Chapter 1

Classification and Physical Properties of Soils

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.

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.

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

It is generally believed that 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,

ments are typically deposited in layers or beds called strata and when compacted and cemented together (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.

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)

Most 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 has been another important transportation agent, and large deposits of boulder clay and moraine are often encountered.

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.
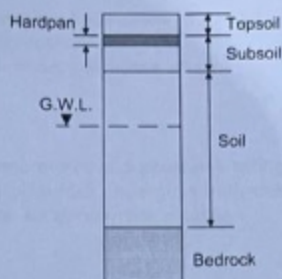
Fig. 1.1 Materials encountered during excavation.

Soil

The soft geological deposits extending from the subsoil to bedrock. 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.

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 Engineering definitions

Geologists class all items of the Earth's crust as rock, whether hard or soft deposits. Civil engineers consider rock and soil separately.

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. Geologists classify all rocks into three basic groups: igneous, sedimentary and metamorphic.

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 (molten rock) 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 in to 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 sedi-

1.5.3 Granular soils – particle size distribution

A standardised system helps to eliminate human error in the classification of soils. The usual method is based on the determination of the particle size distribution by shaking an oven dried sample of the soil (usually after washing the sample over a 63μm sieve) through a set of sieves and recording the mass retained on each sieve. The classification system adopted by the British Standards Institution is the Massachusetts Institute of Technology (MIT) system. The boundaries defined by this system can be seen on the particle size distribution sheet in Fig. 1.2. 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 sizes) the distribution curve must be obtained by sedimentation (pipette or hydrometer). Unless a centrifuge is used, it is not possible to determine the range of clay sizes in a soil, and all that can be done is to obtain the total percentage of clay sizes present. A full description of these tests is given in BS 1377: Part 2.(BSI, 1990).

Examples of particle size distribution (or grading) curves for different soil types are shown in Fig. 1.9. 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_{60} and D_{85}, 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

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.

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

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 earthfill structures, such as dams or embankments. Fill will sometimes contain man-made material such as crushed concrete or bricks from demolished buildings.

1.5   Laboratory classification of soils

Soil classification enables the engineer to assign a soil to one of a limited number of groups, based on the material 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.

1.5.1   Drying soils

Soils can be either oven or air dried. It has become 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 and particle specific gravity (see Section 1.8.3) tests but air drying should be used whenever possible for other soil tests that also require the test sample to be dry.

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.

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

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:

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

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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 soils

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	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 over consolidated clay cannot. Consolidation is described in Chapter 11.

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.

The particle size distribution curve is shown in Fig. 1.2. The soil has approximate proportions of 30% gravel and 70% sand.

$$D_{10} = 0.17 \text{ mm}; \quad D_{60} = 1.5 \text{ mm}; \quad C_u = \frac{D_{60}}{D_{10}} = \frac{1.5}{0.17} = 8.8$$
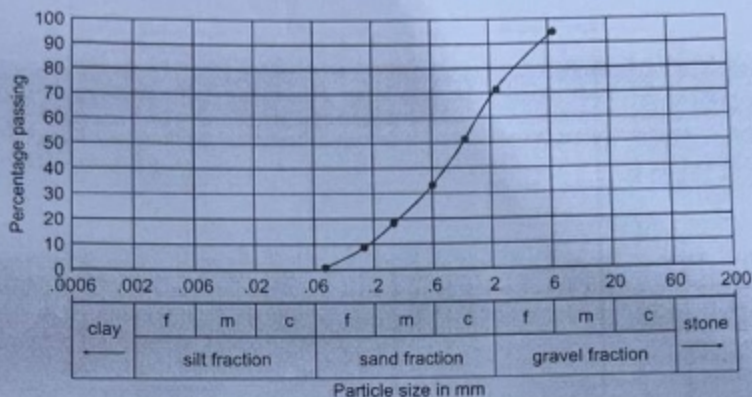

Fig. 1.2 Example 1.2.

1.5.4 Cohesive soils – consistency limit (or index) 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 effect on the strength and compressibility of a soil as the amount of water within it is varied. With a cohesionless soil, i.e. a gravel or a sand, both parameters are only slightly affected by a change in water content whereas a cohesive soil, i.e. a silt or a clay, tends to become considerably stronger and less compressible, i.e. less easy to mould, as it dries out.

