INTRODUCTION - 简介

What are soils, soil mechanics and geotechnical engineering?

Soil is an assembly of mineral particles. The size range of soil particles is wide: from small clay particles, about $1\text{x}10^{-9}$ m or less, up to gravel size, about 0.06 m, in other words a size range covering 8 or more orders of magnitude.

Soil mechanics is the science at the heart of geotechnical engineering. It concerns the mechanical behaviour of the ground. Soil mechanics seeks to describe and understand the fundamental properties and behaviour of the ground when subjected to loading (compressibility and strength), and importantly to the presence or passage of water between the soil particles (permeability).

Geotechnical engineering, or geotechnics, is the branch of civil engineering concerned with the design and analysis of foundations, excavations, slopes, retaining walls, embankments and tunnels. In essence, geotechnical engineering is concerned with the civil engineering aspects pertaining to the ground.

Geotechnical engineering projects

Typical geotechnical engineering projects include the following:

Foundations

The foundation of a structure is in direct contact with the ground and transmits the load of the structure to the ground. Foundations types include pad, strip, raft, and piles. When designing foundations, the bearing capacity of the soil and the potential settlement must be analysed.

Excavations

To permit work within the ground, excavations are made to the required depth. The sides of the excavations must be stable to allow work to be carried out safely.

Slopes

Problems of slope instability occur in both natural and constructed slopes. Analysis is performed to assess the stability of slopes to try to prevent landslides etc.

Retaining walls

Retaining walls are used to support changes in ground level which are too steep or too high to remain stable if left unsupported.

Embankments

Embankments are constructed by compacting successive layers of soil until the required height is reached. The compaction process (e.g. type of equipment, amount of work) is decided by the geotechnical engineer.

Tunnels

Can be constructed through soil or rock. Method of construction depends on ground conditions.

The nature of soils

Soil particles are variable in size, shape and strength. Typical sizes ranges could be higher than 75 mm for cobbles and lower than 1 nanometre for clays. Kaolinite, illite and montmorillonite are the most common clay minerals, all of them platey in shape, but with very different characteristics that give rise to interesting soil behaviour.

Essentially, soils consist of an assembly of particles together with water and/or air. The water and air contents are readily altered by changes in conditions and location: soils can be perfectly dry (have no water content) or be fully saturated (have no air content).

Natural soils are almost never consistently the same from one point in the ground to another. The content and nature of the grains varies, but more importantly, so does their arrangement (structure).

Generally, a soil is a combination of the micro- and macro-features. The micro-features comprise the particle size, shape, microscopic arrangement, and interparticle bonding in some soils). The micro-features are referred to as the “fabric”. On the other hand, macroscopic features comprise the structure and include discontinuities within the soil mass, such as distribution and orientation of fissures in clays, or lenses of other material.

Origin of soils

Soils are the results of geological events. The nature and structure of a given soil depends on the geological processes that formed it. These geological processes affect both the particles and the structure of soils.

Transported soils

As the term suggests, these have been moved from their original location and deposited elsewhere. The principal agents of transportation are: water, ice and wind. The agents of transport, together with mineralogy influence the size and shape of the particles, and thereby control the engineering properties of transported soils.

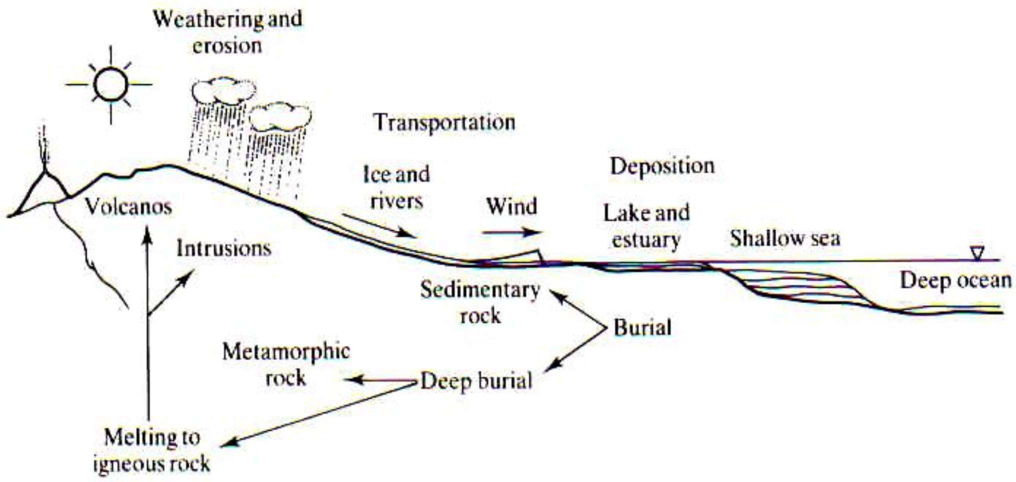


Fig.1.1. The rock cycle (Atkinson, 1993).

Depending on the deposition environment, soils can have either low or high densities. Bedding is also often evident, giving these soils an anisotropic fabric.

Residual soils

These have been formed entirely by in situ weathering and have remained at their original location. They occur mainly in tropical regions and other areas not subjected to transportation.

The mineralogy of the particles varies widely (depending on the source material), especially with depth, and this influences engineering behaviour. In the same manner, depending on the parent material, the fabric of residual soils may change continuously due to weathering and/or chemical effects.

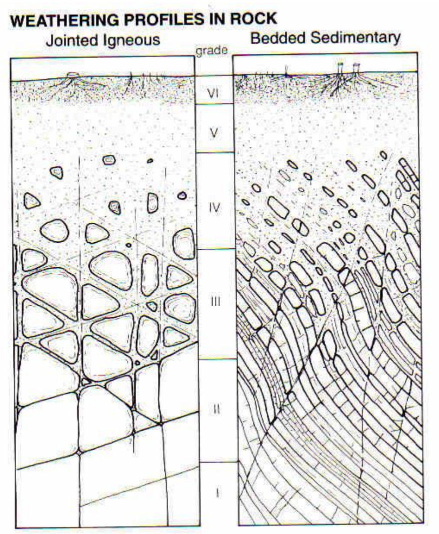


Fig.1.2 Residual soil profiles

Fills

Fills are not normally considered in this subdivision. It is important however, to consider them separately as their characteristics can differ significantly from other soils. Fills are formed by excavating soils and placing them as individual particles or as lumps.

Fills may consist of individual particles (e.g. gravels) or lumps of porous material (e.g. excavated clay and sedimentary rock). The size of the particles depends on the excavated material and on breakdown during placement.

Fill density and structure are controlled by the method of placement and compaction. For example, if placed in layers, the structure will be anisotropic.

PHASE RELATIONS

This section gives the basic terms and definitions used by geotechnical engineers to index and classify soils.

Natural soil comprises a mass of solid particles separated by spaces (pores, voids). Some of these voids are filled with water and some with air (see Fig. 2.1).

