle density is equal to the dry mass of the soil divided by that volume difference.

For sands and fine soils, a sample of the soil (minimum 10 g) is oven dried, weighed and placed into the pycnometer of minimum volume 50 ml along with distilled water at room temperature (Fig. 1.13). Coarse soils can be tested in a larger pycnometer or the gravel portion can be mechanically broken down to pass a 4 mm sieve and placed in the smaller pycnometer. Formerly, in the UK, a 1 l gas jar was used for coarse soils – see earlier editions of this book for details of the gas jar procedure.

The pycnometer and contents are shaken steadily but vigorously to remove all air bubbles. The glass stopper is then removed, the jar topped up carefully to full capacity with further distilled water and the stopper

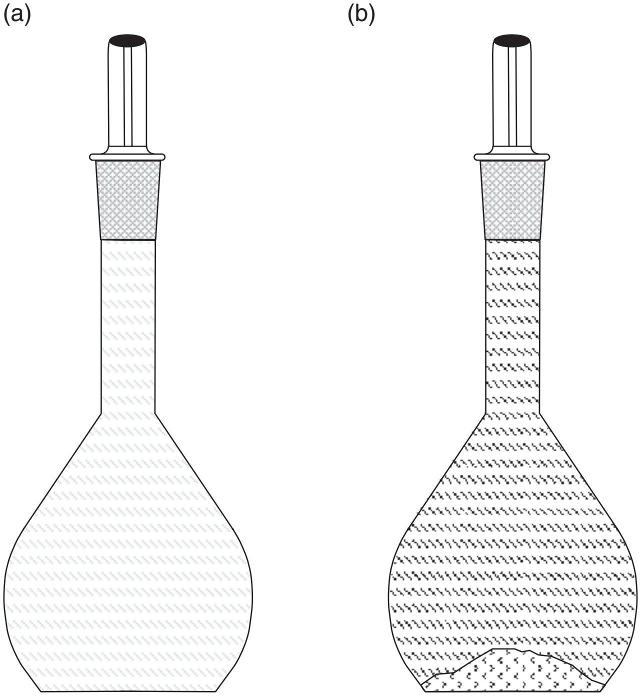

Fig. 1.13 Pycnometer used in the determination of particle density. (a) Pycnometer filled with water only. (b) Pycnometer filled with soil and water.

replaced to seal the vessel without trapping any air inside. The stopper has a capillary tube through it, which permits the water to flow out its top as it is inserted into pycnometer. From various weighings that are made, the particle density of the soil can be calculated (see Example 1.7).

Example 1.7: Particle density

The mass of an empty pycnometer, together with its glass stopper, was 178.0 g. When completely filled with water and the stopper fitted the mass was 228.2 g. An oven dried sample of soil was placed in the pycnometer and the total mass, including the stopper, was 191.2 g. Water was added to the soil and, after a suitable period of shaking, was topped up until the vessel was brim full. The stopper was fitted and the total mass was found to be 236.4 g.

Determine the particle density of the soil.

Solution:

Mass of soil + water = 236.4 – 178.0 = 58.4 g

Mass of dry soil = 191.2 – 178.0 = 13.2 g

Mass of water present with soil = 58.4 – 13.2 = 45.2 g

Mass of water when pycnometer full = 228.2 – 178.0 = 50.2 g.

Therefore, mass of water of same volume as soil = 50.2 – 45.2 = 5.0 g

$$\rho_s = \frac{\text{Mass of soil}}{\text{Mass of same volume of water}} = \frac{13.2}{5.0} = 2.64$$

The particle density can be quickly found from a formula thus:

$$\rho_s = \frac{m_s}{(m_1 - m_2) + m_s}$$

where

m_s = mass of dry soil (g)
m_1 = mass of pycnometer + water (g)
m_2 = mass of pycnometer + water + soil (g)

$$\rho_s = \frac{13.2}{[228.2 - 236.4] + 13.2} = 2.64$$

1.7.4 Density and unit weight

The amount of material in a given volume, V, may be expressed in two ways:

the amount of mass, M, in the volume, or the amount of weight, W, in the volume.

If we consider unit volume, the two systems give the *mass density* and the *weight density* of the material respectively. The *mass density* is usually simply referred to as *density* and the *weight density* is routinely referred to as the *unit weight*:

$$\text{Density}, \rho = \frac{\text{Mass}}{\text{Volume}} = \frac{M}{V} \tag{1.11}$$

$$\text{Unit weight}, \gamma = \frac{\text{Weight}}{\text{Volume}} = \frac{W}{V} \tag{1.12}$$

$$\text{Weight} = \text{mass} \times 9.81$$

As an example, consider water at 20 °C:

Density of water, $\rho_w = 1000\ \text{kg/m}^3 = 1.0\ \text{Mg/m}^3$

Hence the unit weight of water, $\gamma_w = 1.0 \times 9.81 = 9.81\ \text{kN/m}^3$.

