Chapter 1   Physical properties of soils

1.1   Introduction

Any rock exposed to the Earth's surface undergoes weathering process, which results in the formation of discrete solids with various sizes. Under the action of wind flowing water, gravity, active glacier, these solids are subsequently carried to a new location where the deposition occurs. The deposits may eventually be transformed into sedimentary rocks under the action of diagenesis. However, for deposits without being subjected to sufficient compaction and crystallization, the soil forms.

Soil is regarded as an assemblage of solid solids, which are bonded together by attractive force (electrostatic force, chemical bonds, apparent force) and intergranular friction. The voids among solids can be filled either with water or air or even both of them.

To master the behavior of a typical natural composite, it is necessary to study soil's composition, structure, relative content, as well as the interaction between each phase. To facilitate the description, certain indices measured either *in-situ* or in the laboratory, are necessary.

After studying this chapter, you are capable of:

- 1
- 2

1.2   Formation of soils

1.2.1 Origin of soils

The rock cycle in the following figure indicates the origin of soil. Igneous rock (i.e. basalt, granite), sedimentary rock (i.e. sandstone, shale, limestone) and metamorphic rock (quartzite, slate, gneiss) contribute to soil when they are exposed to Earth's surface by uplift action. The solid rocks on the surface of the ground are susceptible to all kinds of long-time attacks, like erosion by wind and acid water, thermal expansion and contraction, and intrusion of plant roots, all these processes belong to weathering process. The principal result of the weathering process is the formation of discrete solids with various sizes. Depending on whether the solids are transported or not, soils are generally divided into transported soil and residual soil:

1) **Residual soil**: It is the soil that formed by the products after weathering process, which remain in the same position as their parent rocks. Typical

features of residual soil are: 1) A wide range of solid sizes; 2) Irregular shape; 3) Rough surface; 4) No foliation;

2) **Transported soil**: It is the soil formed by the products after weathering process, which are moved from their original location to new locations by one or more of the transportation agencies, e.g., water, glacier, wind, and gravity. The transportation process plays an important role in casting the size, shape, surface texture and degree of sorting of solids. Normally, the further the distance, the more chance for solids to interact and collide with one another. Therefore, with the increasing distance of transportation, the solids become smaller, rounder and smoother. Moreover, larger particles are more susceptible to settle than smaller particles during transportation, which lead to certain gradation of solids.
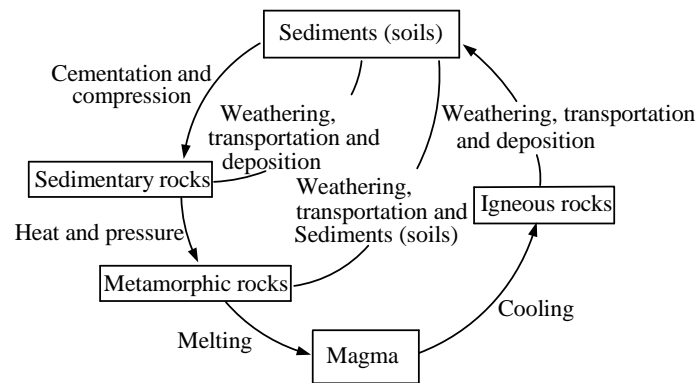

Fig. 1-1 Schematic diagram of rock cycle

1.2.2 Types of transported soils

According to the means of transportation, the soil can be further divided into water-deposited soil, wind-transported soils, glacier-deposited soils and gravity-deposite soils:

■ **Water deposited soil**: The flowing water is capable of displacing solid. The size of solids ranges from boulders to clay. The carrying capacity highly depends on the velocity of the moving water. Therefore, coarser solids are dropped when water velocity decreases, while fine solids still remain in suspension. Under different water environments, fresh water usually forms alluvial deposit (e.g., shale and silt) and lacustrine deposit (e.g., varved marl), while marine water usually forms marine deposit (e.g., marine clay and marl);

■ **Wind transported soil**: The transportation process by wind is almost the same

as that of by water except that it occurs in arid regions. This kind of soil has low density and is highly compressible. Aeoline deposits (e.g., loess and sand dune) are typical wind transported soil;

■ **Glacier deposited soil**: The extremely slow moving glaciers on earth also have the capacity to carry soils of various sizes ranging from clay to boulders. When the glacier melts, large volume solids deposit. Glacial deposits (e.g., eskers, drumlins and glacial till) are typical glacier deposited soil;

■ **Gravity deposited soil**: the weathering products can be move under the action of gravity or short-term water flow (rainfall, melting of snow or ice). Solids can be moved only a very small distance in this case. Colluvial deposits (e.g., talus) at the toe of the slop is a typical gravity deposited soil.

According to the principle of superposition in stratigraphy, the soil layer at the top is always the youngest one if it is not subjected to any tectonically disturbance. If there is no otherwise statement, the soil encountered in the practical engineering belong to the Quaternary period, Holocene and Pleistocene epoch.

Tab. 1-1 Subdivision of quaternary stratigraphy

表 1-1 土的生成年代

纪（或系）	世（或统）		年代（距今）
第四纪（Q）	全新世（Q_4）	Q_4^3（晚期）	<0.25 万年
		Q_4^2（中期）	0.75～0.25 万年
		Q_4^1（早期）	1.3～0.75 万年
	更新世（Q_p）	晚更新世（Q_3）	12.8～1.3 万年
		中更新世（Q_2）	71～12.8 万年
		早更新世（Q_1）	距今 71 万年以前

纪（或系）	世（或统）		年代（距今）
第四纪（Q）	全新世（Q_4）	Q_4^3（晚期）	<0.25 万年
		Q_4^2（中期）	0.75~0.25 万年
		Q_4^1（早期）	1.3~0.75 万年
	更新世（Q_p）	晚更新世（Q_3）	12.8~1.3 万年
		中更新世	71~12.8 万年

| | | (Q_2) | |
| | | 早更新世 (Q_1) | 距今 71 万年 以前 |

1.3 Composition of soil

Soil is regarded as a three-phrase composite with solid solids form the skeleton. The void part is filled with water and air. If the void is filled water or air or both of them, we call it **saturated soil** or **dry soil** or **partially saturated soil** correspondingly.

The interaction among three phrases together with the properties themselves have a great impact on the engineering properties of soil. Therefore, for further study the behavior of soil, it is necessary to have a full insight of its composition.

1.3.1 Solid phase

The solid part plays a key role in the behavior of soil as it forms the skeleton. To obtain the complete information of the solid part, we need to know: 1) Gradation, namely classification of the solid size distribution; 2) Mineral composition; 3) Shape of solids.

1.3.1.1 The gradation

Although the solids play a distinguish role in determine the behavior of soil, study them one by one is almost impossible and needless. In fact, those solids with small gap in size possess almost the same properties. On the basis of the solid size of the solids, common used term in soil mechanics are gravel, sand, silt, and clay. Figure 2.9 shows those names with ranges of solid size. Note that, different standards may have different definitions. For example, 2.0 mm in AASHTO or 4.75 mm in USCS (Unified Soil Classification System) and in the ASTM Soil Classification System are the boundary solid sizes between gravel and sand. 75 μm (0.075 mm) is the boundary between sand and silt in both standards, and 5 μm is the one between silt and clay in AASHTO. In USCS (and also in ASTM), materials that are finer than 75 μm are called "fine."

In general, soils mainly made up of gravel and sand are cohesionless, while those whose main constituents are silt and clay are cohesive. Therefore, to obtain the information of whole soil mass, it is necessary to obtain the mass percentage of different constituent (gradation). That is why the solid size analysis needs to be perfomed.

The widely used methods to determine gradation of soil mass are sieve analysis and hydrometer analysis. The former one is suitable for solids with larger size (>= 75

μm), while the latter one is applied to solids whole size is under 75 μm.
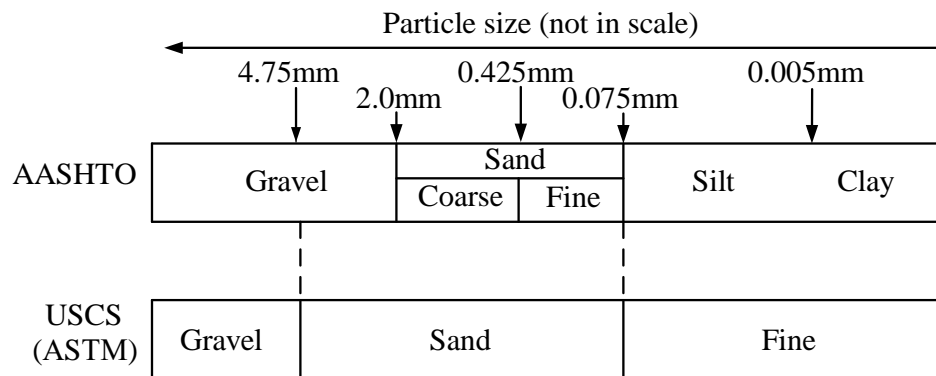
Particle size (not in scale)

Fig. 1-2 Gradation of soils

1.3.1.2 Sieve analysis

The sieve analysis is carried out with a mechanical shaker and a group of standard sieves as Fig. 1-3 shows. The opening of sieves progressively decreases in size from top to bottom. A receiving pan is installed at the bottom of the stack. Typical procedures of a sieve analysis are as follows:

1) Take a small portion of crushed dry soil sample and weigh its weight;

2) Vibrate the whole a stack of sieves with lid and receiving pan vertically and horizontally for no less than 8 minutes;

3) Weigh the mass of soil sample retained on each sieve and determine the corresponding fraction, namely the mass of soil sample retained on each sieve over the total mass of the soil sample;

4) Determine the percentage finer, which means the mass percentage of soil solids passing through the corresponding sieve;

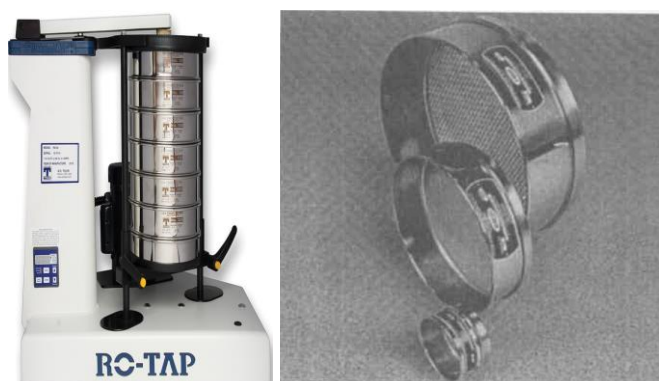5) The soil rest on the receiving pan is further analyzed by a hydrometer test.

Fig. 1-3 Schematic diagram of sieve shaker and sieves

Example 1.3-1

Taken 1000g dry soil sample for sieve analysis, the weight retained on each sieve is as the second column of Tab. 1-2 shows. Determine the percentage retained on any sieve and cumulative percentage retained on any sieve, as well as percentage finer than any sieve.

Tab. 1-2 Computation of sieve analysis

Opening (mm)	Weigh retained (g)	Percentage retained (%)	Cumulative percentage retained (%)	Percentage finer (%)
2	100	10	10	90
1	100	10	20	80
0.5	250	25	45	55
0.25	300	30	75	25
0.15	100	10	85	15
0.075	50	5	90	10
Receiving pan	100	10	100	

Solution

The percentage retained on any sieve and cumulative percentage retained on any sieve, as well as the percentage finer than any sieve can be expressed as:

■ Percentage retained on any sieve $= \dfrac{\text{mass of soil retained}}{\text{total soil mass}} \times 100$

■ Cumulative percentage = Sum of percentages retained on
  retained on any sieve   all coarse sieves

■ Percentage finer than = 100 percent minus cumulative
  any sieve   percentage retained

According to the above definitions, corresponding results are obtained as Tab. 1-2 shows.

