Chapter 17: Soil as a material

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Preamble

Soil is one of the most important materials in construction, however it is often neglected in other construction material textbooks. It is one of the most variable materials to consider as it is naturally occurring. Also, it will be, almost certainly, inconsistent from one site to the next site. The most important elements to consider are: the range of soils, their properties/parameters and what causes variations in these values.

17.1 Soil, rock and mineral types

From an engineering perspective soil can be defined as a material that can be worked without drilling or blasting and consist of relatively soft, loose, uncemented deposits, such as gravels, sand, silts and clays.

A typical ground profile is illustrated in Figure 17.1. Soil can be classed into four main groups:

- **Agricultural soil** (e.g. topsoil, subsoil) may be organic in nature (e.g. peat, etc) – not considered as engineering soils.

- **Engineering soil** (e.g. gravels, sands, silts and clays) consist of soft, loose, uncemented deposits.

- **Organic soil** – is formed from the decomposition of vegetable matter e.g. topsoil and peat (sands, silts and clays may also contain organic matter). Soils containing organic matter are unsuitable for engineering purposes; typically they are weak and subject to large settlement.

- **Fill or made ground** – is material that has been placed in a (semi) controlled manner, e.g. embankments and controlled landfill.

Ground Level

Agricultural soil (topsoil overlying subsoil)

Engineering soil

Bedrock

At any stage the water table could be encountered – upper zone of the soil which is fully saturated
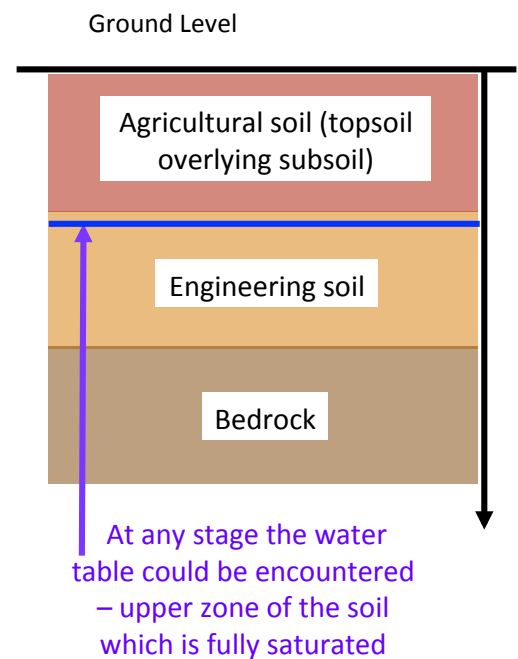
Figure 17.1: Typical ground profile

Rock, is a hard, rigid cemented deposit and is grouped according to how it has been formed. There are three main types of rocks (Table 17.1):

1. **Igneous rocks** are those that solidify from the magma through either intrusive or extrusive processes. Extrusive rocks form when magma cools rapidly on the earth's crust. Intrusive rocks are formed when magma cools very slowly within the earth's crust.

2. **Metamorphic rocks** are those that have been altered by heat and/or pressure that they have lost their original character. They have often been re-crystallized to form new rock types.

3. **Sedimentary rocks** result from external forces on the earth's crust and are formed from particles deposited by rivers, glaciers, the wind, the sea or by chemical deposition from lakes or the sea.

Rocks are formed from minerals. For example:

Granite (rock) = feldspar + quartz + mica + amphibole (a collection of different minerals)

A mineral is a naturally occurring, inorganic (non-living) substance. Mineralogy is the identification of minerals and the study of their properties, origin and classification. There are approximately 3.000 minerals, and each mineral has a particular chemical composition, which can be expressed as a chemical formula. The majority of minerals are compounds comprising two or more elements, for example NaCI, which comprises sodium and chlorine to form sodium chloride or Halite. Although a small number of minerals contain just one element (e.g. sulphur, copper and gold).

Minerals can be grouped into those that contain silica (silicon dioxide), and those that do not (Table 17.1). It is the silicate minerals that tend to be the rock forming minerals. The non-silicate minerals tend not to form rocks but are important in their own right as ore minerals.

Table 17.1: Various mineral and rock types

Silicate minerals	Non-silicate minerals	Igneous rocks	Sedimentary rocks	Metamorphic rocks
Amphibole	Azurite	Andesite	Breccia	Amphibolite
Augite	Barite	Basalt	Chalk	Anthracite
Biotite Mica	Calcite	Camptonite	Chert	Blue Schist
Chiastolite slices	Chromite	Diorite	Coal	Eclogite
Garnet	Fluorite	Dolerite	Conglomerate	Gneiss
Hornblende	Galena	Gabbro	Dolomite	Granulite
Kyanite	Graphite	Granite	Flagstone	Hornfels
Labradorite	Gypsum	Keratophyre	Flint	Kyanite
Lepidolite Mic	Haematite	Lamprophyre	Greywacke	Marble
Muscovite Mica	Halite	Microgranite	Ironstone	Mylonite
Olivine	Magnetite	Obsidian	Limestone	Phyllite
Feldspar	Malachite	Peridotite	Mudstone	Quartzite
Quartz	Copper	Pitchstone	Sandstone	Schist
Sodalite	Pyrite	Rhyolite	Siltstone	Serpentine
Talc	Sphalerite	Volcanic tuff	Shale	Slate

17.2 Engineering soils

Engineering soils occur in two distinct types:

1. **Granular soils**:
   - Boulder, cobbles and gravels are angular to rounded rock fragments.
   - Sands are granular in nature.
   - Silts are similar to sands but have smaller grains with some plasticity and cohesion.

