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.
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 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 sedi-
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.
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,
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 un fissured 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:

<table>
<thead>
<tr>
<th>Fine sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual particles visible</td>
<td>Some particles visible</td>
<td>No particles visible</td>
</tr>
<tr>
<td>Exhibits dilatancy</td>
<td>Exhibits dilatancy</td>
<td>No dilatancy</td>
</tr>
<tr>
<td>Easy to crumble and falls off hands when dry</td>
<td>Easy to crumble and can be dusted off hands when dry</td>
<td>Hard to crumble and sticks to hands when dry</td>
</tr>
<tr>
<td>Feels gritty</td>
<td>Feels rough</td>
<td>Feels smooth</td>
</tr>
<tr>
<td>No plasticity</td>
<td>Some plasticity</td>
<td>Plasticity</td>
</tr>
</tbody>
</table>

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.
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.

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

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:**

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

\[C_u = \frac{D_{60}}{D_{10}}\]
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:

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Mass retained (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.0</td>
</tr>
<tr>
<td>6.3</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>25.7</td>
</tr>
<tr>
<td>1</td>
<td>23.1</td>
</tr>
<tr>
<td>0.6</td>
<td>22.0</td>
</tr>
<tr>
<td>0.3</td>
<td>17.3</td>
</tr>
<tr>
<td>0.15</td>
<td>12.7</td>
</tr>
<tr>
<td>0.063</td>
<td>6.9</td>
</tr>
</tbody>
</table>

2.3 g passed through the $63\mu$m 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:

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Mass retained (g)</th>
<th>Percentage retained (%)</th>
<th>Percentage passing (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>6.3</td>
<td>5.5</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>25.7</td>
<td>22</td>
<td>73</td>
</tr>
<tr>
<td>1</td>
<td>23.1</td>
<td>20</td>
<td>53</td>
</tr>
<tr>
<td>0.6</td>
<td>22.0</td>
<td>19</td>
<td>34</td>
</tr>
<tr>
<td>0.3</td>
<td>17.3</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>0.15</td>
<td>12.7</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>0.063</td>
<td>6.9</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Pass 0.063</td>
<td>2.3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total mass</td>
<td></td>
<td></td>
<td>115.5</td>
</tr>
</tbody>
</table>

E.g. sieve size 2mm:

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

Percentage passing $= 95 - 22 = 73\%$
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 (wL) and plastic limit (wP)**

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 (wL or LL); see Fig. 1.3c.
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 \((w_P \text{ or } PL)\); 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.

\[
I_P = w_L - w_P
\]

or

\[
I_P = LL - PL
\]

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 \((w)\).

\[
l_L = \frac{w - w_P}{I_P}
\]

If \(l_L = 1.0\) the soil is at its liquid limit; if \(l_L = 0\) 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
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).
(2) **One-point cone penetrometer method**

In this test the procedure is similar to that described above, with the exception that only one point is required. The test is thus fairly rapid. Once the average penetration for the point is established, the water content of the soil is determined. The water content is then multiplied by a factor to give the liquid limit. The value of the factor is dependent on both the cone penetration and the range of water content within which the measured water content falls. The factors were determined through experimental work performed by Clayton and Jukes (1978).

(3) **Method using the Casagrande apparatus**

Until 1975 this was the only method for determining liquid that was recognised by the British Standards Institution. Although still used worldwide the test is now largely superseded by cone penetration techniques.

**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 said to be at its plastic limit when it just begins to crumble at a thread diameter of 3 mm. At this stage a section of the thread is removed for water content determination. The test should be repeated at least once more.

It is interesting to note that in some countries, the cone penetrometer is used to determine both $w_L$ and $w_p$. The apparatus used consists of a 30° included angle cone with a total mass of 76 g. The test is the same as the liquid limit test in Britain, a penetration of 17 mm giving $w_L$ and a penetration of 2 mm giving $w_p$. 