1.3.1.3 Hydrometer analysis

After the sieve analysis, the hydrometer analysis is then carried out for the solids rested on the pan. A typical hydrometer analysis test setup is shown. The theoretical foundation for hydrometer analysis is Stoke's law, which expresses that the force on a small sphere, sinking in a viscous fluid, depends upon the viscosity of the fluid, the size of the sphere and the velocity, according to the equilibrium of each solid (suspension):

The velocity of sinking of a solid in certain fluid can be expressed as:

$$v = \frac{\left(\gamma_p - \gamma_f\right)}{18\mu} D^2 \qquad (1\text{-}1)$$

From the above formula, the dimeter of solids can be determined. According to

(ASTM 2004), in the hydrometer laboratory test, a dry soil specimen weighing 50 g is mixed thoroughly with water and placed in a graduated 1000-mL glass flask. A floating instrument called a hydrometer is placed in the flask to measure the specific gravity of the mixture in the vicinity of the hydrometer center. In a 24-hour period the time t and the corresponding depth L are recorded. The measured depth is correlated with the amount of soil that is still in suspension at time t. From Stokes' law, it can be shown that the diameter of the largest soil solids still in suspension is given by:

$$D = \sqrt{\frac{18\eta}{\left(\dfrac{\rho_s}{\rho_w}-1\right)\gamma_w}\frac{L}{t}} \qquad (1\text{-}2)$$

Form the above formula, we can calculate the mass percentage of solids whose solids size are finer than D.
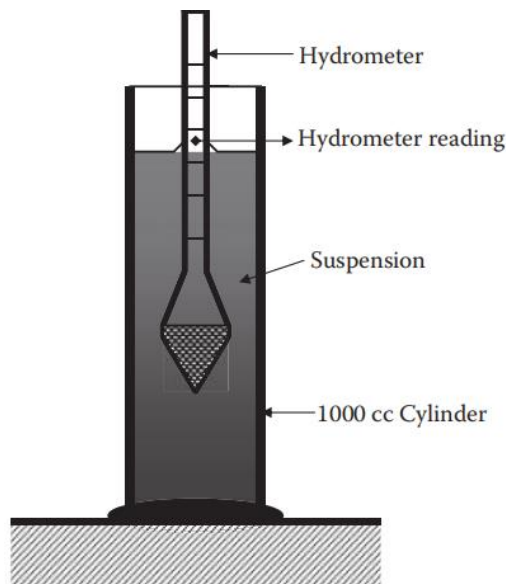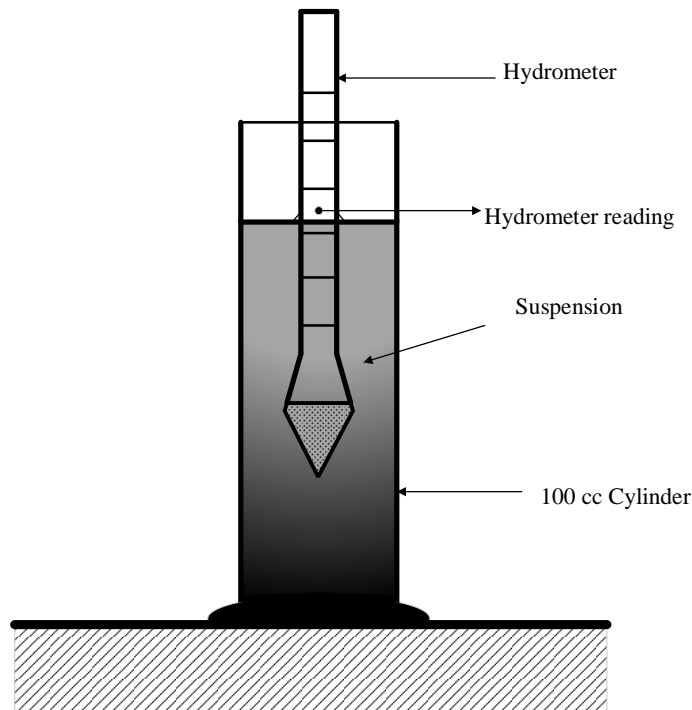
Fig. 1-4 Hydrometer test setup

1.3.1.4 Solid size distribution curve

With the data from sieve analysis and hydrometer analysis, the relationship between the sieve opening and the percentage finer are plotted in a semi-log scale to generate solid size distribution curve as Fig. 1-5 shows.

With this curve, the behavior of the soil can be analyzed qualitatively and quantitatively. From a qualitative point of view, a steep slope of the curve indicates a uniform soil, while a gentle slope of the curve indicates that the soil contains solids of strongly different solid sizes. In certain curves, there may be a platform, which indicates the solid size in that range is missing. From an engineering point of view, the soil mass with nonunion distribution of solids are better.

From a quantitative point of view, the behavior of the soil can be analyzed as:

1) The contents of the corresponding soil type (according to critical solid size) can be directly obtained. Then the behavior of soil can be approximately evaluated.

2) Evaluate the gradation of the soil mass. It is widely accepted that well graded soils can be easily compacted and accordingly, they possesses low permeability and high strength. On the contrary, poorly graded soils are hard to be compacted. Therefore, they have high permeability and low strength.

The first object is somewhat straightforward. To achieve the second object, several key solid sizes are needed to be fixed: D_{10}, D_{30}, and D_{60}, which are the solid sizes corresponding to 10%, 30%, and 60% finer by weight, respectively. D_{10} and D_{60} are

also known as effective solid size and controlling solid size. With the above three critical size, two additional coefficients: coefficient of uniformity C_u and coefficient of gradation C_c are defined as:

$$C_u = \frac{D_{60}}{D_{10}} \tag{1-3}$$

According to the Unified Soil Classification System, $C_u < 4$ for gravels and $C_u < 6$ for sands are classified as uniformly graded soil, while those with higher than 4 for gravels and 6 for sands are classified as well-graded soil:

The coefficient of gradation is defined according to key solid sizes as:

$$C_g = \frac{(D_{30})^2}{D_{10} \cdot D_{60}} \tag{1-4}$$

The soils with C_g less than 1 or higher than 3 are classified as gap-graded soils, while those with C_g larger than 1 but less than 3 are classified as well-graded soils.

As we can see, both the coefficient of uniformity C_u and Coefficient of gradation C_g affect the gradation of the soil mass. Therefore, the soil with well-graded characteristics need to satisfy:

For gravels: $C_u > 4$ and $1 < C_g < 3$. If both of these criteria are not met, the gravels are classified as poorly graded. If both of these criteria are met, the gravels are classified as well graded. For sands: $C_u \geq 6$ & $1 < C_g < 3$. If both of these criteria are not met, the sands are classified as poorly graded or. If both of these criteria are met, the sands are classified as well graded.
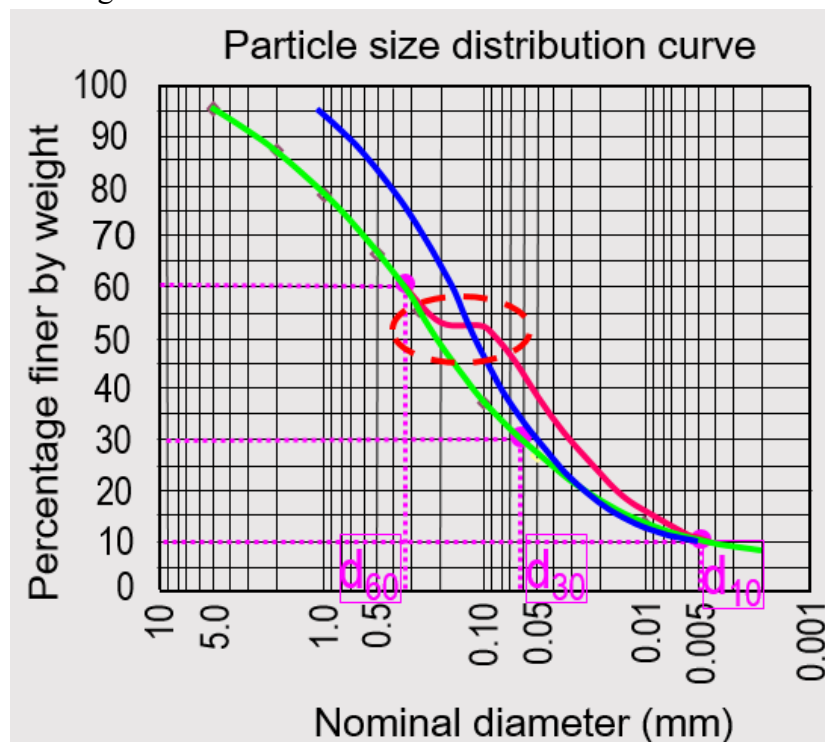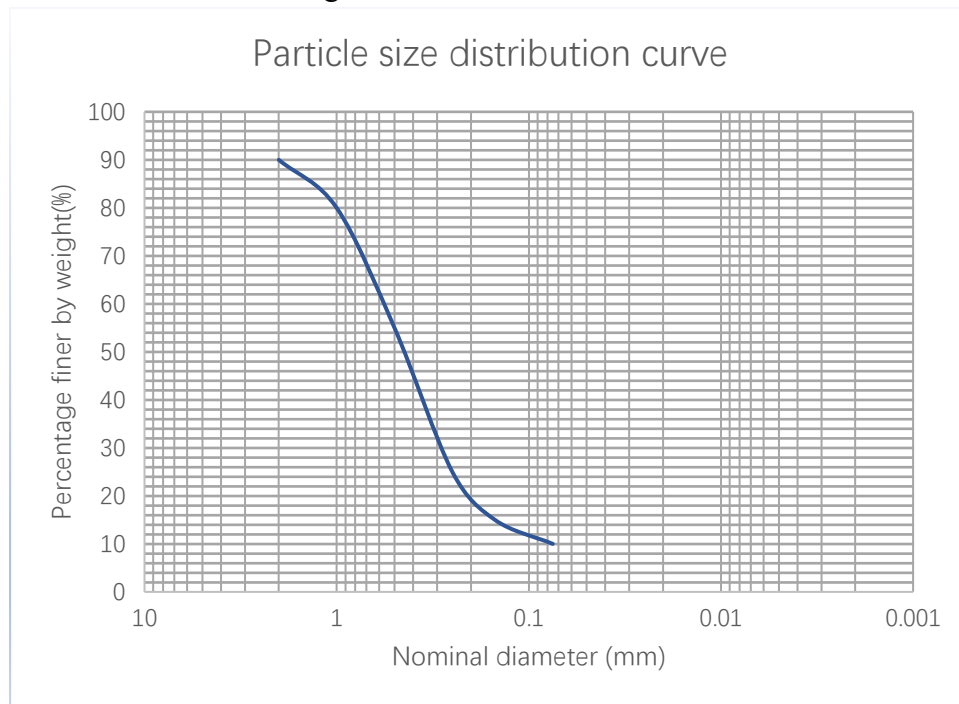
Fig. 1-5 Solid size distribution curve

Particle size distribution curve

1.3.1.5 The chemical composition

Except the organic matter, the solid part of soils are formed by minerals, which are inorganic solids with a specific internal structure and a definite chemical composition. The types of minerals in soil can be divided into two main types: 1) Primary mineral: pieces broken from the parent rock (physical weathering); relatively large (>0.002mm in diameter); cohesionless; generally rounded or angular in shape; weak water adsorption capacity; no plasticity. The representative minerals are quartz, feldspar, mica, without plasticity; 2) Secondary mineral. mainly formed during the chemical weathering of primary minerals. Relative small (<0.002mm in diameter); commonly in flat plate (needles, tubes, rods); unstable; high water adsorption capacity; swell; plasticity. Solid shapes are much flatter and sometimes flaky.

Among various types of secondary minerals, clay minerals are the most common ones, which have distinctive features as compared to primary minerals. The representative minerals are kaolinite, montmorillonite and illite. In general, the clay minerals possess large specific surface area and therefore they are more susceptible to interact with water, i.e. Montmorillonite increases greatly in volume when it absorbs water. Moreover, for solids with relative small size (<0.002mm in diameter), electrical interactive force is far more significant as compared to the physical frictional interactive forces.