   The above particles are formed by the mechanical weathering process of rocks. Their shape tends to be bulky and 'equi-dimensional' (Fig. 17.2a). The structure arrangement of each individual particle is supported by points of contact with adjacent particles forming frictional resistance (Fig. 17.2b).
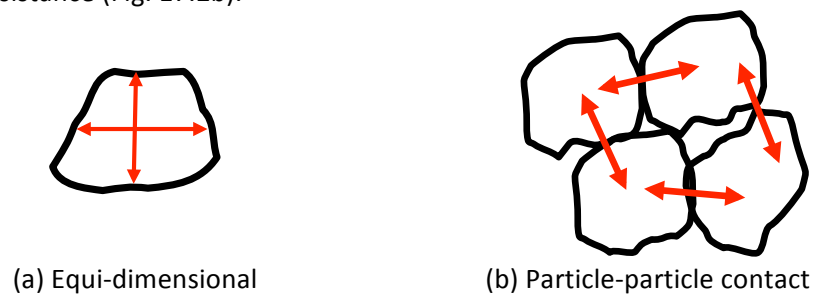

(a) Equi-dimensional   (b) Particle-particle contact

Figure 17.2: Granular soils

2. **Cohesive soils**:
   - Clays are formed from rock weathering, mainly due to chemical action.

   Clay particles are plate like in shape, with varying degrees of plasticity and cohesion (but possess no frictional resistance). A small amount of clay will influence the soil behaviour. The structure arrangement tends to be, either:

   a. **Flocculated** from inter particle attraction (Van der Waal's or secondary bonding), these forces pull particles closer together (Fig. 17.3a).
   b. **Dispersed** from repulsive electrically negative forces from the particle surface, particles are held apart (Fig. 17.3b).

(a) Flocculated structure   **(b) Dispersed structure**

Figure 17.3: Cohesive soils

In reality a soil may contain a mixture of particles. This can be represented by the soil triangle (Fig. 17.4)
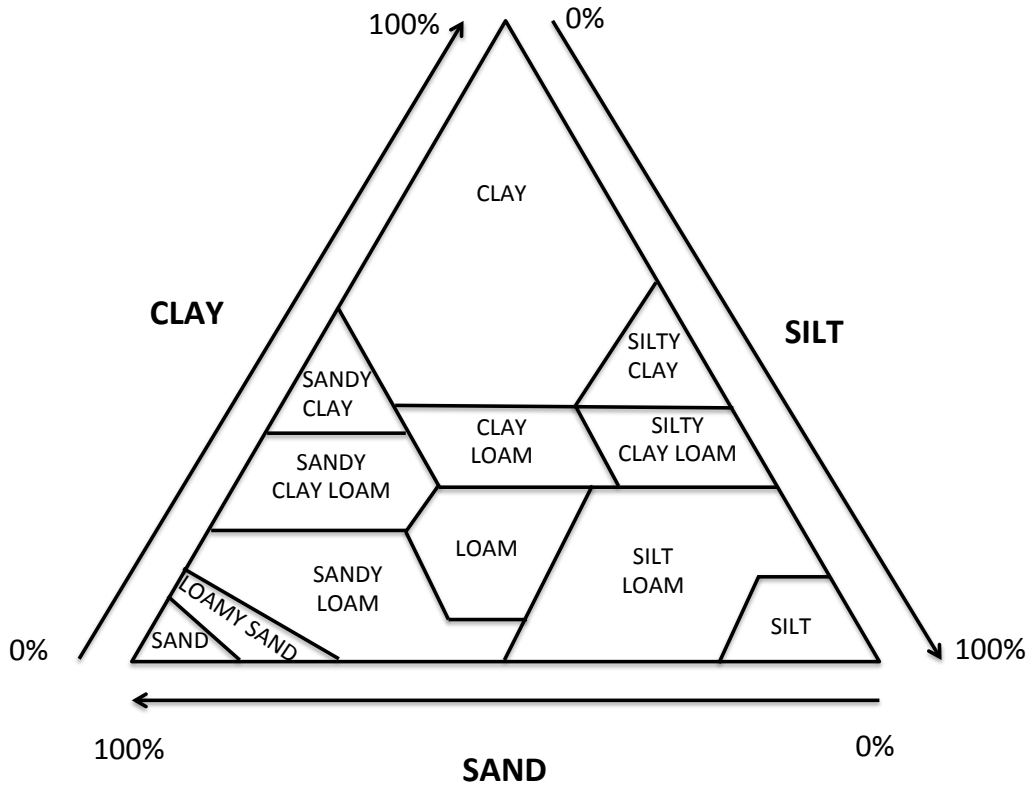
Figure 17.4: Soil triangle

17.3 Soil structure

Soil is a collection of solid individual particles forming a porous structure. The pores or voids will contain air and/or water, depending on the saturation state of the soil. The individual particles can move relative to each other. However, in a rock mass the grains cannot move. Soil is therefore regarded as a 'particulate system' (Fig. 17.5).