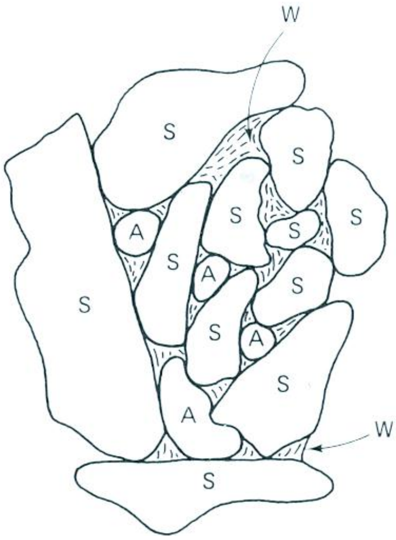


Fig.1.3. Soil skeleton containing solid particles (S), and voids with air (A) and water (W)

A soil skeleton is normally idealised in the form of a phase diagram, as illustrated in Fig. 1.4.

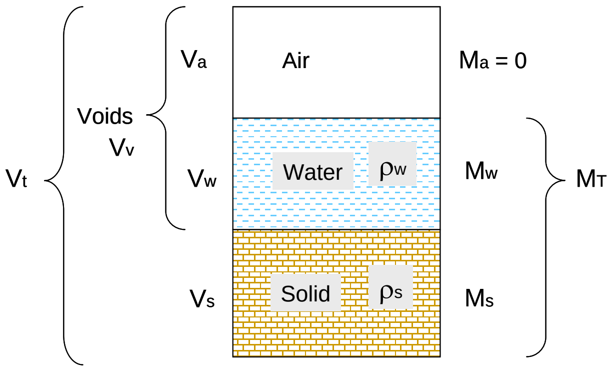


Fig. 1.4 Phase diagram: definition of phase volumes and masses

From the phase diagram, we can see that the total volume (V_t), can be considered as comprising the volume of solids (V_s) and the volume of voids (V_v). The volume of voids is the sum of the volume of air (V_a) and the volume of water (V_w). Therefore:

$V_t = V_s + V_v$

$V_v = V_a + V_w$

In the same manner, looking at the masses, the total mass (M_t) comprises the mass of water (M_w) and the mass of solids (M_s).

$M_t = M_s + M_w$

The mass of air (M_a) is (for obvious reasons) neglected in the expression above. These fundamental quantities are used to define phase relations for soils.

Void ratio

The void ratio (e) is a relationship between the volume of voids (Vv) and the volume of solids (Vs). The void ratio is normally expressed as a decimal and typically ranges from 0.4 to about 1.0 for sands. In clays it may vary from 0.3 to 1.5 or even higher. It is defined as:

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

Porosity

The porosity (n) is defined as:

$$n = \frac{V_v}{V_t}$$

The porosity is the ratio of the volume of voids to the total volume. It is normally expressed as a percentage and varies between 0 and 100%. It can be shown that:

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

Degree of saturation

The degree of saturation (S) tells us the percentage of the total volume of voids that contain water. It can be calculated as:

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

If the soil is dry S=0%, and if the pores are completely full of water the soil is fully saturated and S=100%.

Water content

Perhaps the most important thing you need to know about a soil – how much water is present in the voids relative to the amount of solids. The water content (w) is defined as:

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

This calculation is based on the dry mass of the soil and not on the total mass. w can vary between 0 and 100%, but it can be as high as 500% in some organic soils. A dry sample is obtained by placing in an oven at 105°C for 24 hours.

Density

From school physics you know that density is mass per unit of volume. The density is the ratio that connects the two sides of the phase diagram in Figure 2.2. There are several commonly used densities in geotechnical engineering practice.

Bulk density

The total or bulk density (ρ) is defined as:

$$\rho = \frac{M_t}{V_t} = \frac{M_s + M_w}{V_t}$$

Bulk density depends on how much water happens to be in the voids as well as the density of the grains themselves. It could range between 1000-2400 kg/m^3.

Dry density

This is the density of the dry soil per unit total volume:

$$\rho_d = \frac{M_s}{V_t}$$

Solid or particle density

The density of particles is given by:

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

and could range between 2500-2800 kg/m^3. The particle density of quartz is about 2650 kg/m^3. The particle density is synonymous with the dimensionless specific gravity (see below).

Submerged or buoyant density

In seepage problems and some other calculations it can be useful to work in terms of a submerged or buoyant density,

$$\rho' = \rho - \rho_w$$

Where ρ_w is the density of water, which for geotechnical engineering purposes can be taken as 1000 kg/m^3.

Specific gravity

The specific gravity (G_s) is the ratio of the mass (or weight) of a volume of the material, to the mass (or weight) of an equal volume of water:

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

G_s can be calculated experimentally. For quartzitic sands $G_s \approx 2.65$. For clayey soils it can vary between 2.65 and 2.80 depending on the predominant mineral of the soil.

Unit weights

Unit weight (γ) is the product of density and acceleration due to gravity, g (= 9.81 m/s^2):

$$\gamma = \rho g$$

As in the case of the densities, there are many unit weights, including the dry unit weight (γ_d), the submerged unit weight (γ') and the unit weight of water (γ_w = 9.81 kN/m^3).

Other weight/volume relationships

There are several important inter-relations between the definitions given above. For example:

$$w.G = S.e$$

and

$$\gamma = \gamma_w \frac{(G_s + e.S)}{1+e}$$

and

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

and relative density, which is a useful measure of the state of density of a soil,

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

Although these relationships are easily found in the literature, students should feel confident using them in practice. A comprehensive summary of the phase relations can be found in Appendix A1.

CLASSIFICATION OF SOILS

Soils are normally classified according to their particle size, rather than by origin or mineralogy. There are two major subdivisions:

Cohesionless or coarse-grained soils, which are particles held together by gravitational forces, e.g. sands and gravels.

Cohesive soils, or fine-grained soils, which are mainly small particles, frequently bound together by surface or inter-particle forces, e.g. clays and silts.

The classification of soils into fine-grained and coarse-grained is important as significant differences in their mechanical behaviour can be assigned to each. The difference in behaviour is related to the size of the inter-particle pore spaces, evidenced by their respective hydraulic conductivities (permeability), and thus the time over which certain transient effects occur.

Soil classification systems

The British Soil Classification System (BSCS) considers soil as either fine (>35% passing 63 m sieve) or coarse soil (<35% passing 63 m sieve). Each category is further divided, according to dominant particle size as determined by sieving and the resulting particle size distribution, as described below. If appropriate, laboratory tests can be performed to identify the plasticity characteristics and hence further refine the classification.

Note however, that there are other soil classification systems. Some of them are the Unified Soil Classification System (USCS) and the AASHTO classification systems. These two systems are widely used in the United States and other countries.

Both BSCS and USCS classification tables are contained in the appendix to these notes.

Particle size distribution

In addition to the definition of size ranges of the four main soil particle sizes, as shown in Tale 1.2, the range of soil particle sizes can be defined using a particle size distribution curve or chart. The engineering size scale according to the British Standards is as follows:

Class	Upper size (mm)	Lower size (mm)
Gravel	60	2
Sand	2	0.06
Silt	0.06	0.02
Clay	0.002	-

Table 1.2. Size ranges of soils.

Gravels can be subdivided into coarse (60-20 mm), medium (20-6 mm) and fine (6-2 mm). Similar subdivisions are made for sands and silts.