To understand various unique engineering behaviors of clay, it is most beneficial to study microstructures of clay mineral solids first. Various spectroscopic methods as SEM-EDS or automated mineralogy processes show that these minerals are compounds of aluminum with hydrogen, oxygen and silicates. Clay minerals are fundamentally built of tetrahedral silicate sheets and octahedral hydroxide sheets, which are the periodically arrangement of tetrahedral silicate and octahedral hydroxide in space, as Fig shows. Clay minerals can be classified as 1:1 or 2:1. A 1:1 clay would consist of one tetrahedral sheet and one octahedral sheet, and examples would be kaolinite. A 2:1 clay consists of an octahedral sheet sandwiched between two tetrahedral sheets, and examples are talc, vermiculite, and montmorillonite. Detail information are as follows:

- **Kaolinite**: its basic unit is formed by one tetrahedral sheet and one octahedral sheet to make a two-layer stack. The bond between these two sheets are atomic bond, which has high strength. Many stacks (may hundreds of stacks) of the basic unit forms the kaolinite clay. The bond between the basic unit is hydrogen bond, which also has high strength. As all bounds of kaolinite are tight, water is hard to penetrate. According to above mentioned features, the kaolinite clay have: 1) large size; 2) no swell or shrinkage when intervene with; water; 3) low water-binding capacity.

- **Montmorillonite**: its basic unit is formed by two tetrahedral sheet and one octahedral sheet to make a three-layer stack. Many stacks (about 50 stacks of layers) of the basic unit forms the Montmorillonite clay. The bond between the basic unit is Van der waal's force, which has low strength. As the basic unit are not tightly bounded, water is easy to penetrate. According to above mentioned features, the kaolinite clay have: 1) small size; 2) obvious swell or shrinkage when intervene with; water; 3) high water-binding capacity.

- **Illite**: its microstructure is similar to Montmorillonite except the bond between basic unit is ionic bond, which is higher than Van der waal's force but lower than hydrogen bond. Therefore, The characteristics of this clay are classified as in between those of kaolinite and montmorillonite
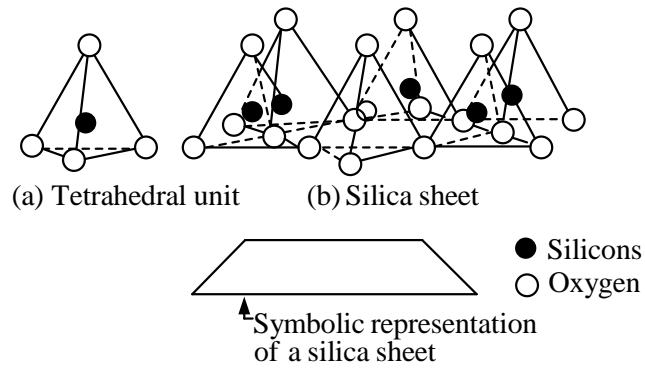
(a) Tetrahedral unit   (b) Silica sheet

● Silicons
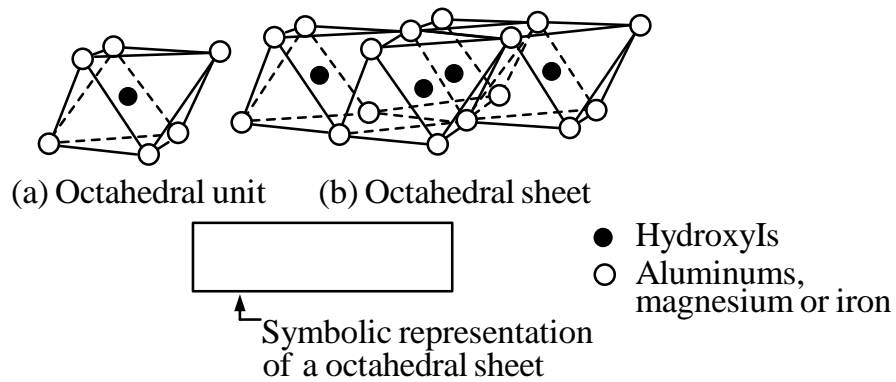○ Oxygen

Symbolic representation
of a silica sheet

Fig. 1-6 Basic structure units in the silicon sheet

(a) Octahedral unit   (b) Octahedral sheet

● HydroxyIs
○ Aluminums,
   magnesium or iron

Symbolic representation
of a octahedral sheet

Fig. 1-7 Basic structure units in octahedral sheet

Ionic bond

Hydrogen bond

Gibbsite sheet

Silica sheet

7Å

7Å

7Å
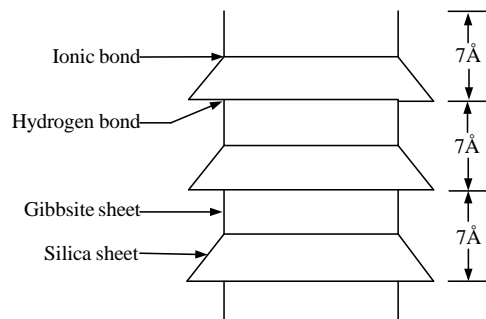
Figure 2.4   Structure of kaolinite layer

Fig. 1-8 Basic structure of kaolinite

Very poor bond

Gibbsite sheet
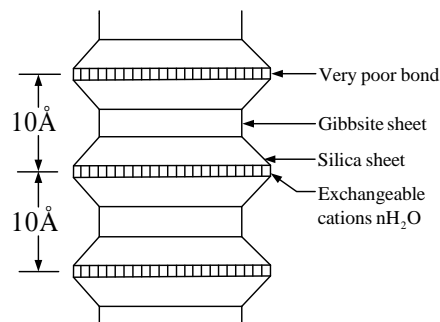
Silica sheet

Exchangeable
cations nH_2O

10Å

10Å

Figure 2.5   Structure of montmorillonite layer

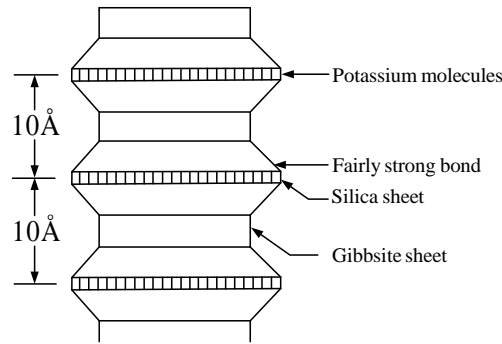Fig. 1-9 Basic structure of montmorillonite

Figure 2.6 Structure of ilite layer

Fig. 1-10 Basic structure of illite

1.3.1.6 The charge on the surface of clay solids

Studies have shown that clay minerals possess a net negative charge on their surface. Main reasons are (李广信): 1) Dissociation. Certain clays dissociate in natural water. After the dissociation, positive charged ions (cations) migrate to water while the negative charged ions (anions) are left; 2) Adsorption. As the clay miners have large specific surface area and accordingly, they have high adsorption capacity. The delocalized ions may be attracted to the surface of solids; 3) Isomorphous substitution. The replacement of silica (Si^{4+}) by lower valence aluminum (Al^{3+}) without changing clay mineral's crystal structure is called isomorphous substitution. The imbalance replacement of the cations leads to whole clay solid negatively charged. Studies also showed that the most recently broken edge of clay solids possess positive charge. Therefore, there must be complex interactive force (attractive or repulsive) when solids are brought together, which may play an important role in forming the clay structures.
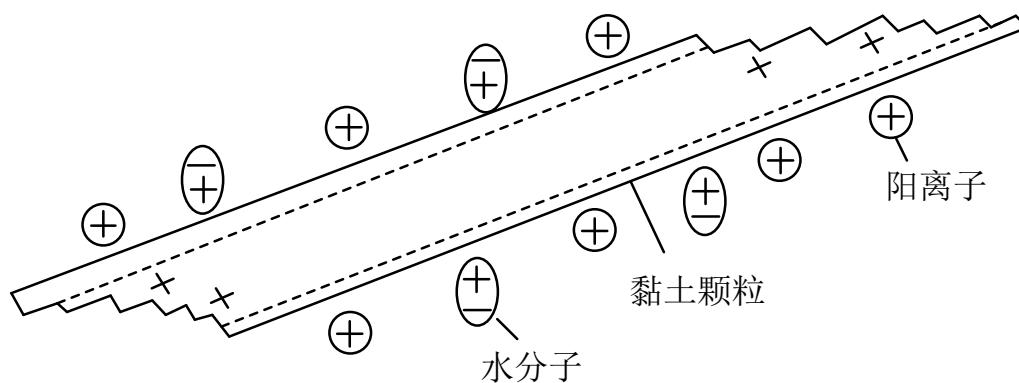

Fig. 1-11 Charge on the surface of clay solids

1.3.1.7 The shape of solids

For solids of gravel and sand, their shapes change from angularity to well rounded depending on the degree of weathering and transportation processes. In general, the

longer time of weathering process and further distance of transportation, the smaller and less irregularities of solids. Comparing with gravity of solids, attractive forces are negligible. Interlocking between solids and contact mechanism determine the mechanical behavior, e.g. strength, rigidity, permeability and compaction.

For silt and clay, their shapes are much flatter. As mention above, the surface of these kinds of solids possess charge. Therefore, short range intersolid forces play an important role.
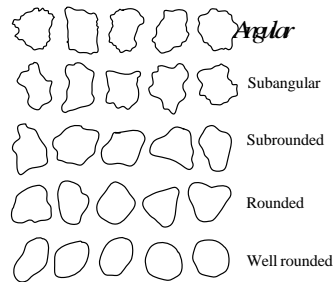

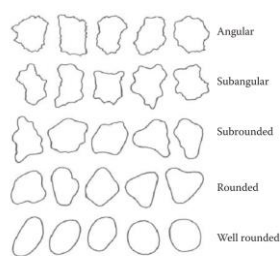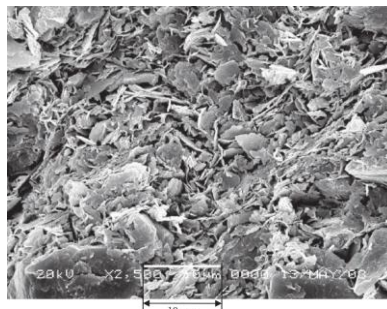FIGURE 2.2   Soil's angularity. (Miller, G, 1967, Methods in Sedimentary Petrology, Hafner.)

Fig. 1-12 Angularity of soil

1.3.2 Liquid phase

Apart from a small portion of water existing in the crystalline structure of certain minerals (water of water of crystallization), water in soils are either hygroscopic water (also named as bounded water) or gravitational water. The water in soil play a profound role in the behavior of soil as it interact with solids.

1.3.2.1 Adsorbed water

As stated above, clay minerals possess a net negative charge on their surface. In this case, the positively charged ions (cations due to ionization or electrolysis) and positive edges of dipoles (water molecules) are attracted to its surface. The thickness of the water layer may reach $10A^o$. According to the Coulomb's law, i.e., the closer two charges are, the stronger electrostatic force between them, the electrostatic force between the dipoles in the vicinity of mineral surface and clay mineral may reach 1000MPa. With the increasing distance of dipoles from the mineral surface, the

interaction force decreases rapidly. The electrically attracted water that surrounds the clay solid is known as the diffused double-layer of water. The water located within the zone of influence is known as the adsorbed layer as shown in Fig. 2.7. According to the magnitude of the electrostatic force, the adsorbed water can be further divided into strong adsorbed water and weak adsorbed water

- ■ Strong adsorbed water：For the inner layer, the water there have the property of a solid due to the strong electrostatic force. Density>1g/cm3 Freezing point below 0o, while boiling point above 100o

- ■ Weak adsorbed water: For the outer layer, the water behavior as a very viscous liquid. However, it could not move under the action of gravity. The thickness of the layer varies under the action of load and the layer could shift from one solid to another. The existence of the weak adsorbed water explains the plasticity of clay.

The adsorbed film of water on coarse solids is thin in comparison with the diameter of the solids. In fine solided soils, however, this layer of adsorbed water is relatively much thicker and might even exceed the size of the solid. The forces associated with the adsorbed layers therefore play an important part in determining the physical properties of the very fine-solided soils, but have little effect on the coarser soils
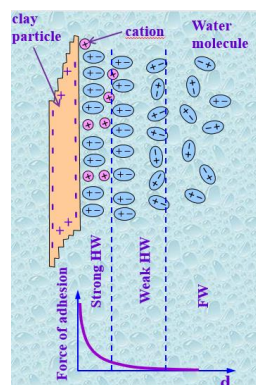

Fig. 1-13 Illustration of the electrical double-layer model

1.3.2.2 Free water

Beyond the zone of electrostatic action, the water is called free water, which can be further categorized into capillary water and gravitational water.