Within the soil structure air is unimportant from an engineering point of view, however air voids should be reduced as far as possible by the process of compaction. Water is, however, very important for the engineering properties and behaviour – particularly for cohesive soils. The solid matter (i.e. the soil skeleton) varies widely in particle shape; size and mineral composition and can contain both organic and inorganic matter.
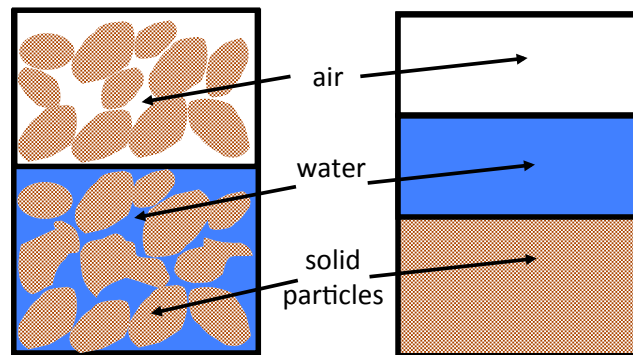
(a) Typical soil structure   **(b) Idealised soil model**

Figure 17.5: Soil structure

17.4 Soil classification

Soil is classified by determining a number of fundamental parameters, which are defined in BS1377: 1990, as:

Moisture content	Part 2: 3.2

Consistency limits (Atterberg Limits)
- Liquid limit   Part 2: 4.3 & 4.4
- Plastic limit   Part 2: 5.3
- Plasticity index   Part 2: 5.4
- Shrinkage limit   Part 2: 6.3

Density
- Linear measurement   Part 2: 7.2
- Immersion in water   Part 2: 7.3
- Water displacement   Part 9: 7.4
- Sand replacement   Part 9: 2.1 & 2.2
- Core cutter   Part 9: 2.4

Particle density
- Gas jar   Part 2: 8.2
- Pyknometer   Part 2: 8.3 & 8.4

Particle size distribution
- Dry sieve   Part 2: 9.2
- Wet sieve   Part 9.3

17.4.1 Moisture content:

The amount of water in a soil has a profound effect on its engineering properties. For example, under compaction dry density varies with water content (Fig. 17.6):

- A soil compacted dry will reach a certain dry density.
- If compacted again with the same compacted effort but with water, a higher dry density will be reached. The water helps to lubricate the soil – the particles move closer on compaction. Also, air in the mixture is removed during the process.
- However, too much water reduces the density.
- Optimum moisture content (OMC) occurs when the compacted dry density is at its maximum ($\rho_{d\,(max)}$).

A point to note is that OMC varies with the nature of the soil and compaction method. Heavier compaction plant produces a higher value of dry density at a lower OMC.
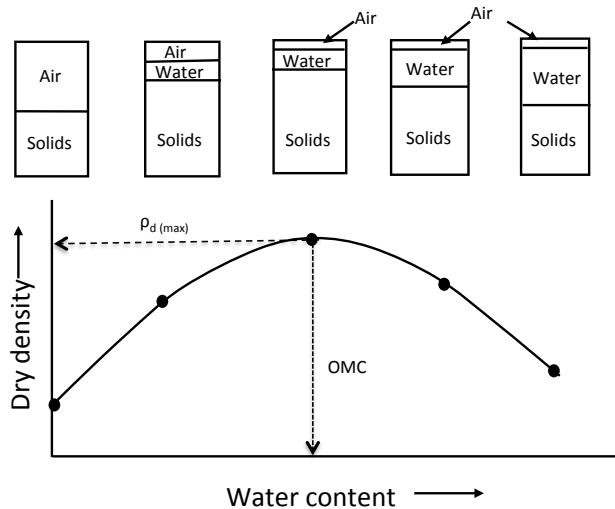
Figure 17.6: Illustration to show how water content influences dry density

To simply determine the moisture content of a soil, the following procedure can be followed:

1. Record the mass of a dry container.
2. Add the wet soil to the container and record the new mass (container + wet soil).
3. Place the container including the wet soil in an oven, at a temperature of around 100 ^{o}C, for about 24 hours.
4. After the duration, record the mass of the container + dry soil.
5. The moisture content is then calculated from the following formula, and is expressed as a percentage:

$$Moisture\,content\,(w) = \frac{mass\ of\ water}{mass\ of\ dry\ solid}\%$$

Example 1: Moisture content of soil:

Calculate the moisture content for the following:

Test	w_1	w_2	w_3
A	16.5	26.6	24.3

where:

w_1 = mass of container (g)

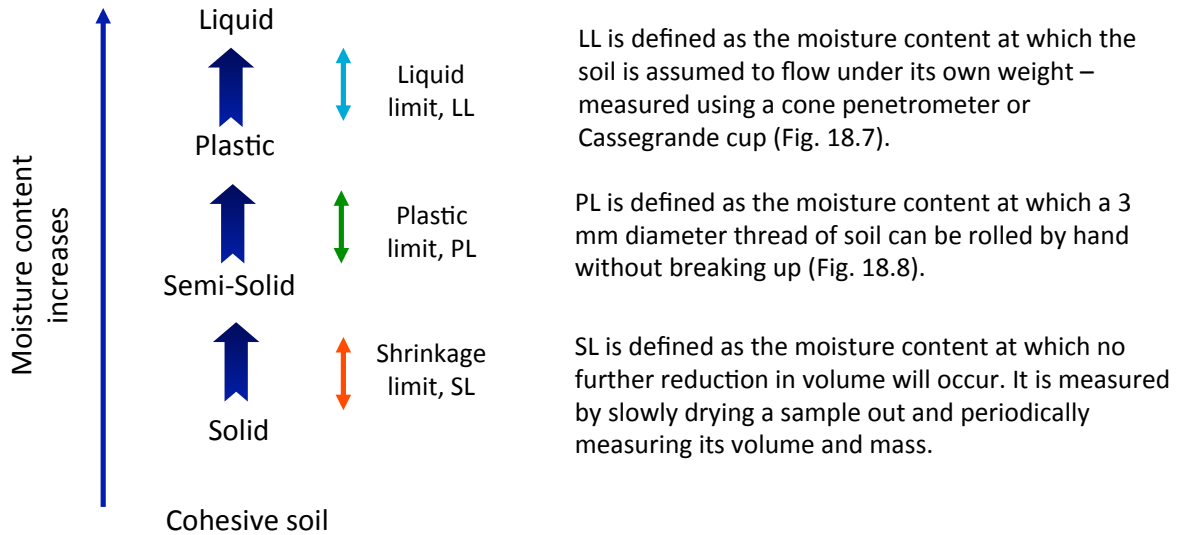w_2 = mass of container and wet soil (g)

w_3 = mass of container and dry soil (g)

The moisture content equation can be written in the form: $w = \dfrac{w_2 - w_3}{w_3 - w_1} \times 100$

The recorded values can be substituted in to give: $w = \dfrac{(26.6 - 24.3)}{(24.3 - 16.5)} \times 100 = 29.5\%$

6

17.4.2: Consistency limits (Atterberg Limits)

These stages describe the consistency of the soil, which in turn relate to its engineering properties.

LL is defined as the moisture content at which the soil is assumed to flow under its own weight – measured using a cone penetrometer or Cassegrande cup (Fig. 18.7).

PL is defined as the moisture content at which a 3 mm diameter thread of soil can be rolled by hand without breaking up (Fig. 18.8).

SL is defined as the moisture content at which no further reduction in volume will occur. It is measured by slowly drying a sample out and periodically measuring its volume and mass.

The range of moisture content over which the soil remains in a plastic condition is defined as the plasticity index (PI) and is calculated from: PI = LL − PL
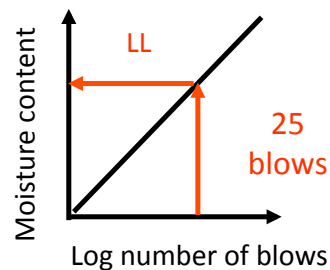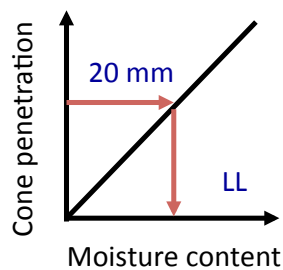
(a) Cone Penetrometer   **(b) Cassegrande cup**