The sizes down to about fine sand/coarse silt can be separated by a nest of stacked sieves. The aperture size of each succeeding sieve is smaller than the one above. By weighing the mass of soil retained on each sieve, we can obtain the particle size distribution (PSD) for the soil (see Figs 1.5 & 1.6).

Determination of particle masses for calculation of PSD for sands and gravel is performed with dry particles. Note however, that depending on the nature of the soil wet sieving may be required. This is necessary when the soil has lumps that need to be separated into individual particles.

When the particles are too small to be sieved, the grain size distribution can be obtained by sedimentation or hydrometer analysis. The basis for this test is Stoke's law for falling spheres in a viscous fluid in which the terminal velocity of fall depends on the grain diameter and the densities of the grains in suspension and of the fluid. The diameter thus can be calculated from knowledge of the distance and time of fall.

The PSD curve indicates the distribution of the soil particles and its shape reflects the uniformity of the particles.

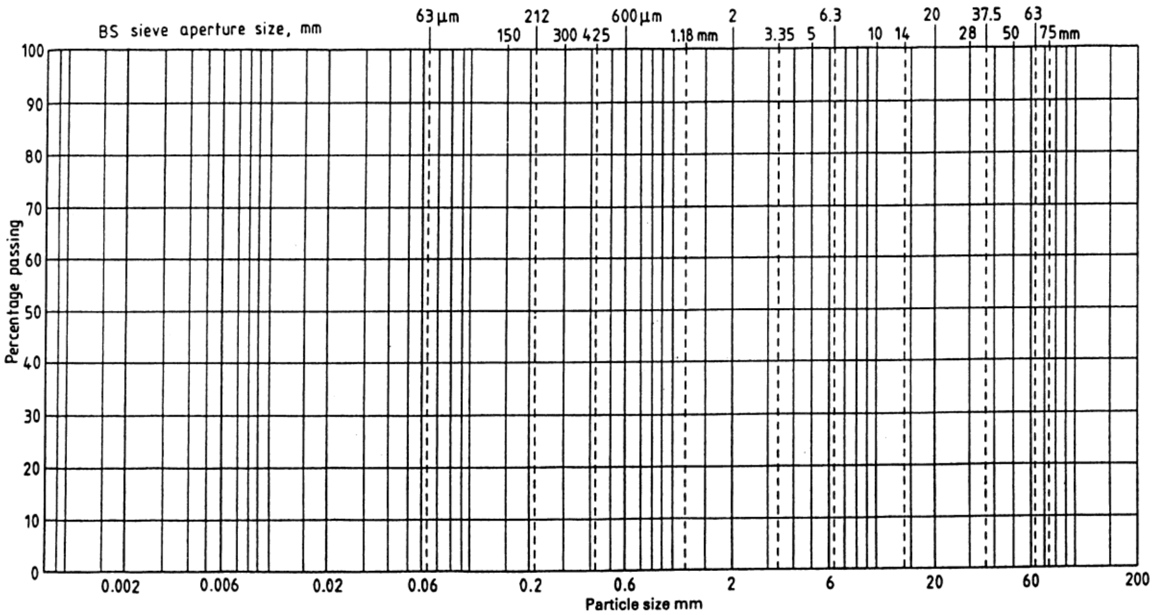
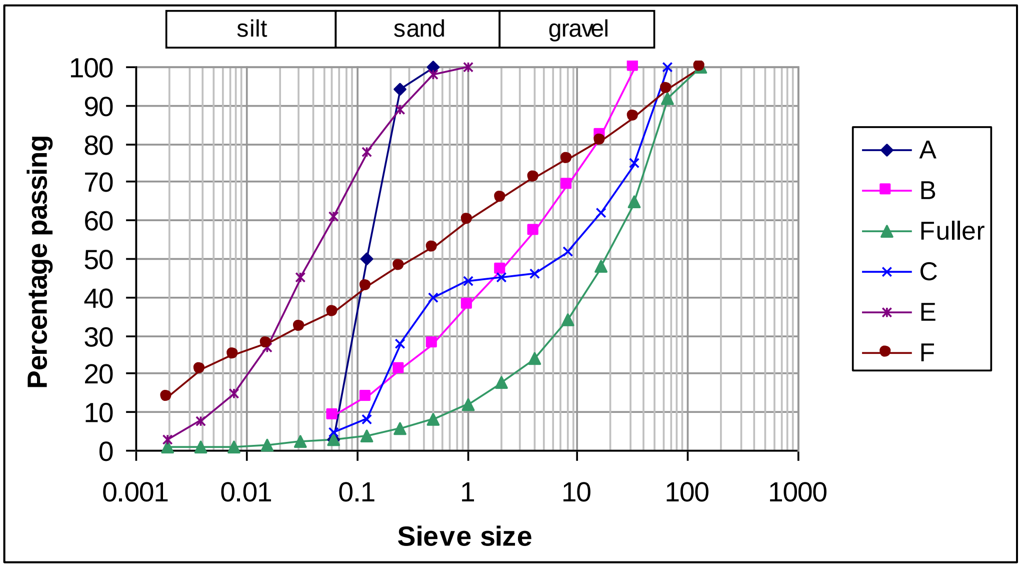


Fig.1.5. Particle size distribution chart



	Description	D_{60}	D_{10}	C_u
A	Uniformly or narrowly graded fine SAND	0.12	0.18	1.5
B	Well-graded silty SAND and GRAVEL	0.07	4.5	64
Fuller	Theoretically densest/ideal	0.66	24	36
C	Poorly or gap graded fine to medium Sand & Gravel	0.14	15	-
E	Well graded sandy SILT	0.0051	0.06	12
F	Boulder clay	0.001	1	1000

Fig. 1.6. Some particle size distribution curves and grading characteristics (some from Head, 1980)

A soil such as the boulder clay (glacial till) in Fig. 1.6 would be described as well-graded. A soil which comprises predominantly one particle size would be described as uniform. There is a third type of grading – gap grading, which refers to a soil comprising small and large particles but with an absence or gap in the medium-sized particles.

Statistical moments can be obtained from the PSD. For example D_{60} is the particle size at which the finer material amounts to 60% of the total sample mass. Coefficients of curvature and uniformity are sometimes calculated to help description. The coefficient of uniformity,

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

Soils with a Cu of less than about 6 are regarded as uniformly graded. Greater values are regarded as well-graded.

Atterberg limits

The index tests (consistency limits, Atterberg limits) describe the water contents in a fine-grained (clayey) soil at which different forms of material behaviour occur, i.e. the transitions between brittle, semi-solid, plastic and liquid behaviours.

Atterberg, in 1911, proposed that the four states in which a soil may exist can be distinguished by:

Shrinkage limit (SL): the boundary between the brittle solid and the semi-solid state.

Plastic limit (PL): the boundary between the semi-solid and the plastic state.

Liquid limit (LL): the boundary between the plastic and the liquid state.

Figure 1.7 shows the relationship between the Atterberg limits, the moisture content and material behaviour. Knowing the moisture content at which these limits occur for a given soil is a basic geotechnical requirement.