1.3.2.3 Capillary water

The interconnect voids within soils form vessel with different diameter. Due to the adhesion of water, it will stick to the wall of a vessel. This will cause an upward force on the liquid at the edges. The surface tension will rise water to certain height, which is above the phreatic surface. The height can be calculated as:

$$h_c = \frac{2T\cos\alpha}{r \cdot \gamma_w} \qquad (1\text{-}5)$$

According to the expression, the height is in close relation to the size and shape of the void, the mineral composition of the soil solids, and the nature of the water. The finer the soil solids, the higher the capillary water rises. For cohesive soil, the capillary water may rise up to 1m or even a few meters, while for the cohesionless soils, there is almost no capillary water.
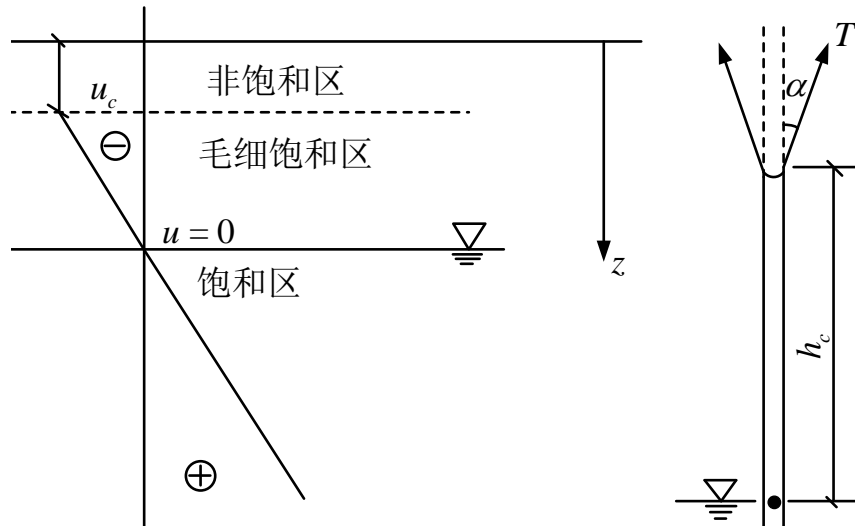

Fig. 1-14 Illustration of capillary water

1.3.2.4 Gravitational water

The water flows under the action of gravity or water head difference is called gravitational water. It has the property of normal water, i.e. it could transmit both hydrostatic and dynamic pressure, exert buoyancy on solids, dissolve or precipitate the soluble salt in the soil, exert drag force (hydrodynamic pressure) on solids in the direction of flow.

It is worth noting that water cannot bear the shear force, but it can withstand the pressure and suction. Meanwhile, the compressibility of water is negligible under normal circumstance.

1.3.3 Gaseous phase

The main components of gas within the soil is air. There may be hydrogen sulfide, carbon dioxide and biogas. The gas in soil can be categorized into connected gas and entrapped one.

For soils with low water content, the gas is connected to the atmosphere. The gas is discharged as soon as the external load is applied. With the increase of water content, there will be entrapped gas, which dissolve with water when loading while recover to

its origin state when the load is released. In this case, the entrapped gas have a greater impact on the behavior of soils. e.g. it increases the elasticity of soils, block the flow path and accordingly reduce the permeability.

1.4 Physical indices

Nine indices will be introduced., which can be classified into two kinds: 1) those quantities which we call independent indices can be measured experimentally; 2) and the quantities which we call dependent indices can be derived from independent ones. To make the definition of indices and the derivation more conveniently, three-phase diagram is introduced, which is schematic representation of the corresponding space of solid and void (air and water) as Fig. 1-15 shows.

The quantities representing the volume are drawn on the right, while those representing the mass are drawn on the left. The subscripts s, w and a represent solid, water and air. The volume of void V_v is the volume of water V_w plus the volume of air V_a. Note that the mass of air m_a is assumed zero.
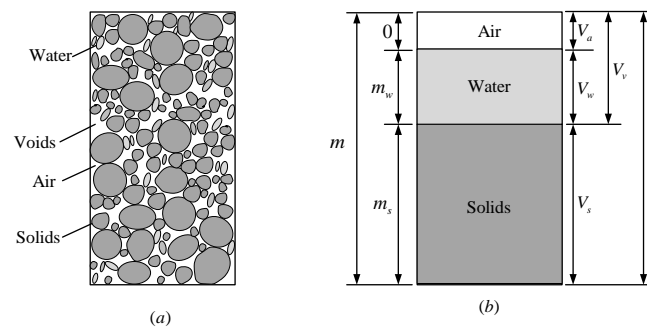
Fig. 1-15 a) Composition of soil; b) Three phase diagram

1.4.1 Independent indices

1.4.1.1 Bulk density

Bulk density ρ is defined as the mass of soil sample over its volume:

$$\rho = \frac{m}{V} \tag{1-6}$$

The unit of the bulk density is kg/m^3 or g/cm^3. Usually, the bulk density is measured by cutting ring method in laboratory. The general procedures are as follows:

1) Measure the mass of the cutting ring m_1;
2) Drive the cutting ring into the soil sample;
3) Remove the excess soil from the cutting ring to make the two ends as smooth as possible. Weigh the total mass m_2;
4) Determine the bulk density according to Eq. (1-6);

$$\rho = \frac{m}{V} = \frac{m_2 - m_1}{V}$$

V is the volume of the cutting ring, which is usually a constant (60cm^3). In practical engineering, the bulk unit weight γ is related to the bulk density as:

$$\gamma = \rho \cdot g \qquad (1\text{-}7)$$

$g = 10\,\text{N/kg}$ is the acceleration of gravity.
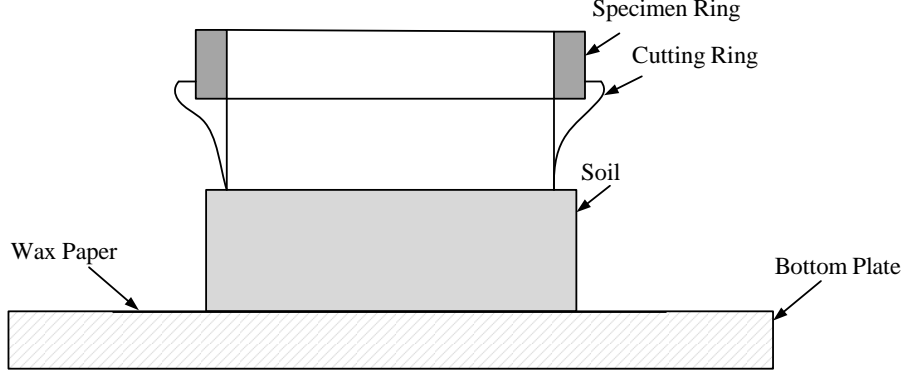

Fig. 1-16 Schematic diagram of the cutting ring method

1.4.1.2 Specific gravity

Specific gravity (G_s) is a dimensionless quantity defined as the ratio of the mass of solids to the mass of an equivalent volume of water at 4°C ($\rho_w^{4°C}$):

$$G_s = \frac{m_s}{m_w} = \frac{\rho_s}{\rho_w^{4°C}} \qquad (1\text{-}8)$$

As $\rho_w^{4°C} = 1\,\text{g/cm}^3$, the value of G_s equals that of ρ_s. As the variation of density is relatively small in practice, the density of water ρ_w at other temperatures may be taken the same as that at 4°C.

In laboratory, pycnometer bottle method is used to determine the specific gravity of solids. The general procedures are as follows:

1) Clean and dry the pycnometer bottle and weigh its mass m_1;
2) Put a small portion (about 300 g) of dry soil sample in pycnometer bottle and weigh the total mass m_2;
3) Fill the pycnometer bottle with de-aired water and weigh the total mass m_3;
4) Clean the pycnometer bottle and fill it with de-aired water. Weigh the total mass m_4;
5) Determine the specific gravity according to the following relation:

$$G_s = \frac{m_2 - m_1}{\left(m_2 - m_1\right) - \left(m_3 - m_4\right)}$$

For rapid evaluation, the specific gravity of 2.7~2.75 can be adopted for clay and

silt, as well as 2.65 for sand.

1.4.1.3 Water content

The water content (w) is defined as the mass of water divided by the mass of solids. The result is often expressed as a percentage:

$$w = \frac{m_w}{m_s} \times 100\% = \frac{m - m_s}{m_s} \times 100\% \tag{1-9}$$

Oven drying method is used to determine the water content. The procedures are as follows:

1) Clean the container and weigh the mass m_1;
2) Place a certain portion of soil in the container and weigh the total mass m_2;
3) Keep the container in the oven and dry it for at least 24 hours under the temperature of $110 \pm 5°$ till the mass remains constant;
4) Cool the container and weigh the total mass m_3;
5) Determine the water content according to Eq.(1-9):

$$w = \frac{m_2 - m_3}{m_3 - m_1} \times 100\%$$

1.4.2 Dependent indices

The dependent indices introduced in this section can be derived from independent indices according to the three-phase diagram.

1.4.2.1 Void ratio and Porosity

The void ratio (e) and porosity (n) are used to quantify the void space. The void ratio is defined as:

$$e = \frac{V_v}{V_s} \tag{1-10}$$

The porosity is defined as:

$$n = \frac{V_v}{V} \times 100\% \tag{1-11}$$

1.4.2.2 Degree of saturation

The degree of saturation (S_r) refers to the ratio of the volume of water to the volume of void:

$$S_r = \frac{V_w}{V_v} \tag{1-12}$$

For dry soils and saturated soils, $S_r = 0$ and $S_r = 1$, respectively. While for partially saturated soils, $0 < S_r < 1$.

1.4.2.3 Saturated density, dry density, and buoyant density

Apart from the bulk density, there are other three definitions of density in pratice. The saturated density (ρ_{sat}) is defined as the mass of soil sample over its volume when it is fully saturated:

$$\rho_{sat} = \frac{m_s + V_v \cdot \rho_w}{V} \tag{1-13}$$

Dry density (ρ_d) is defined as the mass of solid over the volume of soil sample when it is completely dry:

$$\rho_d = \frac{m_s}{V} \tag{1-14}$$

Buoyant density (ρ') is the buoyant mass of solid over the volume of soil sample when it is submerged below water:

$$\rho' = \frac{m_s - V_s \cdot \rho_w}{V} = \rho_{sat} - \rho_w \tag{1-15}$$

Similar to the bulk unit weight, the unit weights correspond to different definitions of density are saturated unit weight (γ_{sat}), dry unit weight (γ_d) and buoyant unit weight γ':

$$\gamma_{sat} = \rho_{sat} \cdot g \quad \gamma_d = \rho_d \cdot g \quad \gamma' = \rho' \cdot g \tag{1-16}$$

According to the definitions of these unit weights, the following relation exists:

$$\gamma_{sat} \geq \gamma \geq \gamma_d \geq \gamma' \tag{1-17}$$

1.4.3 Relationships between dependent and independent indices

The three independent indices and six dependent indices are mutually convertible. Actually, as long as three of them are in hand, the other six indices are available. It is worth noting that for dry and saturated soil, there are the implicit conditions $S_r=0$ and $S_r=1$, respectively.

The physical indices mentioned above are not absolute ones. To facilitate the derivation, $V_s = 1$ is usually assumed.