Figure 17.7: Liquid limit tests

Figure 17.8: Plastic limit test

For fine graded soils the 'A – Line' classification chart can be used (Fig. 17.9). The classification chart divides the soil according to ranges of liquid limit and plasticity index. Generally, the higher the liquid limit, the higher the plasticity of the soil. Silts and organic soils tend to have a low plasticity index (i.e. a small range of moisture content over which they are plastic) compared to their liquid limit. Clays tend to have a high plasticity index in relation to their liquid limit.
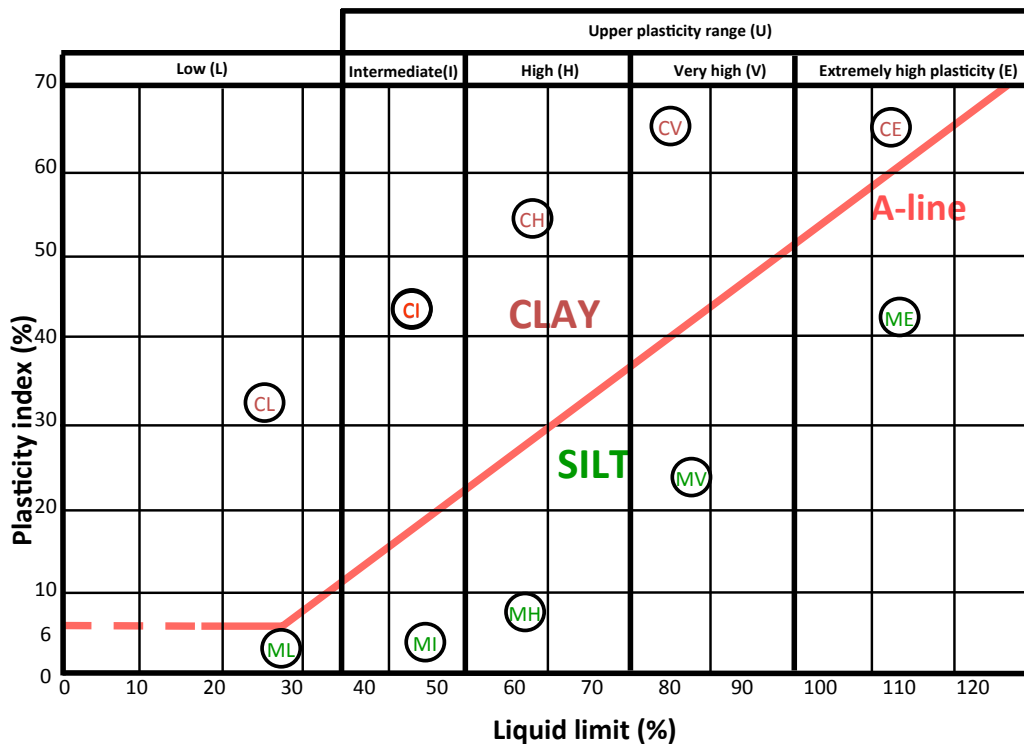

Figure 17.9: A – Line classification chart

To classify a fine soil according to the 'A – Line' chart:

1. Determine liquid and plastic limits; from which calculate the plasticity index.
2. Plot the liquid limit and plasticity index values on the chart.

3. Observe which segment the soil falls into (CL, CI, ML, etc).
4. Write down the soil name, CLAY for 'C' soils, SILT for 'M' soils.
5. Add the plasticity grading to the name, i.e. CI = CLAY of intermediate plasticity.

The classification of fine soils (e.g. silts and clays) is based on plasticity, which is a function of the soil's capacity to absorb water. If water is added to a coarse soil (e.g. sands and gravels), the water will fill the pores and saturate the sample. Any further water will simply drain off and not be absorbed further into the soil structure. Figure 17.10 demonstrates what will happen if water is added to a fine soil, to summarise:

1. Water will initially fill the pores.
2. When the soil is saturated it will continue to absorb water due to the properties of the clay minerals and an increase in volume of the soil mass will occur.
3. At the same time the soil is progressively softened by the water, which results in a decrease cohesion. That is, the water increases the distance between the clay minerals, hence decreases the attracting forces between them.
4. As the soil gets weaker it becomes pliable. When it is sufficiently pliable to be rolled out into a thread it is in a plastic state.
5. Eventually the soil loses all its strength. When it starts to flow under its own weight it is in a liquid state.
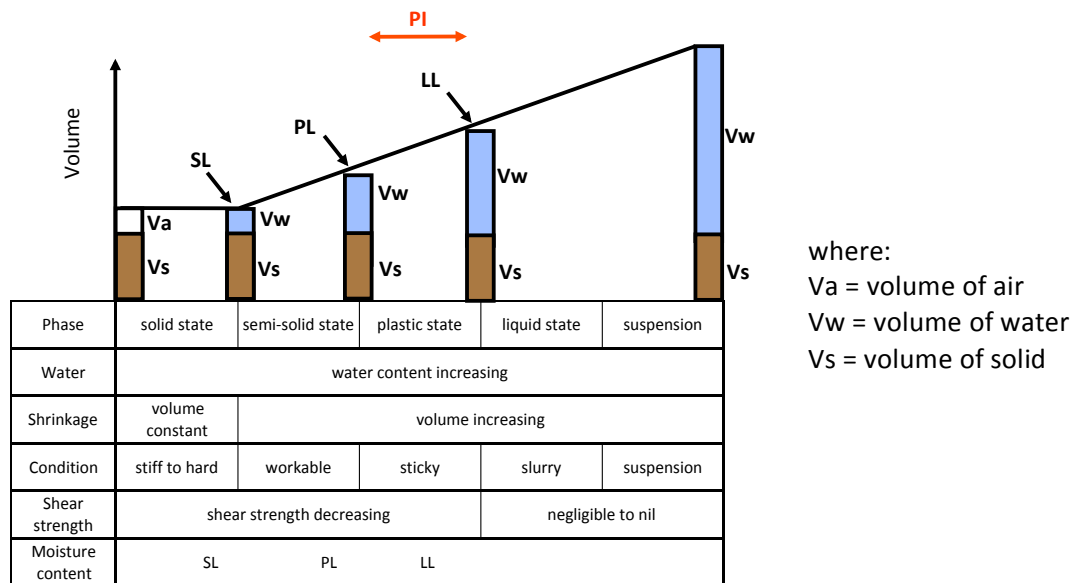