---

![Liquid limit apparatus](image-url)
Example 1.3: Consistency limits tests

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

<table>
<thead>
<tr>
<th>Cone penetration (mm)</th>
<th>16.1</th>
<th>17.6</th>
<th>19.3</th>
<th>21.3</th>
<th>22.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (%)</td>
<td>50.0</td>
<td>52.1</td>
<td>54.1</td>
<td>57.0</td>
<td>58.2</td>
</tr>
</tbody>
</table>

The results from the plastic limit test were:

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Mass of tin (g)</th>
<th>Mass of tin wet soil + tin (g)</th>
<th>Mass of dry soil + tin (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.1</td>
<td>20.7</td>
<td>18.7</td>
</tr>
<tr>
<td>2</td>
<td>8.4</td>
<td>19.6</td>
<td>17.8</td>
</tr>
</tbody>
</table>

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. 1.6. The liquid limit is the water content corresponding to 20 mm penetration, i.e. \( w_L = 55\% \).

The plastic limit is determined thus:

\[
\begin{align*}
wp(1) &= \frac{20.7 - 8.7}{18.7 - 8.1} \times 100 = 18.9 \\
wp(2) &= \frac{19.6 - 17.8}{17.8 - 8.4} \times 100 = 19.1
\end{align*}
\]

Average \( wp = 19\% \)

The plasticity index is the difference between \( w_L \) and \( wp \) i.e.

\[ I_p = 55 - 19 = 36\% \]
1.6 Activity of a clay

In addition to their use in soil classification, the $w_c$ 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. 1.7.

The plot of London clay is also shown on the figure and, from its position, it is seen that the mineral content of this soil is predominantly illite. London Clay has a clay fraction of about 46 per cent and consists of illite (70%), kaolinite (20%) and montmorillonite (10%). The remaining fraction of 54 per cent consists of silt (quartz, feldspar and mica: 44%) and sand (quartz and feldspar: 10%).

In Fig. 1.7 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.

1.7 Soil classification and description

1.7.1 Soil classification systems

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 is the basis of the soil classification system used in the UK.

**The British Soil Classification System (BSCS)**

The British Standard BS 5930 (1999), *Code of practice for site investigations*, gives a full description of the BSCS and the reader is advised to obtain sight of a copy.

The system divides soil into two main categories. If at least 35% of a soil can pass through a 63 μm sieve then it is a *fine soil*. Conversely, if the amount of soil that can pass through the 63 μm sieve is less than 35% then it is a *coarse soil*. Each category is divided into groups, depending upon the grading of the soil particles not passing the 63 μm sieve and upon the plasticity characteristics of the soil particles passing the 425 μm sieve.

A summary of the BSCS is shown in Table 1.1 and its associated plasticity chart in Fig. 1.8.

To use the plasticity chart it is necessary to plot a point whose coordinates are the liquid limit and the plasticity index of the soil to be identified. The soil is 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 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 $I_p = 0$, $W_L = 20\%$ so that its equation is:

$$I_p = 0.73(W_L - 20\%)$$

The main soil types are designated by capital letters:

<table>
<thead>
<tr>
<th>G</th>
<th>Gravel</th>
<th>M</th>
<th>Silt, M-soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Sand</td>
<td>C</td>
<td>Clay</td>
</tr>
<tr>
<td>F</td>
<td>Fine soil, Fines</td>
<td>Pt</td>
<td>Peat</td>
</tr>
</tbody>
</table>

The classification ‘F’ is intended for use when there is difficulty in determining whether a soil is a silt or a clay.

Originally all soils that plotted below the A-line of the plasticity charts were classified as silts. The term ‘M-soil’ has been introduced to classify soils that plot below the A-line but have particle size distributions not wholly in the range of silt sizes.