Soil densities are usually expressed in Mg/m^3 to the nearest 0.01.

Soil weights are usually expressed in kN/m^3.

In soils work, it is generally more convenient to measure the density of a soil through test (e.g. Example 1.8) then to perform the geotechnical analysis using the unit weight, or weight density, derived from the density value.

Density of soil

Bulk density

The bulk density of a soil is a frequently requested, easily determined, geotechnical property. By sampling a soil using a sampler (e.g. a steel tube) of known volume, V, the mass, M can easily be measured on laboratory scales and the bulk density determined:

$$\text{Bulk density}, \rho = \frac{M}{V}$$

The bulk density is the density of the wet soil, as it considers the mass of water in the soil as well as the soil particles.

Dry density

The dry density is the density of the soil particles within the same volume, V as the bulk density.

$$\text{Dry density}, \rho_d = \frac{M_s}{V}$$

The dry density can be determined from the bulk density and the water content (in %):

$$\rho_d = \frac{\rho \times 100}{100 + w} \tag{1.13}$$

Unit weight, or weight density, of soil

As mentioned, the unit weight of a material is its weight per unit volume. In soils work the most important unit weights are:

Bulk unit weight, γ

This is the natural *in situ* unit weight of the soil. Referring to Fig. 1.12 and Section 1.7.3:

$$\gamma = \frac{\text{Total weight}}{\text{Total volume}} = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v}$$

$$\gamma = \frac{G_s V_s \gamma_w + V_v \gamma_w S_r}{V_s + V_v} = \gamma_w \left[\frac{G_s + eS_r}{1 + e}\right] \tag{1.14}$$

Saturated unit weight, γ_{sat}

$$\text{Saturated unit weight}, \gamma_{sat} = \frac{\text{Saturated weight}}{\text{Total volume}}$$

Recall, when soil is saturated, $S_r = 1$. Therefore,

$$\gamma_{sat} = \gamma_w \frac{G_s + e}{1 + e} \tag{1.15}$$

Dry unit weight, γ_d

$$\gamma_d = \frac{\text{Dry weight}}{\text{Total volume}}$$

$$\gamma_d = \frac{\gamma_w G_s}{1 + e} \quad (\text{as } S_r = 0) \tag{1.16}$$

Effective, or buoyant, unit weight, γ'

When a soil is below the water table, part of its weight is balanced by the buoyant effect of the water. This upthrust equals the weight of the volume of the water displaced.

Hence, considering unit volume:

Effective unit weight = Saturated unit weight − Unit weight of water

$$\gamma' = \gamma_w \frac{G_s + e}{1 + e} - \gamma_w = \gamma_w \frac{G_s - 1}{1 + e} \tag{1.17}$$

The effective unit weight is also referred to as the *buoyant unit weight* or the *submerged unit weight*.

Note: The two terms *weight density* and *unit weight* are synonymous, and both are in common use. Both terms are used throughout this book.

Additional expressions for densities

As with the unit weights, similar expressions can be obtained for densities:

$$\text{Bulk density}, \rho_b = \rho_w \frac{(G_s + eS_r)}{1 + e} \tag{1.18}$$

$$\text{Saturated density}, \rho_{sat} = \rho_w \frac{(G_s + e)}{1 + e} \tag{1.19}$$

$$\text{Dry density}, \rho_d = \rho_w \frac{G_s}{1 + e} \tag{1.20}$$

$$\text{Effective density}, \rho' = \rho_w \frac{G_s - 1}{1 + e} \tag{1.21}$$

Relationship between density and unit weight values

In the previous expressions, G_s, e, S_r and the number 1 are all dimensionless.

Hence, a particular unit weight = γ_w times a constant.

The corresponding density = ρ_w times the same constant.

Example 1.8: Dry unit weight

A sample of wet soil was extruded from a sampling tube of diameter 100 mm in a soil testing laboratory. The length of extruded sample was 200 mm. The mass of the wet soil was 3.15 kg. Following a water content determination, the mass of the dry soil was found to be 2.82 kg.

Determine the bulk density, water content, dry density and dry unit weight of the soil.