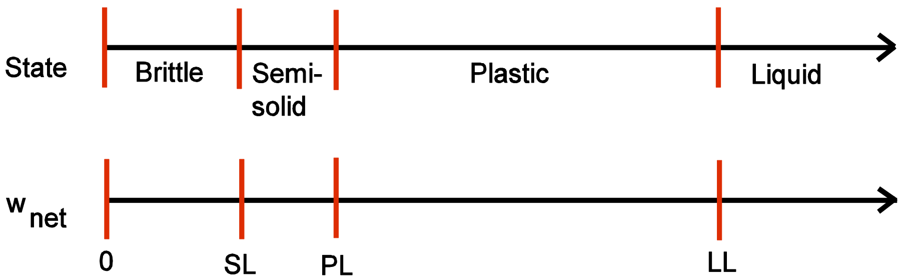


Figure 1.7. Atterberg limits, moisture content and soil behaviour

The plastic limit (PL or w_P) and the liquid limit (LL or w_L) are determined through laboratory tests.

Liquid limit

The liquid limit is commonly assessed by two different methods, the Casagrande or cup method and the falling cone method. The cone method has a direct relation with the shear strength of the soil and yields results that are less dependent on the operators' skill than is the case with the Casagrande method.

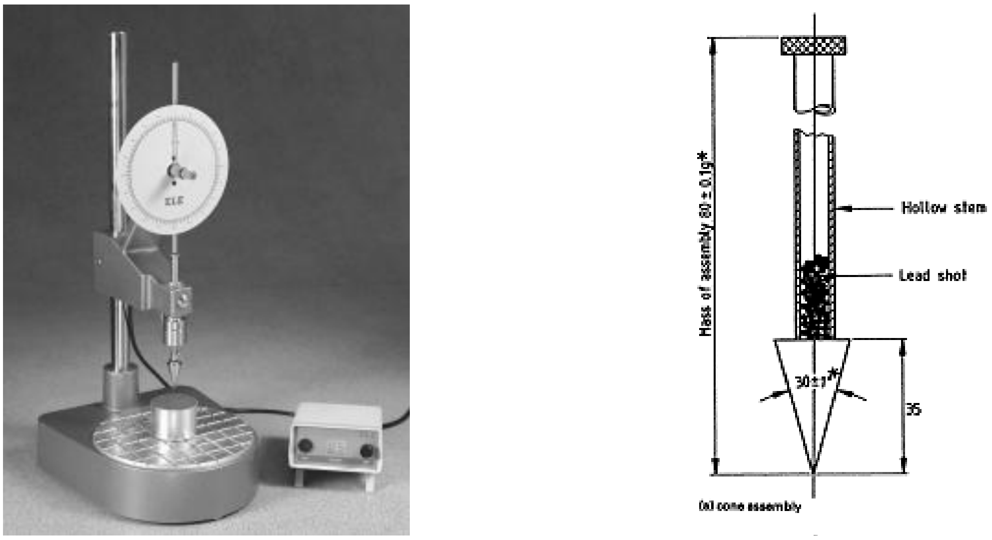


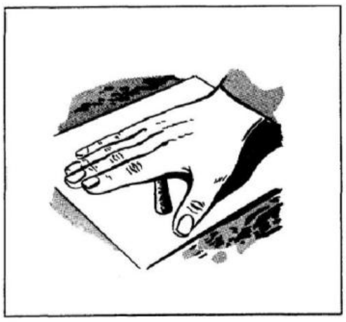
Fig.1.8. Falling cone test equipment (ELE International: http://www.ele.com/) and BS1377-1990

The test is performed on soil that has been dried and passed through a 425 μm sieve. Distilled water is added and the mixed soil paste is placed in a metal cup. The cone tip (angle = 30°, mass = 80 g) is placed in contact with the surface of the clay and allowed to fall freely into the clay. After 5 seconds the cone is locked and its penetration into the soil noted. The test is performed at four different moisture contents and hence different clay consistencies.

The resulting data is analysed by plotting penetration against moisture content and fixing a best-fit line. The liquid limit of the soil is the moisture content at which the penetration of the cone into the soil is 20 mm, as read off the graph.

Plastic limit

In Europe, the plastic limit is rather more arbitrarily being defined as the water content at which a thread of soil with 3 mm diameter just crumbles when it is carefully rolled out.



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In China, the cone penetrometer is used. It has a mass of 76 g and when used to determine liquid limit, targets a penetration depth of 17 mm. It is also used for the plastic limit with penetration depth of 2 mm.

Plasticity index

The difference between these two limits is defined as the plasticity index (PI), and calculated as:

PI = LL – PL or $I_P = w_L - w_P$

The PI, when plotted against the liquid limit (LL) on the plasticity chart, enables the classification of cohesive soils. Some examples are provided in accompanying handouts.

The liquidity index (LI) is also a useful indicator. It gives a ready comparison of the soil's plasticity with its natural moisture content:

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

If LI = 1.0, the soil is at its liquid limit.

If LI = 0.0, the soil is at its plastic limit.

The plasticity index in conjunction with the liquid limit is used to classify the plasticity of fine-grained soils and the dominant particle size, i.e. clay/silt using the chart in Fig. 1.9. The A-line, after Atterberg, separates the clays (= C) from silts (= M).

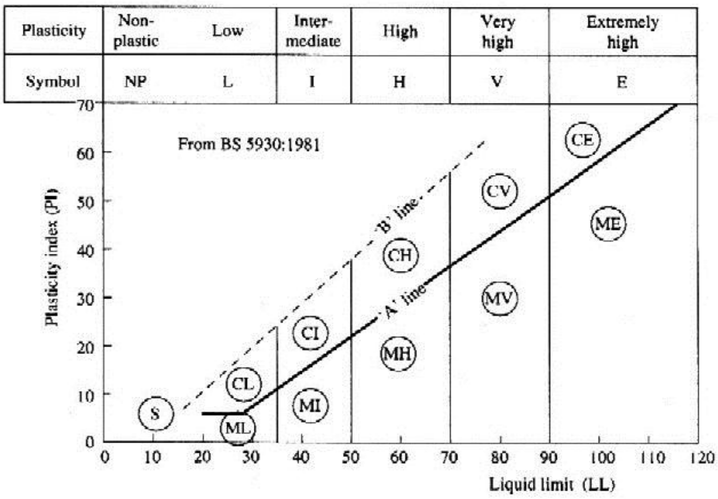

Fig.1.9. Classification system for fine-grained soils

Activity

The Atterberg limits are related to mineralogy and the amount of clay minerals present. A high plasticity index might be due (i) a large amount of a clay mineral with a relatively low moisture holding capability or (ii) a smaller amount of a clay mineral that can hold a lot of moisture. The ability of a clay mineral to hold water is related to its surface area. A relatively large clay mineral with a low specific surface area is kaolinite. In contrast, montmorillonite is a very small clay mineral with large specific surface area.