The variables related to the volume are:

$$e = \frac{V_v}{V_s} \rightarrow V_v = e \cdot V_s = e \tag{1-18}$$

$$S_r = \frac{V_w}{V_v} \rightarrow V_w = V_v \cdot S_r = e \cdot S_r \tag{1-19}$$

$$V = V_s + V_v \rightarrow V = 1 + e \tag{1-20}$$

The variables related to the mass are:

$$m_s = G_s \cdot \rho_w^{4°C} \cdot V_s \rightarrow m_s = G_s \cdot \rho_w^{4°C} = G_s \cdot \rho_w \tag{1-21}$$

$$m_w = w \cdot m_s = w \cdot G_s \cdot \rho_w \tag{1-22}$$

$$m = m_s + m_w = G_s \cdot (1+w) \cdot \rho_w \tag{1-23}$$

The assumption $\rho_w = \rho_w^{4°C}$ is adopted. The units of the variables are omitted for simplicity. In practical design, it is the engineer who should follow the units of consistency. With these variables and the corresponding definition of each index, the relationships can be formulated.

1.4.3.1 Relation between void ratio and porosity

$$n = \frac{V_v}{V} = \frac{e}{1+e} \tag{1-24}$$

1.4.3.2 Relation between void ratio, specific gravity and degree of saturation

According to Eq. (1-19) and Eq. (1-22):

$$w \cdot G_s \cdot \rho_w = m_w = e \cdot S_r \cdot \rho_w \rightarrow S_r = \frac{w \cdot G_s}{e} \tag{1-25}$$

For saturated soil, $S_r = 1$, $e = w \cdot G_s$

1.4.3.3 Relation between bulk density and other indices

For partially saturated soil:

$$\rho = \frac{m}{V} = \frac{m_s + m_w}{V} = \frac{G_s \cdot (1+w)}{1+e} \rho_w \tag{1-26}$$

Replacing w with the relation defined by Eq. (1-25)

$$\rho = \frac{G_s \cdot \left(1 + \dfrac{e \cdot S_r}{G_s}\right)}{1+e} = \frac{G_s + e \cdot S_r}{1+e} \rho_w \tag{1-27}$$

For saturated soil, namely $S_r = 1$, Eq. (1-7) changes to:

$$\rho_{sat} = \frac{G_s + e}{1+e} \rho_w \tag{1-28}$$

For dry soil, namely $S_r = 0$, Eq. (1-7) changes to:

$$\rho_d = \frac{G_s}{1+e} \tag{1-29}$$

If the soil is submerged, the solids undergo the buoyant force, namely:

$$\rho' = \frac{m_s - V_s \cdot \rho_w}{V} = \frac{G_s - 1}{1+e} \tag{1-30}$$

Example 1.4-1

A sample of wet silly clay soil has a mass of 126 kg. The following data were obtained from a series of laboratory tests on the sample: bulk density ρ=2.1 g/cm^3, specific gravity $G_s = 2.7$, water content $w = 15\%$. Determine 1) dry density; 2) porosity; 3) void ratio; 4) degree of saturation.

Solution

Mass of sample: $m = 126$ kg

Volume of sample: $V = \dfrac{m}{\rho} = \dfrac{126}{2.1 \times 10^3} = 0.06$ m^3

Since $m = m_s + m_w = m_s + w \cdot m_s = m_s(1+w)$

Therefore, $m_s = \dfrac{m}{1+w} = \dfrac{126}{1.15} = 109.57$ kg , $m_w = m - m_s = 126 - 109.57 = 16.43$ kg

Now, $V_w = \dfrac{m_w}{\rho_w} = \dfrac{16.43}{1000} = 0.01643$ m^3

$$V_s = \dfrac{m_s}{G_s \cdot \rho_w} = \dfrac{109.57}{2.7 \times 1000} = 0.041 \text{ m}^3$$

$$V_v = V - V_s = 0.06 - 0.041 = 0.019 \text{ m}^3$$

Then required quantities can be determined as:

1) Dry density: $\rho_d = \dfrac{m_s}{V} = \dfrac{109.57}{0.06} = 1826.17$ kg/m^3

2) Porosity: $n = \dfrac{V_v}{V} \times 100\% = \dfrac{0.019}{0.06} \times 100\% = 31.67\%$

3) Void ratio: $e = \dfrac{V_v}{V_s} = \dfrac{0.019}{0.041} = 0.46$

4) Degree of saturation: $S_r = \dfrac{V_w}{V_v} \times 100\% = \dfrac{0.01643}{0.019} \times 100\% = 86.47\%$

Note: The rule that the consistency of units should be always followed.

Example 1.4-2

A sample of silly clay has a volume of 14.88 cm^3, a total mass of 28.81 g, a dry mass of 24.83 g, and a specific gravity of solids 2.7. Determine: 1) void ratio; 2) degree of saturation.

Solution

1) Void ratio

$$V_s = \dfrac{m_s}{G_s \cdot \rho_w} = \dfrac{24.83}{2.7 \times 1} = 9.20 \text{ cm}^3$$

$$V_v = V - V_s = 14.88 - 9.20 = 5.68 \text{ cm}^3$$

$$e = \frac{V_v}{V_s} = \frac{5.68}{9.20} = 0.62$$

2) Degree of saturation

$$w = \frac{m_w}{m_s} = \frac{28.81 - 24.83}{24.83} \times 100\% = 16.03\%$$

$$S_r = \frac{G_s \cdot w}{e} = \frac{2.7 \times 0.1603}{0.62} \times 100\% = 69.81\%$$

Example 1.4-3

A soil sample has a total unit weight of 16.97 kN/m^3 and a void ratio of 0.84 . The specific gravity of solids is 2.70 . Determine: 1) degree of saturation; 2) dry unit weight; 3) water content.

Solution

1) Degree of saturation by Eq. (1-27)
$$\gamma = \rho \cdot g = \frac{\gamma_w (G_s + e \cdot S_r)}{1 + e} \rightarrow 16.97 = \frac{10 \times (2.7 + 0.84 S_r)}{1 + 0.84} \rightarrow S_r = 50.30\%$$

2) Dry unit weight by Eq. (1-14)
$$\gamma_d = \rho_d \cdot g = \frac{\gamma_w \cdot G_s}{1 + e} = \frac{10 \times 2.7}{1 + 0.84} = 14.67 \text{ kN/m}^3$$

3) Water content by Eq. (1-25)
$$w = \frac{S_r \cdot e}{G_s} \times 100\% = \frac{0.5030 \times 0.84}{2.7} \times 100\% = 15.65\%$$

Example 1.4-4

A soil sample in its natural state has, when fully saturated, a water content of 32.5% , The specific gravity of solids is 2.69 . Determine: 1) void ratio; 2) bulk unit weight; 3) dry unit weights; 4) weight of water required to saturate a soil mass of volume 10 m^3 .

Solution

Note that the implicit condition $S_r = 1$ should be taken into account.

1) Void ratio by Eq. (1-25)
$$e = \frac{V_v}{V_s} = \frac{w \cdot G_s}{S_r} = \frac{0.325 \times 2.69}{1} = 0.87$$

2) Bulk unit weight by Eq. (1-27)
$$\gamma = \rho \cdot g = \frac{G_s \cdot \gamma_w \cdot (1 + w)}{1 + e} = \frac{2.69 \times 10 \times (1 + 0.325)}{1 + 0.874} = 19.02 \text{ kN/m}^3$$

3) Dry unit weight by Eq. (1-29)

$$\gamma_d = \rho_d \cdot g = \frac{\gamma_w \cdot G_s}{1+e} = \frac{2.69 \times 10}{1+0.874} = 14.35 \text{ kN/m}^3$$

4) As the soil sample is saturated, the bulk unit weight and saturated unit weight are equal. Then,

Total weight of the soil mass: $W = \gamma_{sat} \cdot V = 19.02 \times 10 = 190.2 \text{ kN}$

Weight of solids: $W_s = \gamma_d \cdot V = 14.35 \times 10 = 143.5 \text{ kN}$

Weight of water: $W_w = W - W_s = 190.2 - 143.5 = 46.7 \text{ kN}$

1.5 Indices describing physical states of soils

For cohesionless soil and cohesive soil, different indices are used to describe the physical state of soils. For the former one, it refers to the compaction, while for the later one, the consistency is adopted.

1.5.1 Compaction of cohesionless soil

The compaction means the number of solids for unit volume of soil. The more the solids, the more compact of the soil, otherwise the less the solids, the looser of the soil. For the physical indices mentioned above, the dry unit weight or void ratio alone, which represents the content of solids and voids within certain soil mass, could not tell its compaction level. The reason is that they ignore the effect of shape and size of solids, gradation, and the manner in which the solids are arranged. The angular shaped solids tend to form looser structures than those with rounded shape as the sharped edges have higher possibility to keep the solids far apart. For well graded soil, the voids formed between large solids can be filled with small solids and the volume of void is reduced. Moreover, the pattern of the arrangement of the solids also influence the compaction. If all the solids are assumed to be spheres of uniform size and packed as shown in Fig. 3.8(a), the void ratio of such a mass amounts to about 0.90. However, if the solids are packed as shown in Fig. 3.8(b), the void ratio of the mass is about 0.35. The index used to indicate the compaction of cohesionless soil is the relative density as:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{1-31}$$

According to Eq. (1-16), the corresponding void ratios are expressed as:

$$e_{max} = \frac{G_s}{\rho_{d\,min}} - 1, \ e = \frac{G_s}{\rho_d} - 1, \text{ and } e_{min} = \frac{G_s}{\rho_{d\,max}} - 1 \tag{1-32}$$

Substituting Eq. (1-10) into Eq. (1-31), the relative density can be recast into:

$$D_r = \frac{(\rho_d - \rho_{d\min})\rho_{d\max}}{(\rho_{d\max} - \rho_{d\min})\rho_d} \qquad (1\text{-}33)$$

$D_r = 0$ means the cohesionless soil is in its loosest state while $D_r = 1$ means it is in its densest state. On the basis of the relative density, the cohesionless soil are classified as loose, medium dense and dense according to Tab.

In laboratory, maximum void ratio $e_{\max}$ and minimum void ratio $e_{\min}$ of dry cohesionless soil can be measured according to ASTM D4253-00 and ASTM D4254-00 respectively. The procedures are briefed as follows.

For maximum void ratio test, the dry soil is dumped to the container through a funnel. With the rise of the cross section of the soil sample, the funnel makes an upward spiral but keep its bottom opening almost 25.4mm above the section. After the filling, the density is calculated from the mass and volume of dry soil. With the known density and zero water content (dry soil), the corresponding maximum void ratio are determined according to Eq.

For minimum void ratio test, the soil used to calculate to the maximum void ratio, is utilized. The soil is firstly surcharged and then vertically shaken for a certain period of time depending on the frequency of vibration table. After the procedure, the settlement of the soil is carefully measured. The density of the densified soil is calculated from the mass and varied volume. The corresponding minimum void ratio are determined according to Eq.
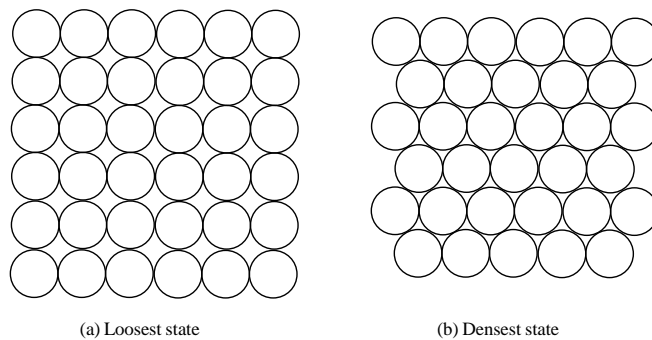

(a) Loosest state   (b) Densest state

Figure 3.8 Packing of grains of uniform size

Fig. 1-17 Packing of solids of uniform size

Tab. 1-3 Classification of sandy soils

Table 3.8 Classification of sandy soils

Relative density, D_r, %	Type of soil
0–15	Very loose
15–50	Loose
50–70	Medium dense
70–85	Dense
85–100	Very dense

Relative density, D_r %	Type of soil
0-15	Very loose
15-50	Loose
50-70	Medium dense
70-85	Dense
85-100	Very dense