Solution:

$$\text{Volume of sample} = \frac{\pi \times 0.1^2}{4} \times 0.2 = 0.0016\ \text{m}^3$$

$$\rho = \frac{M}{V} = \frac{3.15}{0.0016} = 1969\ \text{kg/m}^3 = 1.97\ \text{Mg/m}^3$$

$$w = \frac{3.15 - 2.82}{2.82} = 12\%$$

$$\rho_d = \frac{\rho \times 100}{100 + w} = \frac{197}{112} = 1.76\ \text{Mg/m}^3$$

$$\gamma_d = \rho_d \times 9.81 = 17.3\ \text{kN/m}^3$$

Relationship between w, γ_d and γ

$$\gamma = \frac{W_w + W_s}{V} \tag{1.22}$$

$$\gamma_d = \frac{W_s}{V} \tag{1.23}$$

$$w = \frac{W_w}{W_s} \tag{1.24}$$

Rearranging (1.24) and substituting into (1.22) gives:

$$\gamma = \frac{W_s}{V}(1 + w)$$

And substituting into (1.23) gives:

$$\gamma_d = \frac{\gamma}{1 + w}$$

Thus, to find the dry unit weight from the bulk unit weight, divide the latter by (1 + w) where w is the water content expressed as a decimal.

Relationship between e, w and G_s for a saturated soil

$$w = \frac{W_w}{W_s} = \frac{V_w\gamma_w}{V_s\gamma_w G_s} = \frac{V_v}{V_s G_s} = \frac{e}{G_s} \quad (V_w = V_v \text{ if the soil is saturated})$$

i.e.

$$e = wG_s \tag{1.25}$$

Relationship between e, w and G_s for a partially saturated soil

$$w = \frac{W_w}{W_s} = \frac{V_w\gamma_w}{V_s\gamma_w G_s} = \frac{V_v S_r}{V_s G_s} = \frac{eS_r}{G_s}$$

i.e.

$$e = \frac{wG_s}{S_r} \tag{1.26}$$

Example 1.9: Physical properties determination

In a bulk density determination, a sample of clay with a mass of 683 g was coated with wax. The combined mass of the clay and the wax was 690.6 g. The volume of the clay and the wax was found, by immersion in water, to be 350 ml.

The sample was then broken open and water content and particle specific gravity tests gave respectively 17% and 2.73.

The specific gravity of the wax was 0.89. Determine the bulk density, unit weight, void ratio and degree of saturation of the soil.

Solution:

Mass of soil = 683 g

Mass of wax = 690.6 – 683 = 7.6 g

$$\Rightarrow \text{Volume of wax} = \frac{7.6}{0.89} = 8.55\text{ ml}$$

$$\Rightarrow \text{Volume of soil} = 350 - 8.6 = 341.4\text{ ml}$$

$$\rho_b = \frac{683}{341.4} = 2\text{ g/ml} = 2.0\text{ Mg/m}^3$$

$$\gamma_b = 2 \times 9.81 = 19.6\text{ kN/m}^3$$

$$\rho_d = \frac{2}{1.17} = 1.71\text{ Mg/m}^3$$

Now,

$$\frac{\rho_w G_s}{1 + e} = 1.71$$

$$\Rightarrow e = \frac{2.73 - 1.71}{1.71} = 0.596$$

Now,

$$\rho_b = 2.0 = \rho_w \frac{(G_s + eS_r)}{1 + e}$$

$$\Rightarrow 1.596 \times 2.0 = 2.73 + 0.596 \times S_r$$

$$\Rightarrow S_r = 78.0\%$$

1.7.5 Density index, I_D

A granular soil generally has a large range into which the value of its void ratio may be fitted. If the soil is vibrated and compacted the particles are pressed close together and a minimum value of void ratio is obtained, but if the soil is loosely poured a maximum value of void ratio will result.

These maximum and minimum values can be obtained from laboratory tests and it is often convenient to relate them to the naturally occurring void ratio of the soil. This relationship is expressed as the *density index*, I_D or *relative density*, of the soil:

$$I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{1.27}$$

The theoretical maximum possible density of a granular soil must occur when $e = e_{min}$, i.e. when $I_D = 1.0$. Similarly, the minimum possible density occurs when $e = e_{max}$ and $I_D = 0$. In practical terms this means that a loose granular soil will have an I_D value close to zero whilst a dense granular soil will have an I_D value close to 1.0.