Let us consider a cohesive soil with an extremely high water content, i.e. a suspension of soil particles in water. The soil behaves as a liquid and if an attempt is made to apply a shear stress there will be continual deformation with no sign of a failure stress value. If the soil is allowed to slowly dry out a point will be reached where the soil just begins to exhibit a small shear resistance. If the shear stress were removed it will be found that the soil has experienced a permanent deformation; it is now acting as a plastic solid and not as a liquid.

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 or LL); see Fig. 1.3c.

If $C_u < 4.0$ then the soil is uniformly graded.

If $C_u > 4.0$ then the soil is either well graded or gap and a glance at the grading curve should be sufficient for the reader to decide which is the correct description.

Example 1.2: Particle size distribution

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

Sieve size (mm)	Mass retained (g)
10	0.0
6.3	5.5
2	25.7
1	23.1
0.6	22.0
0.3	17.3
0.15	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	0	100
6.3	5.5	5	95
2	25.7	22	73
1	23.1	20	53
0.6	22.0	19	34
0.3	17.3	15	19
0.15	12.7	11	8
0.063	6.9	6	2
Pass 0.063	2.3	2	
Total mass	115.5		

e.g. sieve size 2 mm:

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

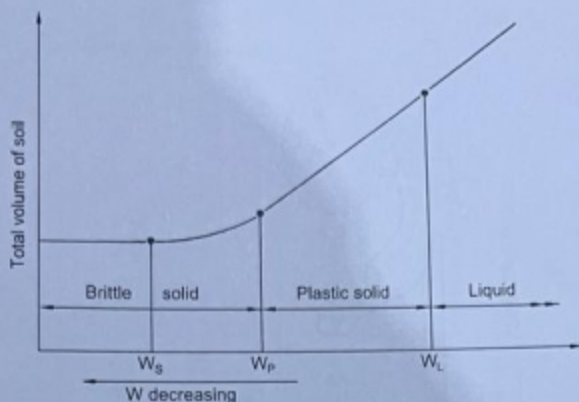$$\text{Percentage passing} = 95 - 22 = 73\%$$

Fig. 1.4 Changes in total volume against water content.

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.

In Fig. 1.4 the variation of the total volume of a soil with its water content is plotted, showing the positions of the liquid, plastic and shrinkage limits.

Determination of liquid and plastic limits

Liquid limit test

BS 1377: Part 2 specifies the following three methods for determining the liquid limit of soil.

(1) Cone penetrometer method (definitive method)
   Details of the apparatus are shown in Fig. 1.5. 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 off 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 5 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. The average penetration is noted and a water content determination is carried out on the soil tested.

   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 to 25 mm.

   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).
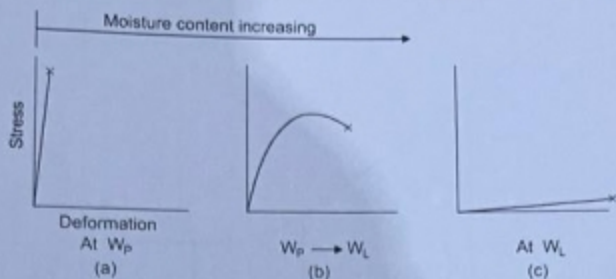
Fig. 1.3   Shear stress/deformation relationships at different water contents.

As further moisture is driven from the soil it becomes possible for the soil to resist large shearing stresses. Eventually the soil exhibits no permanent deformation and simply fractures with no plastic deformation, i.e. it acts as a brittle solid. The limit at which plastic failure changes to brittle failure is known as the *plastic limit* (w_P or PL); see Fig. 1.3a.

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

$$I_P = w_L - w_P$$

or

$$PI = LL - PL$$

The shearing strength to deformation relationship within the plasticity range is illustrated in Fig. 1.3b.

Note: The use of the symbols w_L, w_P and I_P follows the recommendations by the ISSMFE Lexicon (1985). However, the symbols LL, PL and PI are still used in many publications.

Liquidity index

The *liquidity index* enables one to compare a soil's plasticity with its natural water content (w).

$$I_L = \frac{w - w_P}{I_P}$$

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

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