(a) Maximum void ratio determination
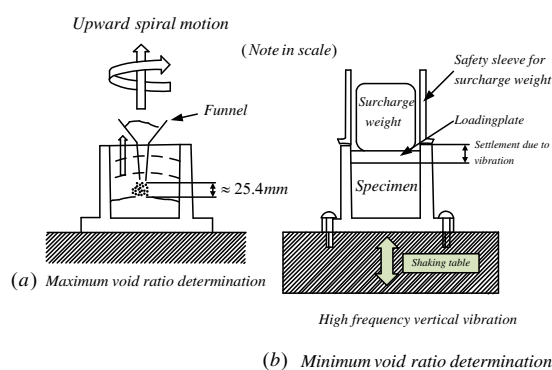
(b) Minimum void ratio determination

High frequency vertical vibration

Fig. 1-18 Packing of solids of uniform size

Example 1.5.1

从某天然砂土层中取得的式样通过实验测得其含水率 ω=11%，天然密度 ρ=1.70 g/cm³，最小干密度为 1.41 g/cm³，最大干密度为 1.75 g/cm³，试判断该砂土的密实程度。

[解] 已知 ρ=1.70 g/cm³，ω=11%，按式（1-22）可计算得该砂土的天然干密度为：

$$\rho_d = \frac{\rho}{1+\omega} = \frac{1.70}{1+0.11} = 1.53 \text{ g/cm}^3$$

再由 $\rho_{d\min} = 1.41$ g/cm³，$\rho_{d\max} = 1.75$ g/cm³，带入式（1-28）可得

$$D_r = \frac{(\rho_d - \rho_{d\min})\rho_{d\max}}{(\rho_{d\max} - \rho_{d\min})\rho_d} = \frac{(1.53-1.41)\times 1.75}{(1.75-1.41)\times 1.53} = 0.4$$

由于 1/3< D_r <2/3，所以该砂土层处于中密状态。

密度 $\rho = 1.70\ g/cm^3$,最小干密度为 $1.41\ g/cm^3$,最大干密度为 $1.75\ g/cm^3$,试判断该砂土的密实程度。

[解] 已知 $\rho = 1.70\ g/cm^3, w = 11\%$,按式(1 22)可计算得该砂土的天然干密度为：

$$\rho_d = \frac{\rho}{1 + w} = \frac{1.70}{1 + 0.11} = 1.53\ g/cm^3$$

再由 $\rho_{dmin} = 1.41\ g/cm^3, \rho_{dmax} = 1.75\ g/cm^3$,代入式(1-28)可得

$$D_r = \frac{(\rho_d - \rho_{dmin})\rho_{dmax}}{(\rho_{dmax} - \rho_{dmin})\rho_d} = \frac{(1.53 - 1.41) \times 1.75}{(1.75 - 1.41) \times 1.53} = 0.4$$

由于 $1/3 < D_r < 2/3$,所以,该砂土层处于中密状态。

1.5.2 Consistency of cohesive soil

Consistency is a term to indicate the degree of firmness of cohesive soils or the capacity of soils to resist the external loading. The consistency is qualitatively expressed as very soft, soft, stiff, very stiff and hard.

The consistency of cohesive soils depends on the water content. When the water content of a cohesive soil is low, the water within it is almost strong adsorbed water. As the strong adsorbed water has a property of solid, the whole soil sample behavior as a solid or semi-solid depending on the thickness of water layer surrounded the solid. As the water content increase, the water layer becomes thicker and the existing attraction force decreases. The weak adsorbed water behavior as a very viscous liquid. However, it could not move under the action of gravity. The thickness of the layer varies under the action of load and the layer could shift from one solid to another. The existence of the weak adsorbed water explains the plasticity of clay. If the water further increases, certain quantity of water may beyond the influence of electrostatic action and become free water. In this case, the solids are separated by water and the shear strength is lost. The soil behavior as fluid.
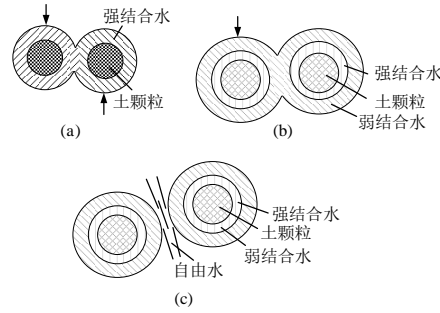
图1-20土中水与稠度状态
(a)固态和半固态；(b)可塑状态；(c)流动状态

Fig. 1-19 Packing of solids of uniform size

1.5.2.1 Limits of water content (Atterberg limits)

As mentioned above, the physical properties of cohesive soils vary distinctively at different water content. Those critical water contents separating the states of soils are called limits of water content (also named Atterberg limits). As shown in the figure, a cohesive soil changes form solid phase to liquid phase with the decrease of water content. Several limits as shrinkage limit, plastic limit and liquid limit are existed.

1) **Shrinkage limit**: a critical water content which separate the solid phase and semi-solid phase. If the water content is less than the shrinkage limit, the volume of the soil sample ceases to change with further drying process (oven-dried method), as fig shows. The shrinkage limit is determined as:

$$\omega_s = \frac{(m_1 - m_s) - (V_2 - V_1)\rho_w}{m_s} \times 100\% \qquad (1\text{-}34)$$

2) It is less frequently used than plastic limit and liquid limit. Refer to ASTM D4943 for more details.

3) **Plastic limit**: a critical water content which separates the semi-solid phase and plastic phase. Strictly speaking, the plastic limit corresponds to the maximum water content of adsorbed water. From an experimental point of view, it corresponds to the water content at which a soil thread just begins to crumble when it is rolled into 3 mm in diameter on a ground glass plate. A trail-and-error technique should be used to obtain the plastic limit. Refer to ASTM D4318 and AASHTO T90 for more details.

4) **Liquid limit**: a critical water content which separates the plastic phase and liquid phase. In the laboratory, liquid limit corresponds to the water content at which a standard 30° and 80 g cone penetrating the soil sample a distance of 20 mm in approximately 5 seconds. A trail-and-error technique should be also used to obtain the liquid limit. Refer to ASTM D4318 and AASHTO T 89 for
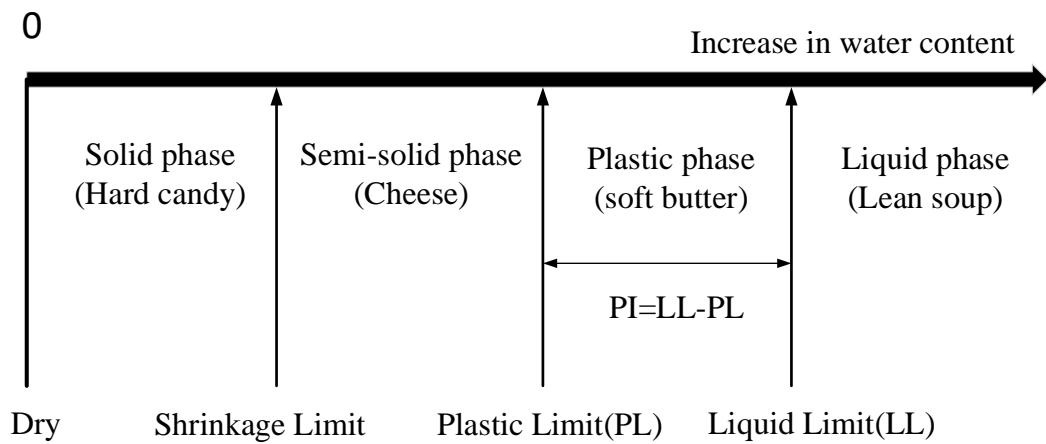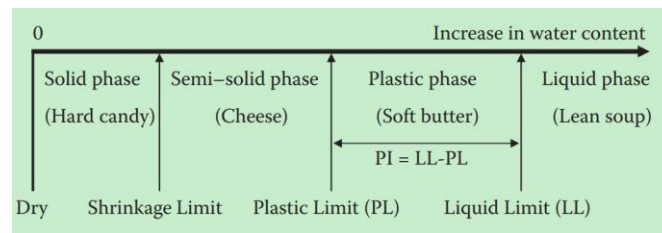
more details.

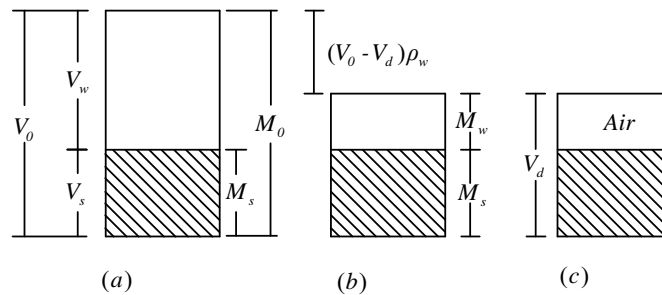Fig. 1-20 Determination of shrinkage limit

(a)   (b)   (c)

Figure 3.15   Determination of shrinkage limit

Fig. 1-21 Determination of shrinkage limit

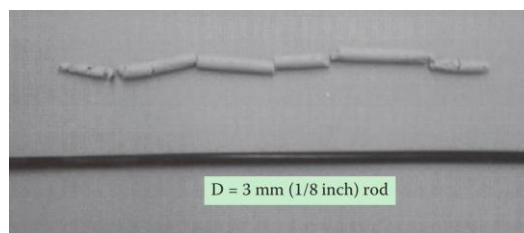D = 3 mm (1/8 inch) rod

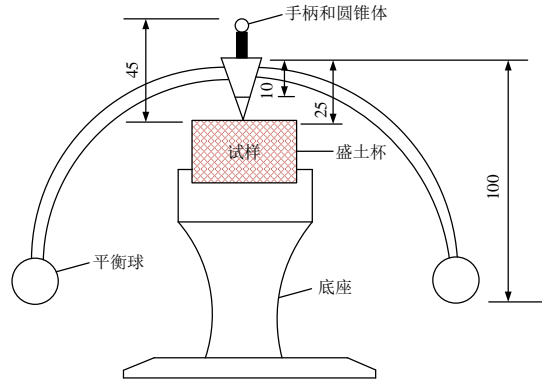Fig. 1-22 Determination of shrinkage limit
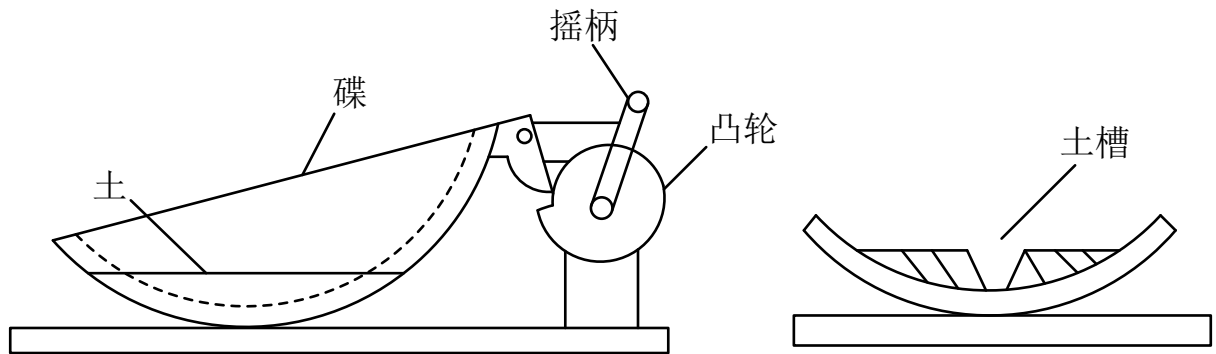
Fig. 1-23 Determination of shrinkage limit

Fig. 1-24 Determination of shrinkage limit

1.5.2.2 Plasticity and liquidity indices

The size of the range of the water content where the soil exhibits plastic properties is called the plasticity index:

$$I_p = \omega_l - \omega_p \tag{1-35}$$

It worth pointing out that the plasticity index is the difference between the numerators of liquid limit and plastic limit (without percentage). From a physical point of view, it equals the ratio of the mass of weak adsorbed water to the mass of solid solids. The plasticity index is useful for cohesive soil classification. Soils with a high PI tend to be clay, those with a lower PI tend to be silt, and those with a PI of 0 (non-plastic) tend to have little or no silt or clay

The liquid index scales the range of the natural water to the plastic limit by the plasticity index:

$$I_L = \frac{\omega - \omega_p}{\omega_l - \omega_p} = \frac{\omega - \omega_p}{I_p} \tag{1-36}$$