In order to distinguish between these two effects, Skempton (1953) proposed a quantity he called the activity,

Activity = plasticity index / % by mass of sample finer than 2 μm

Figure 1.10 shows the results of tests on a range of clay soils. The activity of a clay indicates something of its susceptibility to moisture content changes, i.e. to volume change or shrink-swell behaviour. Values of activity and the corresponding behavioural description are given in Table 1.3

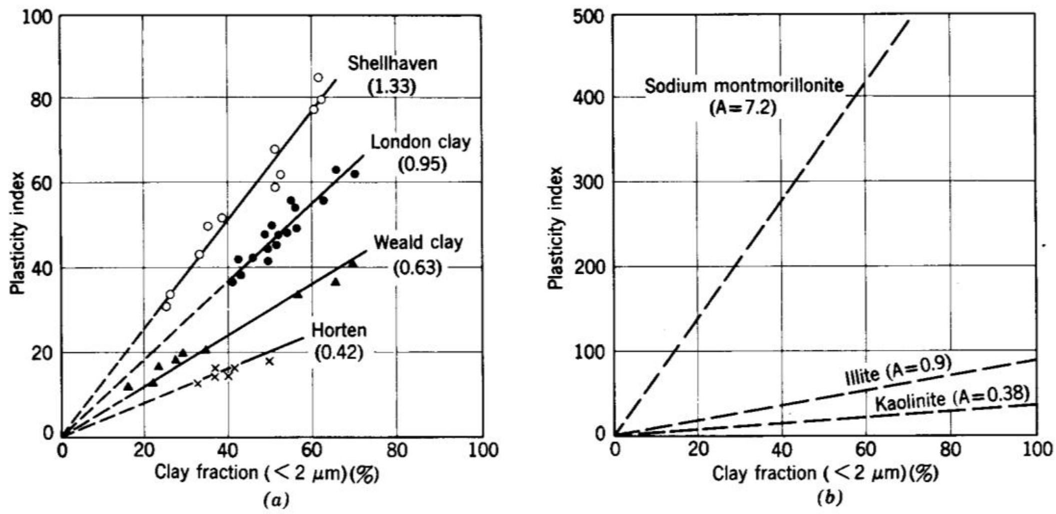

Fig.1.10. Relation between plasticity index and clay fraction. (From Skempton, 1953)

Table 1.3. Typical Clay activity values and descriptions

Activity	Description
<0.75	Inactive
0.75 – 1.25	Normal
1.25 – 2.0	Active
>2	Highly active

SOIL DESCRIPTION

A standard language is essential for the description of soils. A comprehensive description of soils includes the characteristics of both the soil material and the in-situ soil mass. Material characteristics can be determined from disturbed soil samples. The main material characteristics are the grain size distribution and plasticity as described above from which the soil name can be deduced. Secondary material characteristics are the colour of the soil, the shape, texture and composition of particles.

On the other hand, the in-situ soil mass characteristics should be determined in-situ, but they can be determined based on undisturbed samples (i.e. samples in which the soil structure has been preserved). Mass characteristics include an assessment of the compactive state or stiffness and details of bedding, discontinuities, weathering, etc. Minor geological such as macro-fabric should be also described (e.g. thin layers of sand and silt in clay, filling material in fissures and joints, organic inclusions, root holes, etc).

It is important to distinguish between soil description and soil classification. A description includes details of the material and mass characteristics, therefore any two soils are not likely to have the same description. This is opposite to the case of classification where a soil is allocated to one of a limited number of groups based on the material characteristics only. In the case of a soil to be used in-situ for the support of a excavation, a full description is required while the classification is optional and discretionary. For a soil that is going to be used as a construction material classification is particularly useful. Personal experience also plays an important role in these judgements. However, the importance of an adequate soil description is emphasized.

It is clear from the statements above that a soil description can be much more complex to perform than a soil classification based on laboratory experiments. Is for this reason that the following guidelines are included. The simple approach described here is based on experience from all over the world developed over many years. It has been developed by Emeritus Professor John Burland at Imperial College London, and it is based largely in the work of Jennings & Brink (1978). The approach is compact and can be easily memorised.

<u>M C C S S O O W</u>

The letters M C C S S O O W stand for eight descriptors which are used for the engineering description of the soil. They can memorised by forming them into a mnemonic (Greek for mindful). You can also remember it as 'MCC SO What?' and remembering to add the other S and O descriptors.

The eight letters stand for:

M – Moisture condition
C – Colour
C – Consistency
S – Structure
S – Soil type
O – Other features
O – Origin
W – Ground water conditions

Each of these descriptors has an engineering significance and the first seven should be used to describe each horizon in a soil profile and the eighth to describe the ground water conditions.

All soils including fills, considered for engineering purposes should be described using these descriptors.

The method is equally applicable for use in trial pits, shafts, adits, etc. or on samples extracted from the ground. In the former case fresh soil should be exposed by excavating a few centimetres into the walls of the pit or shaft. In the case of samples they should be split along their longitudinal axes and described in their fresh condition. If they are then left to dry the soil structure is more readily identified.

Although the method is very useful for description of soils in-situ, it is recommended that all soil samples tested in the laboratory are fully described after testing.

M – Moisture condition

The following five point descriptors are used:

Dry (Desiccated)
Slightly moist
Moist
Very moist
Wet

In temperate climates this descriptor is sometimes omitted since water tables are usually high and the soil is frequently fully saturated. However it can be of considerable importance to describe the moisture and seepage conditions in the walls of a trial pit. Additionally, the soil can become dried out by the action of vegetation and previous site usage.

The appropriate term is used to describe the moisture condition existing at the time of examination. If the moisture conditions are likely to have changed significantly from the in situ conditions this fact must be noted (e.g. if the trial pit has been open for some time, drying may have occurred).

The moisture condition is important because it has a fundamental influence on the mechanical properties of a soil. In particular a soil which is dry or slightly moist when examined may change its properties very significantly if, subsequently, it wets up. Two obvious examples of this are the swelling of desiccated clays and the collapse of sandy soils or loose fills on wetting.

C – Colour

Colour is an obvious visible feature and can be useful for the recognition of strata in different locations on a site. It is also an indicator of chemical and mineralogical processes mainly associated with iron compounds and can give valuable information about weathering processes.

Colour may change with moisture content and should be judged in the undisturbed state 'in profile' and also in wet remoulded state.

An accurate description of colour can be obtained using a colour chart. However the following basic hues are usually adequate:

Bright colours: pink, red, purple, orange, yellow
Dark colours: olive, green, blue
Shades of grey
Intermediate colours are described by combining terms (e.g. pale reddish orange, or dark bluish green, etc.)

When examining the mass of soil it is important to describe both the colour of the intact soil and also the colour on joints and fissures which are often 'gleyed' when the rest of the soil is oxidised and viceversa. The colour can give important clues about previous groundwater and seepage conditions.

<u>C – Consistency</u>

The consistency describes the hardness or denseness of a soil and is therefore a measure of stiffness and strength.

The following five point descriptors are used:

(i) Clayey soils: very soft, soft, firm, stiff, very stiff (hard)
(ii) Granular soils: very loose, loose, medium dense, dense, very dense

Each term has been defined using simple tactile tests and easy available tools such as a spade, pick or steel rod (see Tables 1 and 2).