Behind the letter designating the main soil type additional letters are added to further describe the soil and to denote its grading and plasticity. These letters are:

<table>
<thead>
<tr>
<th>W</th>
<th>Well graded</th>
<th>L</th>
<th>Low plasticity $(W_L &lt; 35%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Poorly graded</td>
<td>I</td>
<td>Intermediate $(35 \leq W_L \leq 70%)$</td>
</tr>
<tr>
<td>P_o</td>
<td>Uniform</td>
<td>H</td>
<td>High plasticity $(50 \leq W_L \leq 70%)$</td>
</tr>
<tr>
<td>P_g</td>
<td>Gap graded</td>
<td>V</td>
<td>Very high $(70 \leq W_L \leq 90%)$</td>
</tr>
<tr>
<td>O</td>
<td>Organic</td>
<td>E</td>
<td>Extremely high $(W_L &gt; 90%)$</td>
</tr>
</tbody>
</table>

The letter O is applied at the end of the group symbol for a soil, no matter what type, if the soil has a significant amount of organic matter within it.

Examples of the use of the symbols are set out below.

<table>
<thead>
<tr>
<th>Soil description</th>
<th>Group symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well graded silty SAND</td>
<td>SWM</td>
</tr>
<tr>
<td>Organic CLAY of high plasticity</td>
<td>CHO</td>
</tr>
<tr>
<td>Sandy CLAY of intermediate plasticity</td>
<td>CIS</td>
</tr>
<tr>
<td>Uniform clayey sand</td>
<td>SP,F</td>
</tr>
</tbody>
</table>
Table 1.1  British Soil Classification System for Engineering Purposes (after BS 5930: 1999).

<table>
<thead>
<tr>
<th>Soil groups</th>
<th>Subgroups and laboratory identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAVELS – More than 50% of coarse material is of gravel size (coarser than 2mm)</td>
<td></td>
</tr>
<tr>
<td>Slightly silty or clayey GRAVEL</td>
<td>Group symbol</td>
</tr>
<tr>
<td>GW G</td>
<td>GW Gpu Gp g</td>
</tr>
<tr>
<td>Poorly graded/Uniform/Gap graded GRAVEL</td>
<td></td>
</tr>
<tr>
<td>Silty GRAVEL</td>
<td>G-M G-F G-C</td>
</tr>
<tr>
<td>Well graded/Poorly graded silty GRAVEL</td>
<td></td>
</tr>
<tr>
<td>Very silty GRAVEL</td>
<td>GM GF GC</td>
</tr>
<tr>
<td>Very clayey GRAVEL (clay of low, intermediate, high, very high, extremely high plasticity)</td>
<td></td>
</tr>
<tr>
<td>Very clayey GRAVEL (clay of low, intermediate, high, very high, extremely high plasticity)</td>
<td></td>
</tr>
<tr>
<td>Very clayey GRAVEL (clay of low, intermediate, high, very high, extremely high plasticity)</td>
<td></td>
</tr>
<tr>
<td>Very clayey GRAVEL (clay of low, intermediate, high, very high, extremely high plasticity)</td>
<td></td>
</tr>
<tr>
<td>Very clayey GRAVEL (clay of low, intermediate, high, very high, extremely high plasticity)</td>
<td></td>
</tr>
<tr>
<td>Very clayey GRAVEL (clay of low, intermediate, high, very high, extremely high plasticity)</td>
<td></td>
</tr>
<tr>
<td>SANDS – More than 50% of coarse material is of sand size (finer than 2mm)</td>
<td></td>
</tr>
<tr>
<td>Slightly silty or clayey SAND</td>
<td>Group symbol</td>
</tr>
<tr>
<td>SW S</td>
<td>SW SPu SPg</td>
</tr>
<tr>
<td>Well graded SAND</td>
<td></td>
</tr>
<tr>
<td>Poorly graded/Uniform/Gap graded SAND</td>
<td></td>
</tr>
<tr>
<td>Silty SAND</td>
<td>S-M S-F S-C</td>
</tr>
<tr>
<td>Well graded/Poorly graded silty SAND</td>
<td></td>
</tr>
<tr>
<td>Clayey SAND</td>
<td></td>
</tr>
<tr>
<td>Classification and Physical Properties of Soils</td>
<td>FINE SOILS - more than 35% of the material is finer than 0.06 mm</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Very silty SAND, subdivided as for SC</td>
<td></td>
</tr>
<tr>
<td>Very clayey SAND (clay of low, intermediate, high, very high, extremely high plasticity)</td>
<td></td>
</tr>
<tr>
<td>Gravelly SILT, subdivided as for CG</td>
<td></td>
</tr>
<tr>
<td>Gravelly CLAY of low plasticity of intermediate plasticity of high plasticity of very high plasticity of extremely high plasticity</td>
<td></td>
</tr>
<tr>
<td>Sandy SILT, subdivided as for CG</td>
<td></td>
</tr>
<tr>
<td>Sandy CLAY of low plasticity of intermediate plasticity of high plasticity of very high plasticity of extremely high plasticity</td>
<td></td>
</tr>
<tr>
<td>ORGANIC SOILS</td>
<td>Descriptive letter 'O' suffixed to organic matter suspected to be a significant constituent. Example MHO: any group of organic matter which may be fibrous or amorphous.</td>
</tr>
<tr>
<td>Pt Peat soils consist predominantly of plant remains which may be fibrous or amorphous.</td>
<td></td>
</tr>
</tbody>
</table>
When classification tests are carried out on a stony soil sample any particles nominally greater than 60 mm are removed by sieving (with a standard 63 mm sieve) and their percentage determined. The tests are then carried out on the remaining soil. The material removed is classed as cobbles, 66 to 200 mm in size, with symbol Cb, or boulders, greater than 200 mm in size, with the symbol B.