1.7.6 Summary of soil physical relations

A summary of the relationships established in Section 1.7 is given below:

Water content $w = \frac{W_w}{W_s} = \frac{M_w}{M_s}$

Void ratio $e = \frac{V_v}{V_s}$

$e = wG_s$ (saturated)

$e = \frac{wG_s}{S_r}$ (partially saturated)

Porosity $n = \frac{V_v}{V} = \frac{e}{1 + e}$

Degree of saturation $S_r = \frac{V_w}{V_v}$

Particle specific gravity $G_s = \frac{M_s}{V_s\rho_w} = \frac{W_s}{V_s\gamma_w}$

Bulk density $\rho_b = \rho_w\frac{(G_s + eS_r)}{1 + e}$

Dry density $\rho_d = \frac{\rho_w G_s}{1 + e} = \frac{\rho \times 100}{100 + w}$ (w as a percentage)

Saturated density $\rho_{sat} = \rho_w\frac{(G_s + e)}{1 + e}$

Effective density $\rho' = \rho_w\frac{G_s - 1}{1 + e}$

Bulk unit weight $\gamma = \gamma_w\frac{G_s + eS_r}{1 + e}$

Dry unit weight $\gamma_d = \frac{\gamma_w G_s}{1 + e} = \frac{\gamma}{1 + w}$ (w as a decimal)

Saturated unit weight $\gamma_{sat} = \gamma_w\frac{G_s + e}{1 + e}$

Effective unit weight $\gamma' = \gamma_w\frac{G_s - 1}{1 + e}$

Density index $I_D = \frac{e_{max} - e}{e_{max} - e_{min}}$

Exercises

Exercise 1.1

The results of a sieve analysis on a soil were:

Sieve size (mm)	Mass retained (g)
50	0
37.5	15.5
20	17.0
14	10.0
10	11.0
6.3	33.0
3.35	114.5
1.18	63.3
0.6	18.2
0.15	17.0
0.063	10.5

The total mass of the sample was 311 g. Plot the particle size distribution curve and, from the inspection of this curve, determine the effective size and uniformity coefficient. Classify the soil.

Answer D_{10} = 0.7 mm; D_{60} = 5.2 mm. C_u = 7.4. 70% gravel, 30% sand. Well graded sandy GRAVEL.

Exercise 1.2

Plot the particle size distribution curve for the following sieve analysis, given the sieve sizes and the mass retained on each. Classify the soil.

Sample mass = 642 g.

Retained on 425 μm sieve – 11 g, 300 μm sieve – 28 g, 212 μm sieve – 77 g, 150 μm sieve – 173 g, 63 μm sieve – 321 g.

Answer By inspection of grading curve soil is a uniform SAND. This is confirmed from the value of C_u = 2.3.

Exercise 1.3

A BS cone penetrometer test carried out on a sample of boulder clay gave the following results:

Cone penetration (mm)	15.9	17.1	19.4	20.9	22.8
Water content (%)	32.0	32.8	34.5	35.7	37.0

Determine the liquid limit of the soil.

Answer $w_L = 35\%$

Exercise 1.4

A liquid and plastic limit test gave the following results:

Test no.	1	2	3	4	PL	PL
Wet mass (g)	33.20	32.10	28.20	31.00	11.83	15.04
Dry mass (g)	28.20	26.50	22.40	23.90	11.25	14.07
Tin (g)	7.02	7.04	7.10	7.02	7.04	7.25
Penetration (mm)	14.5	17.0	20.9	22.7	–	–

Determine the plasticity index of the soil and classify the soil.

Answer 22, CI

If the natural water content was 28%, determine the liquidity index in the field.

Answer 0.64

Exercise 1.5

A sand sample has a porosity of 35% and the specific gravity of the particles is 2.73. What is its dry density and void ratio?

Answer $e = 0.54$, $\rho_d = 1.77\ \mathrm{Mg/m^3}$

Exercise 1.6

A sample of silty clay was found to have a volume of 14.88 ml, whilst its mass at natural water content was 28.81 g and the particle specific gravity was 2.7. Calculate the void ratio and degree of saturation if, after oven drying, the sample had a mass of 24.83 g.

Answer $e = 0.618$, $S_r = 70\%$

Exercise 1.7

A sample of moist sand was cut from a natural deposit by means of a sampling cylinder. The volume of the cylinder was 478 ml and the mass of the soil was 884 g before drying, and 830 g after drying. The volume of the dried sample, when rammed tight into a graduated cylinder, was 418 ml and its volume, when poured loosely into the same cylinder, was 616 ml. If the particle specific gravity was 2.67, determine the density index and the degree of saturation of the deposit.

Answer $I_D = 69\%$, $S_r = 32\%$

Exercise 1.8

In order to determine the density of a clay soil, an undisturbed sample was taken in a sampling tube of volume 0.001 664 m^3.

The following data were obtained:

Mass of tube (empty) = 1.864 kg
Mass of tube and clay sample = 5.018 kg
Mass of tube and clay sample after drying = 4.323 kg

Calculate the water content, the bulk, and the dry densities.

If the particle specific gravity was 2.69, determine the void ratio and the degree of saturation of the clay.

Answer $w = 28\%$, $\rho_b = 1.90\,\text{Mg/m}^3$, $\rho_d = 1.49\,\text{Mg/m}^3$, $e = 0.82$, $S_r = 93\%$