Ignoring the presence or otherwise of joints and other discontinuities, consistency is related to strength. Approximate values of undrained strength (clayey soils) and Standard Penetration Test (SPT) blow count (granular soils) have been assigned to the various descriptors in the British standard)

It is important to assess the influence of vigorous remoulding on the consistency. Sensitive clays will lose strength dramatically on remoulding. Some carbonate sands, when rubbed strongly in the palm of the hand, will break down and turn into a slurry. A desiccated clay may appear granular until it is strongly re-worked when it may turn out to be mainly clay. Such observations are of outstanding importance.

The question is frequently asked: 'Why not use a pocket penetrometer or hand vane to determine consistency of clayey soils? This practice has dangers for the simple reason that most penetrometers give shear strength values directly. The danger is that this shear strength might be used in design without taking account of the many factors (such as size, structure, rate and anisotropy) which dictate the strength to be used in design. If a penetrometer were to be graduated with the descriptors given in 4.2 (i) it would be more acceptable provided it does not discourage the observer from studying the soil structure by the action of picking and handling the soil as described next.

Descriptor	Test	Approximate undrained shear strength (kN/m^2)
Very soft	Exudes between fingers when squeezed	< 20
Soft	Moulded by light finger pressure. Easy to pick	20 – 40
Firm	Moulded by strong finger pressure. Fairly easy to pick	40 – 75
Stiff	Cannot be moulded by fingers. Difficult to pick	75 – 150
Very stiff	Very tough and difficult to pick	> 150

Table 1. Consistency of clayey soils

Descriptor	Test	SPT
Very loose	Very easy to excavate with spade	< 4
Loose	Fairly easy to excavate with spade or penetrate with handbar	4 – 10
Medium dense	Difficult to excavate with spade or penetrate with handbar	10 – 30
Dense	Very difficult to penetrate with handbar. Requires pick for excavation	30 – 50
Very dense	Difficult to pick	> 50

Table 2. Consistency of granular soils*

*Note: It is very important to note degree of cementation (e.g. slightly cemented)

S – Structure

In this context, structure means the presence or absence of discontinuities within the soil mass and not the particle arrangement within the soil skeleton. The structure of the soil mass is a vital feature since it can play a dominant role in controlling its behaviour, in particular its strength and permeability.

The descriptors refer to what can be seen. They relate to features that are due to (i) bedding, (ii) fracturing, (iii) fabric and (iv) shearing. They are dealt with in that order.

(i) Bedding. This indicates visible bedding planes. The spacing (and dip) should be indicated. A scale of bedding spacing from ‘very thickly bedded’ through ‘thinly laminated’ is given in the British standard. Note any special bedding characteristics such as cross bedding. The term interbedded is used to describe alternating soil types (e.g. SAND with interbedded CLAY).

The term parting describes bedding surfaces that separate easily (e.g. a thin layer of silt or sand between clay soil). The thickness and soil type of parting should be noted.

(ii) Fractures. These are referred to as joints or fissures[1]. Intact means no fractures. Fissure or jointed. State whether closed (tight) or open and, if possible, their persistence. Note spacing – a scale of spacing from ‘very widely spaced’ to ‘extremely closely spaced’ is also given in the British standard.

State whether randomly oriented and if not the dominant dips (e.g. predominantly vertical and horizontal).

The texture of the fracture surface should be described together with a note of any staining or discolouration as this may indicate weathering, seepage of water or shearing.

(iii) Fabric. Weathering or transportation can result in a distinct ‘fabric’ in the soil mass. Thus the weathering process will frequently give rise to lumps of intact less weathered material surrounded by a softer matrix of deeply weathered material. Similarly mudsliding will generate a fabric of disordered stiff lumps in a soft remoulded matrix.

(iv) Shearing. In granular soils shearing is indicated by a zone of mixing forming what is often termed a ‘melange’.

Shear (or slip) surfaces are characterised by being ‘polished’ as a result of the strong orientation of the flaky clay crystals, parallel to the surface produce by shearing. Polishing is sometimes accompanied by striations (usually produced by the gouging of larger grains), grooving and fluting. These features enable the bearing of the shearing movement (or movements) to be established and this information should always be determined where possible during logging. The geological term describing such sheared surfaces is ‘slicken-sided’.

[1] The terms ‘fissure’ and ‘joint’ are not clearly distinguished in the literature. In general the term ‘joint’ is used to describe a prominent planar discontinuity along which there has been no major displacement (as opposed to a ‘fault’). ‘Fissures’ are less prominent and extensive than ‘joints’.

Sometimes 'shear surfaces' exist which are continuous over some distance. These can usually only be identified in trial pits and shafts. Their presence will usually play a dominant role in determining the stability of the mass of the ground.

When examining and describing the structure of the ground it is very important to keep in mind the particular building or engineering works involved.

For an excavation, opening of fissures due to stress release, in the presence of wet permeable horizons may cause a dramatic increase in mass permeability and rapid softening.

For an embankment, the presence of partings or laminated soils will result in very high permeability parallel to the bedding which may be significant in the rapid transmission of pore water pressures into unstable areas.

The presence of pre-existing shear surfaces may have a major influence on the stability of a slope or embankment.

S – Soil type

Soil type is primarily based on grain size following the standard descriptors of boulders, gravel, sand, silt and clay.

The importance of grain size lies primarily in the drainage characteristics of the soil thereby influencing the permeability and the rate at which the strength and volume change respond to changes in loading.

Grain size also influences basic strength and deformation properties

The proportions of various grain sizes (i.e. the grading) also have a profound influence on the mechanical and drainage characteristics of soils.

The simple visual and tactile tests summarised in Table 3 can give reasonably accurate and extremely valuable assessment of soil type and grading.

Very few soils in nature fall entirely within one size distribution. Mostly soils are mixtures (e.g. silty CLAY; subangular very sandy, fine to coarse GRAVEL with small pockets of soft grey clay).

Considerable judgement is required in describing mixtures. As a rough rule greater than approximately 35% of the finest classification present determines the dominant soil type. The following are some examples:

A soil with 40% clay and the rest silt and sand would be a 'silty CLAY' or a 'sandy silty CLAY'.

A soil with 20% clay and the remainder silt or silt and sand would be a 'clayey SILT' or a 'clayey, sandy SILT' or a 'clayey, silty SAND'

Soil type		Visual or tactile description
Boulders		Visible to naked eye
Gravel	Coarse	
	Medium	Particle shape: Angular, subangular, rounded, flat, elongated.
	Fine	
Sand	Coarse	Texture: Rough, smooth, polished
	Medium	
	Fine	Grading: well-graded – wide range of grain sizes. Poorly (uniformly) graded Gap-graded
Silt		Not visible to naked eye. Gritty to hand or teeth. Exhibits dilatancy when squeezed in hand. Disintegrates in water quickly.
Clay		Feels soapy when rubbed with water in the hand. Sticks to fingers and dries slowly. No dilatancy.
Organic soils		Contain substantial amounts of organic vegetable matter
Peats		Predominantly plant remains, dark brown or black. Low bulk density.

Table 3. Soil type

<u>O – Other features</u>

This descriptor is intended to remind the observer to look for any special or unusual features not covered by the other descriptors. For example the presence of roots, especially those so fine that they are barely visible, can have a profound influence on shrinking and swelling of clays. The presence of root holes will significantly affect the mass permeability of the ground. The presence of man made objects, ranging from stone age flints to modern artefacts will obviously provide important information about the origin of the soil horizons.