Fine and coarse soils that contain cobbles, or cobbles and boulders, are indicated in symbols by the use of the addition sign. For instance, a well graded SAND with gravel and cobbles would have the group symbol SWG + Cb.

**Example 1.4: Soil classification (i)**

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

**Solutions:**

The value for $C_u$ already been found to be 8.8. From Fig. 1.2 it is seen that the grading curve has a regular slope and therefore contains roughly equal percentages of particle sizes. The soil is a well graded gravelly SAND with the group symbol SWG.

Note that when classifying the soil it is customary to indicate the main soil type in capital letters, i.e. SAND.
Example 1.5: Soil classification (ii)

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

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Soil A</th>
<th>Soil B</th>
<th>Soil C</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>90</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>56</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>6.3</td>
<td>47</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>44</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>0.6</td>
<td>40</td>
<td>95</td>
<td>–</td>
</tr>
<tr>
<td>0.425</td>
<td>–</td>
<td>80</td>
<td>–</td>
</tr>
<tr>
<td>0.300</td>
<td>29</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td>0.212</td>
<td>–</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>0.150</td>
<td>–</td>
<td>–</td>
<td>100</td>
</tr>
<tr>
<td>0.063</td>
<td>5</td>
<td>1</td>
<td>91</td>
</tr>
</tbody>
</table>

Soil C: Since more than 10% passed the 63 μm sieve, a pipette analysis (described in BS 1377: Part 2 and by Head (1992)) was performed. The results were:

<table>
<thead>
<tr>
<th>Particle sizes (mm)</th>
<th>Soil C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>78</td>
</tr>
<tr>
<td>0.02</td>
<td>61</td>
</tr>
<tr>
<td>0.006</td>
<td>47</td>
</tr>
<tr>
<td>0.002</td>
<td>40</td>
</tr>
</tbody>
</table>

Soil C was found to have a liquid limit of 48% and a plastic limit of 21%. Plot the particle size distribution curves and classify each soil.

Solution:

The particle size distribution curves for the three soils are shown in Fig. 1.9. The curves can be used to obtain the following particle sizes for soils A and B.