The introduction of liquid index is to more accurately describe the state of a soil sample. The soil sample with high water content does not mean it is softer than that with lower water content. It is known that both chemical composition and specific surface of clay

miners play an import role in determining water adsorption capacity. It is possible that the soil sample with high water content has large amounts of adsorbed water, which has little effect on the physical state of soils. In most in-situ soils, liquidity index ranges from 0% to 100%, detailed divisions are shown in

Tab. 1-4 Soil classification according to plasticity index

Table 3.9 Soil classifications according to Plasticity Index

Plasticity index	Plasticity
0	Non-plastic
<7	Low plastic
7–17	Medium plastic
>17	Highly plastic

Plasticity index	Plasticity
0	Non-plastic
<7	Low plastic
7-17	Medium plastic
>17	Highly plastic

Tab. 1-5 Soil classification according to liquidity index

表 1-11　黏性土（细粒土）的状态分类

液性指数 I_L	状态
$I_L \leqslant 0$	坚硬（半固态）
$0 < I_L \leqslant 0.25$	硬塑
$0.25 < I_L \leqslant 0.75$	可塑
$0.75 < I_L \leqslant 1$	软塑
$I_L > 1$	流塑

液性指数 I_L	状态
$I_L \leq 0$	坚硬（半固态）
$0 < I_L \leq 0.25$	硬塑
$0.25 < I_L \leq 0.75$	可塑
$0.75 < I_L \leq 1$	软塑
$I_L > 1$	流塑

Example 1.5.2

【例题 1-5】 某砂层的天然密度 $\rho=1.75\text{g/cm}^3$，含水量 $w=10\%$，土粒比重 $G_s=2.65$。最小孔隙比 $e_{\min}=0.40$，最大孔隙比 $e_{\max}=0.85$，问该土层处于什么状态。

【解】

（1）求土层的天然孔隙比 e。绘三相草图，见图 1-22。设 $V_s=1.0\text{cm}^3$，由公式（1-11）在数值上得孔隙体积 $V_v=e$。因为 $G_s=2.65$，由公式（1-9）得 $m_s=\rho_s=2.65\text{g}$。因为，$w=10\%$，由式（1-10），$m_w=wm_s=0.265\text{g}$。

图 1-22　例题 1-5 三相草图

因为，$\rho=1.75\text{g/cm}^3$，由式（1-7），$\rho=\dfrac{m_s+m_w}{V}=\dfrac{2.65+0.265}{1+e}$

解得 $e=0.666$

（2）求相对密度

由式（1-19）

$$D_r=\frac{e_{\max}-e}{e_{\max}-e_{\min}}=\frac{0.85-0.666}{0.85-0.40}=0.409$$

$$\frac{2}{3}>D_r>\frac{1}{3}$$

故该砂层处于中密状态。

【例题 1-6】 从某地基取原状土样，测得土的液限 $w_L=47\%$，塑限 $w_p=18\%$，天然含水量 $w=40\%$，问地基土处于什么状态。
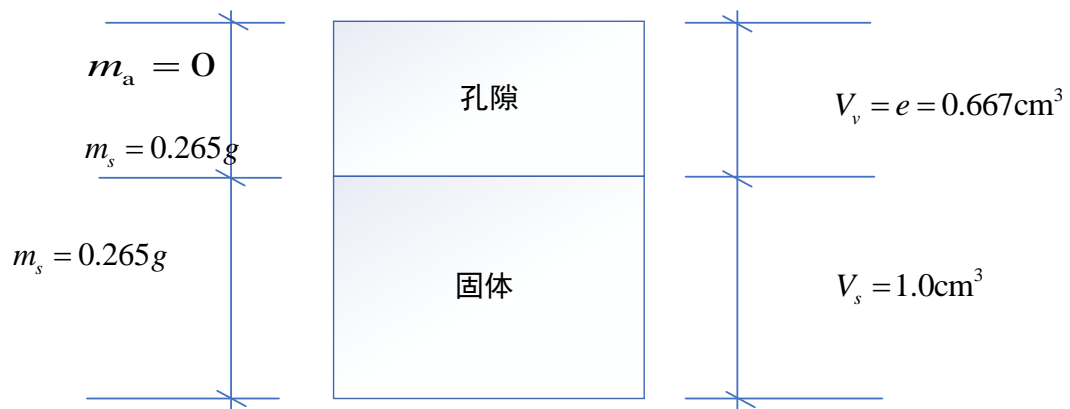
【解】 由式（1-22）求液性指数：

$$I_L=\frac{w-w_p}{w_L-w_p}=\frac{40-18}{47-18}=0.759$$

查表 1-11，$1.0>I_L>0.75$，土处于软塑状态，但实际上地基土是原状土，用式（1-22）计算的结果偏大，故该天然土体实际上也可能处于可塑状态。

某砂层的天然密度 $\rho=1.75\text{ g/cm}^3$，含水量 $\omega=10\%$，土粒比重 $G_s=2.65$。最小孔隙比 $e_{\min}=0.40$，最大孔隙比 $e_{\max}=0.85$，问该土层处于什么状态。

【解】

（1）求土层的天然孔隙比 e。绘三相草图，见图 1-22。设 $V_s=1.0\text{ cm}^3$，由公式（1-11）在数值上得空隙体积 $V_v=e$。因为 $G_s=2.65$，由公式（1-9）得 $m_s=\rho_s=2.65g$。因为 $\omega=10\%$，由式（1-10），$m_\omega=\omega m_s=0.265g$。

因为，ρ=1.75 g/cm³，由式（1-7），$\rho = \dfrac{m+m_\omega}{V} = \dfrac{2.65+0.265}{1+e}$

解得 e=0.666

（2）求相对密度

由式（1-19）　$D_r = \dfrac{e_{\max}-e}{e_{\max}-e_{\min}} = \dfrac{0.85-0.666}{0.85-0.40} = 0.409$

$$\dfrac{2}{3} > D_r > \dfrac{1}{3}$$

故该砂层处于中密状态。

从某地基取原状土样，测得土的液限 ω_L =47%，塑限 ω_p =18%，天然含水量 ω=40%，问地基土处于什么状态。

【解】　由式（1-22）求液性指数

$$I_L = \dfrac{\omega-\omega_p}{\omega_L-\omega_p} = \dfrac{40-18}{47-18} = 0.759$$

查表 1-11，1.0> I_L >0.75,土处于软塑状态，但实际上地基土是原状土，用式（1-22）计算的结果偏大，故该天然土体实际上也可能处于可塑状态。

1.6 Structure of soil

Soil structure refers to the way soil solids group together to form aggregates with various shapes and sizes. It is found that the soil structure plays an import role in determining the mechanical behavior of a soil sample. A good example is that the soil sample taken from in-situ and the remolded soil sample (the original soil sample is crushed and then remold) may have distinctive behavior even if certain index is the same.

1.6.1 Structure of cohesionless soil

For coarse solids, the force of gravity plays a critical role in establishing its final structure. During settlement, a coarse solid reaches its final position when it is in contact with the existed solids. If the settlement is slow and there is no violent external force, the single solid structure forms. Under the action of dynamic force, the voids are compacted and certain amount of solids are crushed, which forms the denser single solid structure.
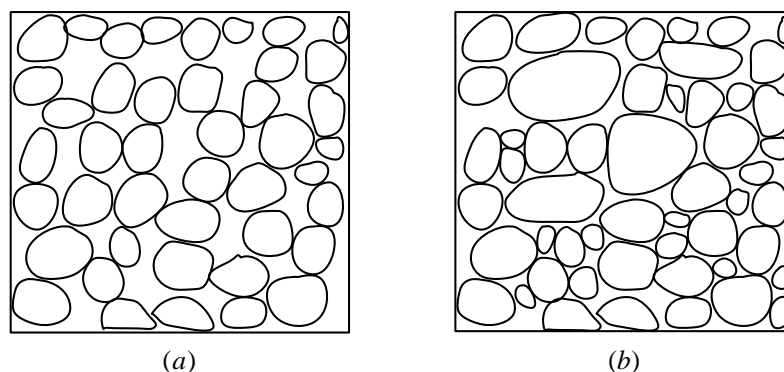

(a)   (b)

Fig. 1-25 Determination of shrinkage limit

1.6.2 Structure of cohesive soil

For soil with fine solids, the electrical surface and edge charges play an important role in forming the clay structures. Moreover, when the external force (Van der Waals force, Coulomb force, cementation, capillary force et al.) is taken into account, the situation become more complex. The final structures of clay are established from the balance of interactive forces and external forces applied to the clay assemblage during deposition.

When clay solids are settled in fresh water, the final intersolid forces are repulsive. The reason is that few delocalized cations are existed in fresh water and accordingly less anions on the surface of solids are neutralized, which make the whole clay solid negatively charged. The repulsive force make the solids separate from each other when

the boundary confinements are removed. This is a situation of dispersed clay. When clay solids are settled in marine water, the final intersolid forces are attractive. The reason is that there are more delocalized cations in marine water and accordingly more anions on the surface of solids are neutralized. The decrease of the repulsive force make the solids want to come together. This is the case of flocculated clay.
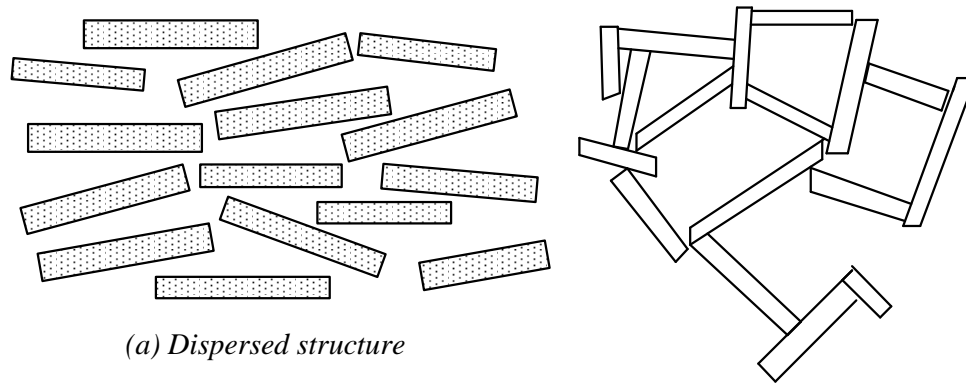
(a) Dispersed structure

Fig. 1-26 Dispersed structure

1.6.3 Thixotropy, sensitivity and activity of cohesive soils

1.6.3.1 Thixotropy

The structure of cohesive soils will be destroyed and their strength decrease when they are disturbed or remolded. However, when they are allowed to stand without further disturbance and change in water content, they regain at least part of its original strength and stiffness, which is manly due to the gradual reorientation of the absorbed molecules of water, and is known as **thixotropy**. The thixotropy has important applications in certain area such as pile-driving in soft clay.

1.6.3.2 sensitivity

Sensitivity is a term to estimate the degree of disturbance to an undisturbed cohesive soil due to remolding. From a quantative point of view, it is the ratio of unconfined compressive strength in the natural or undisturbed state q_u to that in the remoulded state $\bar{q}_u$, but without any change in the water content:

$$S_t = \frac{q_u}{\bar{q}_u} \tag{1-37}$$

On the basis of S_t, cohesive soils can be classified as in Tab.