O – Origin

The origin, mode of formation and subsequent geological and more recent history can be of outstanding engineering importance both in terms of extrapolating experience from other similar deposits and for assessing engineering characteristics.

A full and accurate evaluation requires and expert geologist and at the very least the appropriate geological map and/or memoir should be consulted.

An attempt should be made to assess the genesis of the soil, and if possible, identify its geological name (e.g. London Clay, Ecca Shale, etc.) or stratigraphic unit. However, where there is doubt, the words 'thought to be', or 'possibly', should prefix the name in the recorded profile sheet.

In assessing the origin it is particularly important to distinguish between (i) sediments, (ii) residual soils and (iii) pedocretes.

(i) Sediments. Derived from materials transported in various ways. (Transported soils).

(ii) Residual soils. Soils remaining in-situ from the weathering of rocks. When such soils have been identified it is useful to assign 'weathering grades' to them in accordance with the appropriate standard.

(iii) Pedocretes. Soils which have become cemented or partially replaced by chemical action. Laterites, ferricretes, calcretesa and silicretes are examples of such soils.

W – Ground water

The ground water conditions at a given location are one of the most important factors determining ground behaviour and the description of the ground profile is incomplete unless reference has been made to them.

Where exploration is carried out using boring and sampling it is necessary to install standpipes to determine the water table. Drilling records, though worth taking, are not reliable for this purpose.

Trial pits and shafts are particularly valuable in assessing ground water conditions (e.g. level and rates of inflow, the influence of such seepage on the consistency and stability of the sides. Such information is vital for assessing construction difficulties.

If ground water is not encountered, a statement to this effect must be given on the profile sheet.

Fill

The engineering description of fill should follow the guidelines set out in the previous sections. Since deposits of fill may be very variable and the materials difficult to sample, their description is often best carried out using properly supported trial trenches. The following factors are of great importance:

(i) Degree of compaction. This is largely a function of the method of placement. A high density can be achieved when placed in thin layers and heavily compacted. However, waste material which is end tipped in high lifts without compaction will have a low density. End tipping into water will be particularly loose. A fine-grained waste material transported in suspension and left out to settle down produces a fill with a high moisture content and low undrained shear strength.
(ii) Nature of waste material. In recently-placed domestic refuse there is a large organic content and the material is liable to decay and decompose. However refuse more than about 30 years old is likely to consist predominantly of ashes which, when compact, can form a good foundation material. The chemical composition and the presence of combustible material are important considerations.
(iii) Depth. In general the deeper the waste deposit the more severe the problems the problems that are likely to be encountered. Sudden changes in depth of the waste fill can cause serious problems of differential settlement.
(iv) Age. The length of time that has elapsed since the waste material was placed is of particular significance, especially when the waste contains organic matter liable to rot or metallic objects likely to corrode and crush.
(v) Water table. The presence or absence of a water table within the waste fill is a factor of great importance. It should be established whether or not fluctuations in water level occur and in particular whether it is likely to rise in the future.

Recording the soil profile

When ground description is being carried out in a trial pit or down a trial shaft it is helpful to dictate to someone at the surface who can also be of assistance in reminding the observer of features to look for.

Once the various soil horizons in a soil profile have been examined and described the information should be recorded on a profile sheet.

It is helpful to have a legend down the left hand side of the sheet with symbols for the principal soil types encountered. The symbols for the different soils and rock types can be found in the appropriate standard (i.e. BS 5930:1999). In this way a good graphical picture emerges which is of the greatest importance when correlating a number of profiles on a given site and attempting to obtain a general picture with a view to planning additional exploration or as a starting point in the design process.

The writing on the profile sheets should be kept to a minimum – every word or symbol must have significance.

In addition to the descriptors above, the following should be also recorded:

(i) Positions and reference number of any soil samples
(ii) Brief reference to any equipment installed in the hole (e.g. standpipes, bench marks, etc)
(iii) In the case of a pit or shaft, the material on the bottom, the reason for stopping at that depth and the date the pit or shaft was open up.
(iv) The reduced level of ground surface.
(v) The initials of the observer and the date on which the profile was recorded.

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Appendices:

A1 Phase relations summary

Moisture content	$w = \frac{W_w}{W_s} = \frac{M_w}{M_s}$
Void ratio	$e = \frac{V_v}{V_s}$ $e = wG_s$ (saturated) $e = \frac{wG_s}{S_r}$ (partially saturated)
Porosity	$n = \frac{V_v}{V} = \frac{e}{1+e}$
Degree of saturation	$S_r = \frac{V_w}{V_v}$
Particle specific gravity	$G_s = \frac{W_s}{V_s \gamma_w} = \frac{M_s}{V_s \rho_w}$
Bulk density	$\rho_b = \rho_w \frac{(G_s + eS_r)}{1+e}$
Dry density	$\rho_d = \frac{\rho_w G_s}{1+e} = \frac{\rho_b}{1+w}$
Saturated density	$\rho_{sat} = \rho_w \frac{(G_s + e)}{1+e}$
Submerged density	$\rho' = \rho_w \frac{(G_s - 1)}{1+e}$
Bulk unit weight	$\gamma_b = \gamma_w \frac{(G_s + eS_r)}{1+e}$
Dry unit weight	$\gamma_d = \frac{\gamma_w G_s}{1+e} = \frac{\gamma_b}{1+w}$
Saturated unit weight	$\gamma_{sat} = \gamma_w \frac{(G_s + e)}{1+e}$
Submerged unit weight	$\gamma' = \gamma_w \frac{(G_s - 1)}{1+e}$