<table>
<thead>
<tr>
<th>Soil</th>
<th>$D_{10}$ (mm)</th>
<th>$D_{30}$ (mm)</th>
<th>$D_{60}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1</td>
<td>0.31</td>
<td>11.0</td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>0.42</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Fig. 1.9 Example 1.5.
1.7.2 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, geological details, etc., obtained from borehole data and site observations should also be included in the soil’s description.

Further information is available in BS 5930 Code of Practice for Site Investigations, and Clayton et al. (1995).

1.8 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. 1.10a.

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. 1.10b. The soil mass has a total volume $V$ and a volume of solid particles that summates to $V_s$. The volume of the voids, $V_v$, is obviously equal to $V - V_s$. 

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.

The soil is a gap graded sandy GRAVEL. Group symbol GP$_g$S.

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.

The soil is a uniformly graded SAND. Group symbol SP$_u$.

Soil C: It is interesting to note that, as the whole of soil C passed the 425 $\mu$m sieve, there would be no need to remove any of the soil before subjecting it to the consistency limit tests. From the grading curve, by considering particle sizes only, the soil is a mixture of 10% sand, 50% silt and 40% clay. The soil is undoubtedly fine and the group symbol could be F, although, as the silt particles are more dominant than the clay, it could be given the symbol MC. The liquid limit of the soil is 48% which, according to BS 5930, indicates an intermediate plasticity. The group symbol of the soil could therefore be either FI or MCI.

However, for mixtures of fine soils BS 5930 suggests that classification is best carried out by the use of the plasticity chart shown in Fig. 1.8. The liquid limit of the soil = 48% and the plasticity index, $(w_l - w_p) = 27%$. Using Fig. 1.8 it is seen that the British system classifies the soil as an inorganic clay with the group symbol CI.
1.8.1 Void ratio and porosity

From a study of Fig. 1.10 the following may be defined:

**Void ratio**

\[ e = \frac{\text{Volume of voids}}{\text{Volume of solids}} = \frac{V_v}{V_s} \]

**Porosity**

\[ n = \frac{\text{Volume of voids}}{\text{Total volume}} = \frac{V_v}{V} = \frac{V_v}{V_v + V_s} = \frac{e}{1 + e} \]

1.8.2 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 Figs 1.11a, b and c.

The degree of saturation is simply:

\[ S_r = \frac{\text{Volume of water}}{\text{Volume of voids}} = \frac{V_w}{V_v} \] (usually expressed as a percentage)

1.8.3 Particle density (\( \rho_s \)) 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 $V_s$ and weight of solids $W_s$,

$$G_s = \frac{W_s}{V_s \gamma_w}$$

where $\gamma_w =$ weight of water and, if the sample has a mass of solids $M_s$,

$$G_s = \frac{M_s}{V_s \rho_w}$$

where $\rho_w =$ density of water (1.0 Mg/m$^3$ at 20°C) i.e.

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

The density of the particles $\rho_s$ is defined as:

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

therefore,

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

BS 1377: Part 2 specifies methods of test for determining the particle density. For fine, medium or coarse soils the Standard specifies the use of a one litre gas jar fitted with a rubber bung and a mechanical shaking apparatus which can rotate the gas jar, end over end, at 50 rpm (Fig. 1.12).

The test consists briefly of placing oven dried soil (approximately 200 g for a fine soil and 400 g for a medium or coarse soil) into the gas jar along with about 500 ml of distilled water at room temperature. The jar is sealed with the bung and shaken, first by hand and then in the machine, for 20 to 30 minutes. The bung is then removed, the jar topped up carefully to full capacity with further distilled water and the glass plate slid on top to seal the jar without trapping any air inside. From various weighings that are made the specific gravity of the soil can be calculated. (See Example 1.6.)