Phase	solid state	semi-solid state	plastic state	liquid state	suspension
Water	water content increasing				
Shrinkage	volume constant	volume increasing			
Condition	stiff to hard	workable	sticky	slurry	suspension
Shear strength	shear strength decreasing			negligible to nil	
Moisture content	SL	PL	LL		

where:
Va = volume of air
Vw = volume of water
Vs = volume of solid

Figure 17.10: Variation in cohesive soil's properties with increasing moisture content

17.4.3 Density

Density is the ratio in mass of a material compared to its volume:

$$Density = \frac{Mass}{Volume} \quad \text{which can be written as:} \quad \rho = \frac{M}{V} \quad \text{the units are:} \quad \frac{Mg}{m^3}$$

Bulk density represents the *in situ* density of the soil at a current moment in time, e.g. the soil might also contain some water and air in the pores:

$$Bulk\ density\ (\rho_b) = \frac{Total\ mass}{Total\ volume}$$

Dry density is when water has been removed from the soil:

$$Dry\ density\ (\rho_d) = \frac{Mass\ of\ solids}{Total\ volume} \quad or \quad \rho_d = \frac{\rho}{1+w}$$

where w = the moisture content, and is expressed as a decimal in this equation

Saturated density is when the weight of the water is included in the weight of the soil:

$$Saturated\ density\ (\rho_{sat}) = \frac{Saturated\ mass}{Total\ volume}$$

When a volume of soil is submerged (e.g. below the water table), it displaces an equal volume of water, so that its effective or submerged density is:

$$Submerged\ density\ (\rho') = \rho_{sat} - \rho_w$$

where ρ_w = density of water

Note:
Mass is when gravity is not included.
Weight includes gravity.
Therefore, a soil's unit weight = density x gravity, where gravity is equal to 9.81 m/s^2, for example:

- Bulk density (ρ_b) Mg/m^3 x 9.81 m/s^2 = Bulk unit weight (γ_b) kN/m^3
- Dry density (ρ_d) Mg/m^3 x 9.81 m/s^2 = Dry unit weight (γ_d) kN/m^3
- Saturated density (ρ_{sat}) Mg/m^3 x 9.81 m/s^2 = Saturated unit weight (γ_{sat}) kN/m^3
- Submerged unit weight (γ') kN/m^3 = γ_{sat} - γ_w
- If the density of fresh water (1 Mg/m^3) is multiplied by gravity (9.81 m/s^2) the unit weight of water (γ_w) is obtained, i.e. 9.81 kN/m^3. Note the density of seawater is 1.025 Mg/m^3 or 1025 kg/m^3.

Tests to determine the density of cohesive soils include:

1. Linear measurement:

This involves extracting an undisturbed cylindrical sample of soil. Measuring its mass and volume (Fig. 17.11), and then compare the ratio of the two to compute the density.

Figure 17.11: Linear density method

2. Immersion or displacement in water

Based on Archimedes' principle, which states that a body immersed in water loses weight equal to the weight of the fluid it displaces. The procedure involves extracting an irregular cohesive soil sample and determining its mass. The sample is then coated in wax (to prevent water ingress), by dipping it into the wax pot. The mass of the coated sample is also recorded. In the immersion method, the sample's mass is recoded when suspended in water. In the displacement method the mass, or volume, of water displaced by the sample is recorded (Fig. 17.12). In the calculation stage the density of the wax is eliminated from the sample.

Figure 17.12 Immersion/Displacement in water – density methods

17.4.4 Particle density

The particle density (ρ_s) of a material is the ratio of the mass of a soil, to the mass of an equal volume of water.

For coarse-grained soils, a 500–1000 ml density bottle (gas jar) may be used, but for fine-grained soils, a special conical topped glass jar, called a pyknometer, should be used (Fig 17.13).

Figure 17.13: Glass jars used in particle density tests

The procedure to determine particle density is simply illustrated in Figure 17.14. It should be noted that the range of particle density of common soil particles is very narrow, typically between 2.60 and 2.70 Mg/m^3.

(1) Weighing the empty jar + stopper (M_1):

(2) A suitably sized specimen of dried soil is placed inside and the weight again obtained (M_2):

(3) The jar is then filled with de-aired water and the contents stirred to remove any air bubbles.