Phase relations matrix

	G_s	γ_d	γ_{sat}	w (Sat.)	n	e
$G_s,\ \gamma_d$			$\left(1-\frac{1}{G_s}\right)\gamma_d+\gamma_w$	$\frac{\gamma_w}{\gamma_d}-\frac{1}{G_s}$	$1-\frac{\gamma_d}{G_s\gamma_w}$	$\frac{G_s\gamma_w}{\gamma_d}-1$
$G_s,\ \gamma_{sat}$		$\frac{\gamma_{sat}-\gamma_w}{G_s-1}G_s$		$\frac{\gamma_w-\gamma_{sat}/G_s}{\gamma_{sat}-\gamma_w}$	$\frac{G_s-\gamma_{sat}/\gamma_w}{G_s-1}$	$\frac{G_s\gamma_w-\gamma_{sat}}{\gamma_{sat}-\gamma_w}$
$G_s,\ w$		$\frac{G_s}{1+wG_s}\gamma_w$	$\frac{1+w}{1+wG_s}G_s\gamma_w$		$\frac{wG_s}{1+wG_s}$	wG_s
$G_s,\ n$		$G_s(1-n)\gamma_w$	$(G_s-n(G_s-1))\gamma_w$	$\frac{n}{(1-n)G_s}$		$\frac{n}{1-n}$
$G_s,\ e$		$\frac{G_s}{1+e}\gamma_w$	$\frac{G_s+e}{1+e}\gamma_w$	$\frac{e}{G_s}$	$\frac{e}{1+e}$	
$\gamma_d,\ \gamma_{sat}$	$\frac{\gamma_d}{\gamma_d+\gamma_w-\gamma_{sat}}$			$\frac{\gamma_{sat}}{\gamma_d}-1$	$\frac{\gamma_{sat}-\gamma_d}{\gamma_w}$	$\frac{\gamma_{sat}-\gamma_d}{\gamma_d+\gamma_w-\gamma_{sat}}$
$\gamma_d,\ w$	$\frac{\gamma_d}{\gamma_w-w\gamma_d}$		$(1+w)\gamma_d$		$w\frac{\gamma_d}{\gamma_w}$	$\frac{w\gamma_d}{\gamma_w-w\gamma_d}$
$\gamma_d,\ n$	$\frac{\gamma_d}{(1-n)\gamma_w}$		$\gamma_d+n\gamma_w$	$\frac{n\gamma_w}{\gamma_d}$		$\frac{n}{1-n}$
$\gamma_d,\ e$	$(1+e)\frac{\gamma_d}{\gamma_w}$		$\frac{e\gamma_w}{1+e}\gamma_d$	$\frac{e}{1+e}\frac{\gamma_w}{\gamma_d}$	$\frac{e}{1+e}$	
$\gamma_{sat},\ w$	$\frac{\gamma_{sat}}{\gamma_w+w(\gamma_{sat}-\gamma_w)}$	$\frac{\gamma_{sat}}{1+w}$			$\frac{w\gamma_{sat}}{(1+w)\gamma_w}$	$\frac{w\gamma_{sat}}{\gamma_w-w(\gamma_{sat}-\gamma_w)}$
$\gamma_{sat},\ n$	$\frac{\gamma_{sat}-n\gamma_w}{(1-n)\gamma_w}$	$\gamma_{sat}-n\gamma_w$		$\frac{n\gamma_w}{\gamma_{sat}-n\gamma_w}$		$\frac{n}{1-n}$
$\gamma_{sat},\ e$	$(1+e)\frac{\gamma_{sat}}{\gamma_w}-e$	$\gamma_{sat}-\frac{e}{1+e}\gamma_w$		$\frac{e\gamma_w}{\gamma_{sat}+e(\gamma_{sat}-\gamma_w)}$	$\frac{e}{1+e}$	
$w,\ n$	$\frac{n}{(1-n)w}$	$\frac{n}{w}\gamma_w$	$n\frac{1+w}{w}\gamma_w$			$\frac{n}{1-n}$
$w,\ e$	$\frac{e}{w}$	$\frac{e}{(1-e)w}\gamma_w$	$\frac{(1+w)e}{(1+e)w}\gamma_w$		$\frac{e}{1+e}$	

A2: Soil classification tables.

British Soil Classification System BS5930

Soil groups			Subgroups and laboratory identification			
GRAVEL and SAND may be qualified sandy GRAVEL and gravelly SAND, etc., where appropriate			Group symbol	Subgroup symbol	Fines (% less than 0.06 mm)	Liquid limit
COARSE SOILS less than 35% of the material is finer than 0·06 mm	GRAVELS More than 50% of coarse material is of gravel size (coarser than 2 mm)	Slightly silty or clayey GRAVEL	GW G GP	GW GPu GPg	0 to 5	
		Silty GRAVEL Clayey GRAVEL	G–M G–F G–C	GWM GPM GWC GPC	5 to 15	
		Very silty GRAVEL Very clayey GRAVEL	GM GF GC	GML, etc GCL GCI GCH GCV GCE	15 to 35	
	SANDS More than 50% of coarse material is of sand size (finer than 2 mm)	Slightly silty or clayey SAND	SW S SP	SW SPu SPg	0 to 5	
		Silty SAND Clayey SAND	S–M S–F S–C	SWM SPM SWC SPC	5 to 15	
		Very silty SAND Very clayey SAND	SM SF SC	SML, etc SCL SCI SCH SCV SCE	15 to 35	
FINE SOILS more than 35% of the material is finer than 0·06 mm	Gravelly or sandy SILTS and CLAYS 35% to 65% fines	Gravelly SILT Gravelly CLAY	MG FG CG	MLG, etc CLG CIG CHG CVG CEG		 < 35 35 to 50 50 to 70 70 to 90 > 90
		Sandy SILT Sandy CLAY	MS FS CS	MLS, etc CLS, etc		
	SILTS AND CLAYS 65% to 100% fines	SILT (M-SOIL) CLAY	M F C	ML, etc CL CI CH CV CE		 < 35 35 to 50 50 to 70 70 to 90 > 90
ORGANIC SOILS		Descriptive letter 'O' suffixed to any group or subgroup symbol				
PEAT		Pt				

United States Classification System: ASTM STANDARD D2487

MAJOR DIVISIONS			GROUP SYMBOLS	TYPICAL NAMES	CLASSIFICATION CRITERIA		
COARSE-GRAINED SOILS MORE THAN 50% RETAINED ON NO. 200 SIEVE	GRAVELS 50% OR MORE OF COARSE FRACTION RETAINED ON NO.4 SIEVE	CLEAN GRAVELS	GW	Well-graded gravels and gravel-sand mixtures, little or no fines	CLASSIFICATION ON BASIS OF PERCENTAGE OF FINES LESS THAN 5% PASS NO. 200 SIEVE: GW, GP, SW, SP MORE THAN 12% PASS NO. 200 SIEVE: GM, GC, SM, SC 5% TO 12% PASS NO. 200 SIEVE: BORDERLINE CLASSIFICATION REQUIRING USE OF DUAL SYMBOLS	$C_u = D_{60}/D_{10}$ Greater than 4 $C_z = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			GP	Poorly graded gravels and gravel-sand mixtures, little or no fines		Not meeting both criteria for GW	
		GRAVELS WITH FINES	GM	Silty gravels, gravel-sand-silt mixtures		Atterberg limits plot below "A" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.
			GC	Clayey gravels, gravel-sand-clay mixtures		Atterberg limits plot above "A" line or plasticity index less than 7	
	SANDS MORE THAN 50% OF COARSE FRACTION PASSES NO.4 SIEVE	CLEAN SANDS	SW	Well-graded sands and gravelly sands, little or no fines		$C_u = D_{60}/D_{10}$ Greater than 6 $C_z = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			SP	Poorly graded sands and gravelly sands, little or no fines		Not meeting both criteria for SW	
		SANDS WITH FINES	SM	Silty sands, sand-silt mixtures		Atterberg limits plot below "A" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.
			SC	Clayey sands, sand-clay mixtures		Atterberg limits plot above "A" line & plasticity index greater than 7	
FINE-GRAINED SOILS 50% OR MORE PASSES NO. 200 SIEVE	SILTS AND CLAY LIQUID LIMIT 50% OR LESS		ML	Inorganic silts, very fine sands, rock flour, silty or clayey fine sands			
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			OL	Organic silts and organic silty clays of low plasticity			
	SILTS AND CLAY LIQUID LIMIT GREATER THAN 50%		MH	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts			
			CH	Inorganic clays of high plasticity, fat clays			
			OH	Organic clays of medium to high plasticity			
HIGHLY ORGANIC SOILS			PT	Peat, muck, and other highly organic soils			