If $\rho_s$ is measured in units of Mg/m$^3$ and the water temperature is assumed to be 20°C, it follows that $\rho_s$ and $G_s$ are numerically equal. $G_s$ is dimensionless.
Example 1.6: Particle specific gravity

The mass of an empty gas jar, together with its glass cover plate, was 478.0 g. When completely filled with water and the cover plate fitted the mass was 1508.2 g. An oven dried sample of soil was inserted in the dry gas jar and the total mass, including the cover plate, was 676.6 g. Water was added to the soil and, after a suitable period of shaking, was topped up until the gas jar was brim full. The cover plate was fitted and the total mass was found to be 1632.6 g.

Determine the particle specific gravity of the soil.

Solution:

\[
\text{Mass of soil} + \text{water} = 1632.6 - 478.0 = 1154.6 \text{ g}
\]

\[
\text{Mass of dry soil} = 676.6 - 478.0 = 198.6 \text{ g}
\]

\[
\text{Mass of water present with soil} = 1154.6 - 198.6 = 956.0 \text{ g}
\]

\[
\text{Mass of water when gas jar full} = 1508.2 - 478.0 = 1030.2 \text{ g}
\]

Therefore, mass of water of same volume as soil = 1030.2 - 956.0 = 74.2 g

\[
G_s = \frac{\text{Mass of soil}}{\text{Mass of same volume of water}} = \frac{198.6}{74.2} = 2.68
\]

Alternative solution

The specific gravity can be quickly found from a formula thus:

\[
G_s = \frac{S}{(J + W) - (J + W + S) + S}
\]

Where

\[
S = \text{mass of dry soil (g)}
\]

\[
J + W = \text{mass of jar + water (g)}
\]

\[
J + W + S = \text{mass of jar + water + soil (g)}
\]

i.e.,

\[
G_s = \frac{198.6}{(1508.2 - 1632.6) + 198.6} = 2.68
\]

1.8.4 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 density and the unit weight of the material:

\[
\text{Density, } \rho = \frac{\text{Mass}}{\text{Volume}} = \frac{M}{V}
\]

\[
\text{Unit weight, } \gamma = \frac{\text{Weight}}{\text{Volume}} = \frac{W}{V}
\]

Weight = 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 1.7) then to perform the geotechnical analysis using the unit weight derived from the density value.

**Note: Weight density**

With the introduction of Eurocode 7 to geotechnical design the term *weight density* is likely to eventually replace the term *unit weight*. The two terms are synonymous and since the term *unit weight* has been in use for many decades it will certainly remain in use for many years to come and for this reason it is used throughout this book.

**Unit weight 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 as follows:

**Bulk unit weight (\( \gamma \))**

This is the natural *in situ* unit weight of the soil:

\[
\gamma = \frac{\text{Total weight}}{\text{Total volume}} = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v} = \frac{G_v \gamma_w + V_v \gamma_s S_v}{V_s + V_v} = \gamma_w \frac{(G_s + e S_v)}{1 + e}
\]

**Saturated unit weight (\( \gamma_{sat} \))**

\[
\gamma_{sat} = \frac{\text{Saturated weight}}{\text{Total volume}}
\]

When soil is saturated \( S_v = 1 \), therefore

\[
\gamma_{sat} = \gamma_w \frac{G_s + e}{1 + e}
\]
Dry unit weight ($\gamma_d$)

\[
\gamma_d = \frac{\text{Dry weight}}{\text{Total volume}} = \gamma_w \frac{G_s}{1+e} \quad (\text{as } S_i = 0)
\]

Buoyant unit weight ($\gamma'$)

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:

\[
\text{Buoyant unit weight} = \text{Saturated unit weight} - \text{Unit weight of water} = \gamma_w \frac{G_s + e}{1+e} - \gamma_w = \gamma_w \frac{G_s - 1}{1+e}
\]

Buoyant unit weight is often referred to as the submerged unit weight or the effective unit weight.