(4) The jar is topped-up with water and then weighed again (M_3):

(5) Finally, the jar is emptied and cleaned, and then filled with de-aired water and weighed again (M_4):

$$\rho_s = \frac{mass\ of\ soil}{mass\ of\ water\ displaced\ by\ soil}$$

$$\rho_s = \frac{M_2 - M_1}{\left(M_4 - M_1\right) - \left(M_3 - M_2\right)} \cdot \rho_w$$

$$where\ \rho_w = density\ of\ water = 1 Mg/m^3$$

Figure 17.14: Outline to the procedure to determine particle density
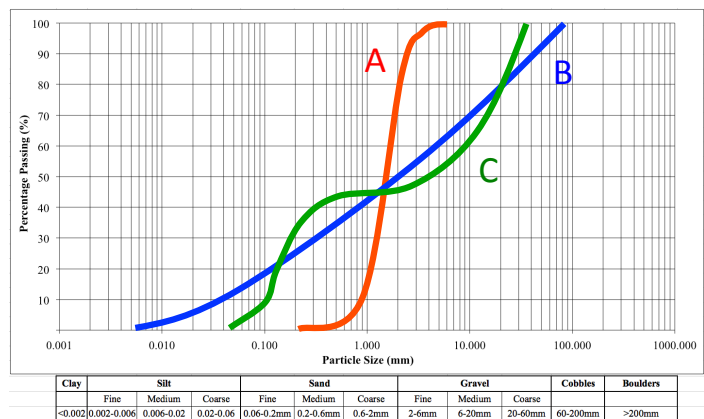
17.4.5 Particle size distribution (PSD)

The classification of coarse graded granular soils involves passing a mass of soil through a series of interconnecting sieves with decreasing aperture size (Fig. 17.15a). The mass retained on each sieve is then recorded, from which the percentage of material passing a given sieve can be calculated. The results are then plotted on a graph to determine the shape of the grading curve. For a given soil mass, the shape of the curve can be defined as (Fig. 17.15b):

    A. Uniformly Graded, indicating that the particles are all the same size.
    B. Well Graded, indicating that there is a large range of particle sizes.
    C. Gap Graded, indicating that there are only small and large particles.

NB the curve can lie anywhere along the horizontal axis and still retain its grading characteristics of: A = Uniformly Graded; B = Well Graded; C= Gap Graded

(a) Apparatus　　　　　　　　　　**(b) Curves**

Figure 17.15 Particle size distribution

17.5 Soil's strength

The strength of soil is defined in terms of its shear strength (Fig. 17.16). This is the maximum shear stress that can be applied to the soil in any direction. When this maximum has been reached the soil yields and is regarded to have failed.
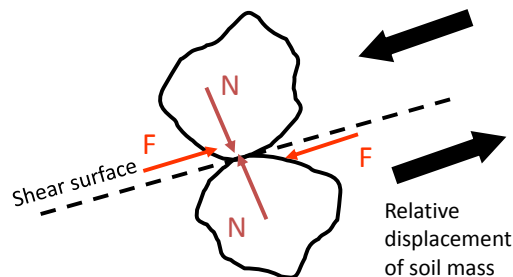

Figure 17.16 Shear strength of soil

There are two components of shear strength:

1. Friction (ϕ)
2. Cohesion (c)

NB pore water has no shear strength.

The values of c and ϕ are known as the shear strength parameters. In 1773 Coulomb developed an expression for these parameters, which defines a straight-line failure envelope (Fig. 17.17):

$$\tau_f = c + \sigma_n \tan \phi$$

where: c = apparent cohesion
         ϕ = angle of shearing resistance
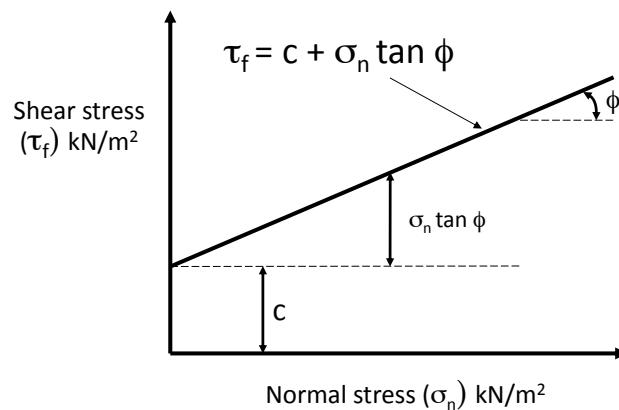 σ_n = normal stress on failure plane

Figure 17.17 Coulomb general failure envelope

In certain soils both cohesion and friction contribute to shear strength, however in other soil types only one of the shear strength parameters may be present. The failure envelopes in Figures 17.18–17.20 illustrate a range of soil types
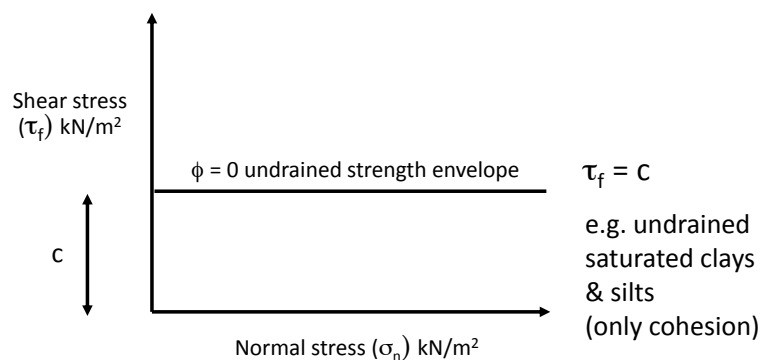

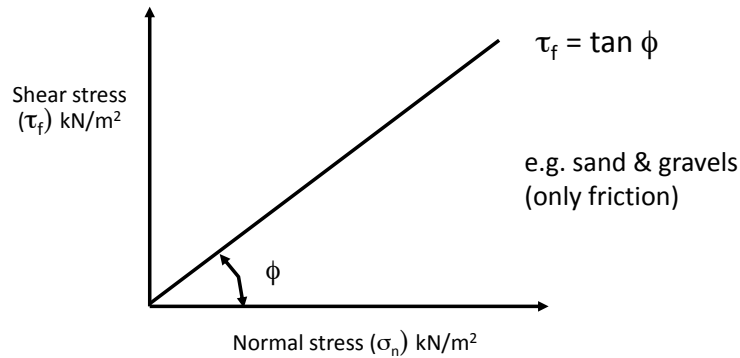**Figure 17.18: Failure envelope for a frictionless soil**

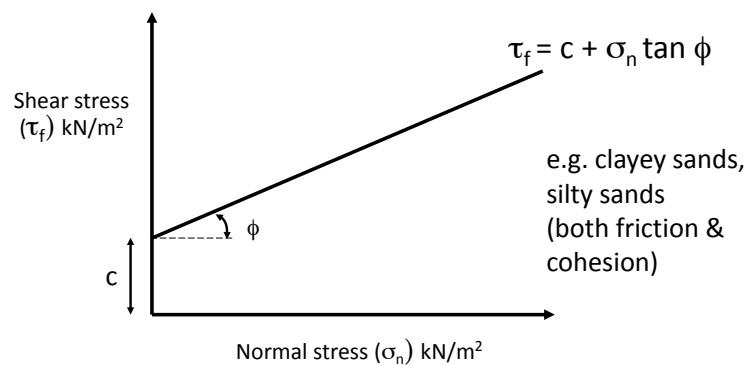**Figure 17.19: Failure envelope for a cohesionless soil**

Figure 17.20: Failure envelope for a partially saturated mixture of cohesive and frictional soil

17.6 Settlement and consolidation of soil

When a soil is subjected to an applied load, such as from a newly constructed building, a degree of compression will probably happen. There are four main types of settlement that can occur:

- **Immediate settlement** occurs instantaneously upon loading and is recoverable (elastic deformation), i.e. it will expand to its original volume if the load is removed. This type of settlement is usually small and occurs during construction.

- **Consolidation** or **primary settlement** results in a decrease in the volume of voids. This type of settlement is not normally recoverable on the removal of the load. In a saturated soil the decrease in voids also results in the dissipation of excess pore water. The rate at which this type of settlement occurs depends on the permeability of the soil. High Permeability soils (e.g. sands and gravels) settle quickly; thus increase in effective stress occurs over a short

time period. Low Permeability soils (e.g. silts and clays) require a longer time to settle or consolidate (years); thus the increase in effective stress is slow.

- **Plastic deformation or secondary consolidation** is due to lateral flow of soil particles and is not recoverable on the removal of load.

- **Creep** occurs in organic soil (e.g. peat) due to the collapse of fibrous matter and it is not recoverable on the removal of load.

Of these four types of compression, the greatest contribution to the settlement of a structure is generally consolidation or primary settlement.

17.7 Site investigation

To establish the suitability of a location for the proposed work a site investigation is normally undertaken. This typically involves three stages:

1. **Desk study** – where a geotechnical engineer will search through relevant maps and documents in order to discover as much about the site and its surroundings as possible. For example, the following information will be studied: geological solid and draft maps, hydro-geological maps, ordnance survey maps (including historical versions), aerial photographs, past activities within the area such as mining and waste tips, public utilities, etc.

2. **Site reconnaissance** – where a geotechnical engineer visits the proposed site and undertakes a visual inspection. For example, tree cover will be assessed, as this can indicate soil type and saturation levels, e.g. Willows trees require very wet ground.

3. **Ground investigation** – is really the only true way to ascertain the underlying soil conditions of the site. During the investigation accurate information relating to water should be obtained. Suitable soil samples for both visual classification and laboratory testing should be extracted. These could be in a disturbed or undisturbed state, the latter representing the 'exact' *in situ* state of the soil, for example, in terms of moisture content and degree of compaction. The soil samples are normally extracted from the ground by drilling some form of borehole or excavating a trial pit.

From the information gained from the site investigation, the following, *inter alia*, should be established:

- Adequate and economic design to be prepared.
- The best method of construction.
- Suitable use (or disposal) of *in situ* materials.
- The changes that may arise in the ground and environmental conditions as a result of work.