Density of soil

Similar expressions can be obtained for densities:

**Bulk density**, \( \rho_b = \rho_w \frac{(G_s + eS_i)}{1+e} \)

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

**Dry density**, \( \rho_d = \rho_w \frac{G_s}{1+e} \)

**Buoyant density**, \( \rho' = \rho_w \frac{G_s - 1}{1+e} \)

**Relationship between density and unit weight values**

In the above expressions, \( G_s, e, S_i \) and the number 1 are all dimensionless.

Hence a particular unit weight = \( \gamma_w \) times a constant.

The corresponding density = \( \rho_w \) times the same constant.

---

**Example 1.7: 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:**

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

\[
\rho_b = \frac{M}{V} = \frac{3.15}{0.0016} = 1969 \text{ kg/m}^3 = 1.97 \text{ Mg/m}^3
\]

\[
w = \frac{3.15 - 2.82}{2.82} = 11.7\%
\]

\[
\rho_d = \frac{\rho_b}{1 + w} = \frac{1.97}{1.117} = 1.76 \text{ Mg/m}^3
\]

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

**Relationship between \( w \), \( \gamma_d \) and \( \gamma \)**

\[
\gamma = \frac{W_w + W_s}{V} \quad (1)
\]

\[
\gamma_d = \frac{W_s}{V} \quad (2)
\]

\[
w = \frac{W_w}{W_s} \quad (3)
\]

From Equation (3) \( W_w = wW_s \) and, substituting in Equation (1),

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

i.e.

\[
\gamma_d = \gamma \frac{1}{1 + w}
\]

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**

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

i.e.

\[
e = w G_s
\]
Example 1.8: 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 and unit weight, void ratio and degree of saturation.

Solution:

Mass of soil = 683 g
Mass of wax = 690.6 – 683 = 7.6 g

⇒ Volume of wax = \( \frac{7.6}{0.89} = 8.55 \text{ ml} \)

⇒ Volume of soil = 350 – 8.6 = 341.4 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

\[ \frac{\rho_w G_s}{1+e} = 1.71 \]

⇒ \( e = \frac{2.73 - 1.71}{1.71} = 0.596 \)

Now

\[ \rho_b = 2.0 = \rho_w \frac{(G_s + eS_i)}{1+e} \]

⇒ \( 1.596 \times 2.0 = 2.73 + 0.596 \times S_i \)

⇒ \( S_i = 77.0\% \)
1.8.5 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 is obtained. 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, or relative density, of the soil:

\[ I_D = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}} \]

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

1.8.6 Summary of soil physical relations

A summary of the relationships established in Section 1.8 is given below:

<table>
<thead>
<tr>
<th>Property</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content</td>
<td>( w = \frac{W_w}{W_s} = \frac{M_w}{M_s} )</td>
</tr>
<tr>
<td>Void ratio</td>
<td>( e = \frac{V_v}{V_s} )</td>
</tr>
<tr>
<td></td>
<td>( e = wG_s ) (saturated)</td>
</tr>
<tr>
<td></td>
<td>( e = \frac{wG_s}{S} ) (partially saturated)</td>
</tr>
<tr>
<td>Porosity</td>
<td>( n = \frac{V_v}{V_s} = \frac{e}{1 + e} )</td>
</tr>
<tr>
<td>Degree of saturation</td>
<td>( S_r = \frac{V_w}{V_v} )</td>
</tr>
<tr>
<td>Particle specific gravity</td>
<td>( G_s = \frac{W_s}{V_s \gamma_w} = \frac{M_s}{V_s \rho_w} )</td>
</tr>
<tr>
<td>Bulk density</td>
<td>( \rho_b = \rho_w \frac{(G_s + eS_r)}{1 + e} )</td>
</tr>
<tr>
<td>Dry density</td>
<td>( \rho_d = \frac{\rho_w G_s}{1 + e} = \frac{\rho_b}{1 + w} )</td>
</tr>
<tr>
<td>Saturated density</td>
<td>( \rho_{\text{sat}} = \rho_w \frac{(G_s + e)}{1 + e} )</td>
</tr>
<tr>
<td>Submerged density</td>
<td>( \rho'_s = \rho_w \frac{(G_s - 1)}{1 + e} )</td>
</tr>
<tr>
<td>Bulk unit weight</td>
<td>( \gamma_b = \gamma_w \frac{(G_s + eS_r)}{1 + e} )</td>
</tr>
</tbody>
</table>
Dry unit weight \[ \gamma_d = \frac{\gamma_w G_s}{1 + e} = \frac{\gamma_b}{1 + w} \]

Saturated unit weight \[ \gamma_{sat} = \frac{\gamma_w (G_s + e)}{1 + e} \]

Submerged unit weight \[ \gamma' = \frac{\gamma_w (G_s - 1)}{1 + e} \]

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:

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Mass retained (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>37.5</td>
<td>15.5</td>
</tr>
<tr>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>6.3</td>
<td>33</td>
</tr>
<tr>
<td>3.35</td>
<td>114.5</td>
</tr>
<tr>
<td>1.18</td>
<td>63.3</td>
</tr>
<tr>
<td>0.6</td>
<td>18.2</td>
</tr>
<tr>
<td>0.15</td>
<td>17</td>
</tr>
<tr>
<td>0.063</td>
<td>10.5</td>
</tr>
</tbody>
</table>

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 \[ D_{10} = 0.7 \text{ mm}; \ D_{60} = 5.2 \text{ mm}; \ C_u = 7.4. \ 70\% \ gravel, 30\% \ sand. \ Well \ graded \ sandy \ GRAVEL – \ symbol \ GWS. \]

**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 642 g. Retained on 425\(\mu\)m sieve – 11 g, 300\(\mu\)m sieve – 28 g, 212\(\mu\)m sieve – 77 g, 150\(\mu\)m sieve – 173 g, 63\(\mu\)m sieve – 321 g.

Answer By inspection of grading curve soil is a uniform SAND – symbol SPu. This is confirmed from the value of \( C_u = 2.35. \)
Exercise 1.3

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

<table>
<thead>
<tr>
<th>Cone penetration (mm)</th>
<th>15.9</th>
<th>17.1</th>
<th>19.4</th>
<th>20.9</th>
<th>22.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (%)</td>
<td>32.0</td>
<td>32.8</td>
<td>34.5</td>
<td>35.7</td>
<td>37.0</td>
</tr>
</tbody>
</table>

Determine the liquid limit of the soil.

Answer \( w_L = 35\% \)

Exercise 1.4

A liquid and plastic limit test gave the following results:

<table>
<thead>
<tr>
<th>Test No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>PL</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet mass (g)</td>
<td>33.20</td>
<td>32.10</td>
<td>28.20</td>
<td>31.00</td>
<td>11.83</td>
<td>15.04</td>
</tr>
<tr>
<td>Dry mass (g)</td>
<td>28.20</td>
<td>26.50</td>
<td>22.40</td>
<td>23.90</td>
<td>11.25</td>
<td>14.07</td>
</tr>
<tr>
<td>Tin (g)</td>
<td>7.02</td>
<td>7.04</td>
<td>7.10</td>
<td>7.02</td>
<td>7.04</td>
<td>7.25</td>
</tr>
<tr>
<td>Penetration (mm)</td>
<td>14.5</td>
<td>17.0</td>
<td>20.9</td>
<td>22.7</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

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, CI

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 \( e = 0.54, \rho_d = 1.77 \text{ Mg/m}^3 \)

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 out of a natural deposit by means of a sampling cylinder. The volume of the cylinder was 478 ml; the weight of the sample alone was 884 g 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, compute 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 \( \text{m}^3 \).

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 percentage saturation of the clay.

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