Tab. 1-6 Soil classification on the basis of sensitivity

Table 3.14 Soil classification on the basis of sensitivity (after Skempton and Northey, 1954)

S_t	Nature of clay	S_t	Nature of clay
1	Insensitive clays	4–8	Sensitive clays
1–2	Low-sensitive clays	8–16	Extra-sensitive clays
2–4	Medium sensitive clays	>16	Quick clays

S_t	Nature of clay	S_t	Nature of clay
1	Insensitive clays	4-8	Sensitive clays
1-2	Low-sensitive clays	8-16	Extra-sensitive clays
2-4	Medium sensitive clays	>16	Quick clays

1.6.3.3 Activity

Activity is a term to represent the activity of clay minerals in a cohesive soil sample. It is also a index to represent the capacity of holding adsorbed water for cohesive soils. Skempton (1953) proposed the following expression to estimate the activity of cohesive soils:

$$A = \frac{I_p}{p_{0.002}} \tag{1-38}$$

$p_{0.002}$ is the mass fraction of solids whose size is less than 0.002 mm. On the basis of A, cohesive soils can be classified as in Tab

Tab. 1-7 Soil classification according to activity

Table 3.12 Soil classification according to activity

A	Soil type
<0.75	Inactive
0.75–1.40	Normal
>1.40	Active

A	Soil type
<0.75	Inactive
0.75-1.40	Normal
>1.40	Active

Example 1.5.2

Atterberg limits (LL and PL) and percentage of clay fraction (≤2 μm) are obtained for the following soils. For each soil
(a) Computer activity
(b) Evaluate the severity for swelling potential

	Soil 1	Soil 2	Soil 3
LL	140	53	38
PL	73	32	27
Clay fraction(%)	50	50	50

1.7 Compaction of soil

In certain practical cases, .e.g. earth fill dam, ground of foundations for structure and pavement, plinth filling and backfilling with soil are necessary. The soil's shear strength, bearing capacity, compressibility and permeability, all depends on how well the soil is compacted. Moreover, compaction could destroy the structure of certain special soils. The collapsibility of loess, swelling and shrinkage of expansive soil, or freeze-thaw susceptibility could be controlled. For sand, the densification due to compaction of void may reduce the possibility of liquefaction.

The coarse solids (gravel and sand) and fine solids (silt and clay) have completely different compaction characteristics. For fine solids, roller compaction is commonly used. During compaction, the water content should be strictly controlled. For coarse solids, vibration compaction is preferred and the water content should as high as possible.

1.7.1 Laboratory compaction test

The compaction characteristics of fine solids can be studied in laboratory with standard proctor method. The general procedure are as follows:

1) Take sufficient quantity of representative soil, air dry & pulverize it with a rubber mallet. Sieve the soil through No: 4 sieve & reject the coarser material.

2) Take about, 3 kg of soil, add water to bring its water content to about 5% below the estimated optimum moisture content. (for coarse-solided soil 4% initial

water content & for fine-solided soil 10% initial water content is preferable).
Then Mix it thoroughly.

3) Fit the collar & compact the moist soil in three equal layers by the rammer
   with evenly distributed blows to each layer.

4) Use 25 blows for 4 inches diameter & 56 blows for 6 inches diameter mold to
   the total height of mold with collar.

5) Remove the collar trim the compacted soil even with the top of the mold with
   a straight steel edge.Clean outside of the mold & base plate & weigh it.

6) 6. Remove the soil from the mold, split it & take about 100 grams sample for
   water content determination.

7) 7. Break the soil lamps, mix it with remaining soil in the tray. Add more water
   to increase the water content by 2 to 3% & repeat the compaction procedure
   for each increment of water until the mass of the compacted soil decreases.

8) 8. Calculate Water content for each trail & corresponding dry density.

9) 9. Plot the compaction curve between water-content as abscissa & dry density
   as ordinate.

10) 10. Note the water content against the peak of the curve as optimum moisture
    content & the corresponding dry density as maximum dry density.

Refer to ASTM D4943 for more details. After completing the experiment, the relation
between dry density and water content can be plot. From the compaction curve, the
maximum dry density corresponds to the optimum water content. On the contrary, if
the soil for filling is prepared according to the optimum water, the good compaction
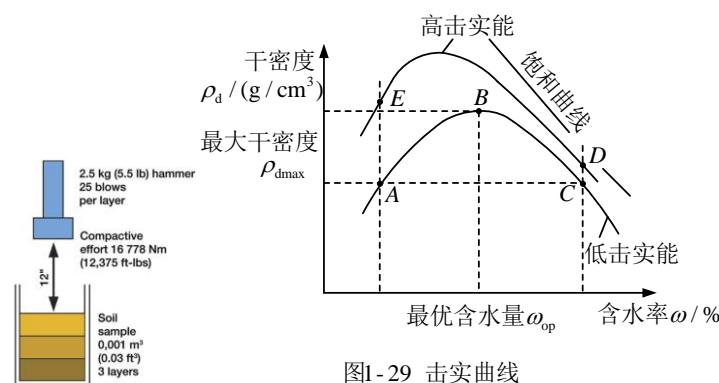would be available.

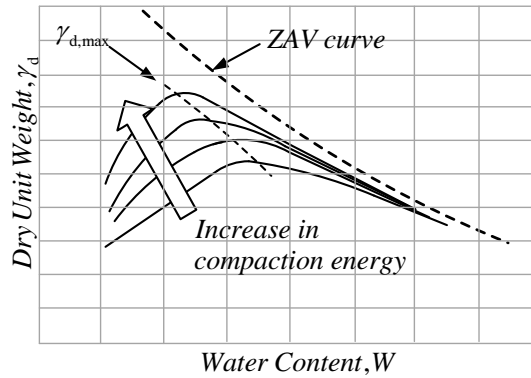图1-29 击实曲线

Fig. 1-27 Dispersed structure

Fig. 1-28 Dispersed structure

1.7.2 Effect of water content

According to the compaction curve, the relation between the dry density and water content is non-linear. Moreover, the dry density does not monotonically increase with the increase of water content. When the water content is low, the dry density increases with the increase of the water content. However, when water the content exceeds the optimum water content, the dry density decreases with the increase of water content. The phenomena can be explained as follows: at the beginning, the addition of water works as a lubricant between solids to reduce the void and then to increase the dry unit weight. However, the effect of lubrication decreases with the increase the water. This is due to: 1) the decrease of connected air; 2) The gaseous left is entrapped air which works as a cushion against compaction energy.

1.7.3 Effect of compaction energy and gradation

For the same type of soil, the relation between the dry density and compaction energy (number of blows) are shown in Fig. When the water content is low, the higher the compaction energy, the higher the dry density but the lower the optimum water content. However, when the water content is high, the compact energy does not have obvious effect on the dry density.

The gradation also plays a critical role in compaction. The more uniform of soil solids, the more difficulty to be compacted.

1.7.4 Relative compaction

After the compaction curve for a given soil is obtained from laboratory tests, the compaction in the field can be controlled according to relative compaction (R.C.), which is defined as:

$$\text{R.C.} = \frac{\gamma_{d,\text{field}}}{\gamma_{d,\max}} \times 100\% \tag{1-39}$$

$\gamma_{d,\text{field}}$ is the specified dry unit weight in the filed. $\gamma_{d,\text{max}}$ is the maximum dry unit weight obtained from the laboratory compaction test. The value of R.C. highly depends on the fields of application. Refer to corresponding design code for detailed information.

1.7.5 Compaction of cohesionless soil

Similar to the cohesive soil, water content also plays an important role in compaction. However, there is no optimum water content for cohesionless soil. Accordingly, to the compaction curve, it could attain maximum dry density either under very low or high water content. The maximum dry density is mainly due to the capillary force, which enhances the attraction force between solids. However, as long as the water content increases, the apparent force disappear and then the dry density increases.
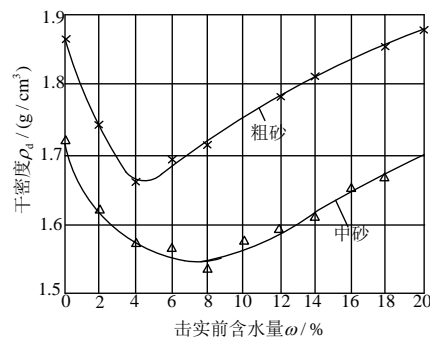

图1-31 粗粒土的击实曲线

Fig. 1-29 Compaction curve of coarse solid soil

1.8 Engineering classification of soil

The properties of sols are affected by many factors, e.g., origins, compositions, locations, geological histories. Therefore, to gain a full insight of its behavior, both *in-situ* and laboratory tests are necessary. However, it will be convenient for engineers if soils are categorized into several groups with similar engineering behaviors. In this case, engineer could roughly but quickly evaluate the performance of soils, which helps engineer a lot during the stage of site selection and preliminary design.

Soil classification systems are different from country to country. Even if in the same country, the systems may different as each area has its own concern. For example, two standards are widely used in China: Specification of Soil Test and Code for Design of Building Foundation, while in the Unite states, two standards are also widely used: the Unified Soil Classification System (USCS) and AASHTO (American Association of State Highway and Transportation Officials). Although there are many systems in use, the classifications are mainly based on gradation and consistency of soils.

1.9 Exercises

Why are the clay surfaces charged negatively?

Why are the clay surfaces charged negatively?

Why does montmorillonite clay swell more than kaolinite clay?

Why does montmorillonite clay swell more than kaolinite clay?

Taken 500g dry soil sample for sieve analysis, the weight retained on each sieve is as the second column of Tab. 1-8 shows. Determine:

a) Fill the blank column

b) Plot the solid size distribution curve

b) Determine D_{10}, D_{30}, and D_{60}

c) Compute C_u and C_g

Tab. 1-8 Computation of sieve analysis

Opening (mm)	Weigh retained (g)	Percentage retained (%)	Cumulative percentage retained (%)	Percentage finer (%)
2	50			
1	150			
0.5	150			
0.25	100			
0.075	30			
Receiving pan	20			

2)

(b) Degree of saturation S
(c) Dry unit weight γ_d if the water in the void is removed

For a given soil, the void ratio e, water content w, and specific gravity G, are found to be 0.50, 15%, and 2.65, respectively, Find:

(a) total unit weight of the soil γ_t

(b) Degree of saturation S

(c) Dry unit weight γ_d if the water in the void is removed

3)
(c) Submerged unit weight of the soil γ
(d) Total unit weight of the soil γ_t if the air void is filled with water

For a given soil, G_s =2.70, γ_t =19.0 kN/m³, and ω=12.5% were measured. Determine:

(a) Degree of saturation S

(b) Dry unit weight of the soil γ_d

(c) Submerged unit weight if the soil γ'

(d) Total unit weight of the soil γ_t if the air void is filled with water

4)

The dry unit weight of a soil is found to be 15.8 kN/m³ and its porosity n=0.40.

Determine:

(a) The total unit weight of the soil γ_t when the soil's degree of saturation S is increased to 50%

(b) The total unit weight of the soil γ_t when the soil is fully saturated

(c) The specific gravity G, of this soil

5)

At a borrow site, sandy soil was excavated. The soil had $\gamma_t = 19.3 \text{ kN/m}^3$, $w = 12.3\%$, and $G_s = 2.66$. The soil was dried, the maximum and minimum void ratio tests were performed, and $e_{max} = 0.564$ and $e_{min} = 0.497$ wer obtained. Determine the relative density of the soil at the borrow site

1) The volume of a soil specimen is 60cm³, and its mass is 108g. After being dried, the mass of the sample is 96.43g. The value of G_s is 2.7. Determine bulk density, dry density, water content, porosity and the degree of saturation.

Solution

Bulk density:

$$\rho = \frac{m}{V} = \frac{108}{60} = 1.8 \text{ g/cm}^3$$

Dry density:

$$\rho_d = \frac{m_s}{V} = \frac{96.43}{60} = 1.61 \text{ g/cm}^3$$

Water content:

$$m_w = m - m_s = 108 - 96.43 = 11.57 \text{ g}$$

$$w = \frac{m_w}{m_s} \times 100\% = \frac{11.57}{96.43} \times 100\% = 12\%$$

Porosity:

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

$$V_s = \frac{m_s}{G_s \rho_w} = \frac{96.43}{2.7 \times 1} = 35.71 \text{ cm}^3$$

$$V_v = V - V_s = 60 - 35.71 = 24.29 \text{ cm}^3$$

$$n = \frac{V_v}{V} \times 100\% = \frac{24.29}{60} \times 100\% = 40.48\%$$

Degree of saturation:

$$V_w = \frac{m_w}{\rho_w} = \frac{11.57}{1} = 11.57 \text{ g/cm}^3$$

$$S_r = \frac{V_w}{V_v} = \frac{11.57}{24.29} = 0.48 \text{ or } 48\%$$

Exercise 2.

A saturated clay specimen has the water content of 36.0, and particle specific gravity of 2.70. Determine the void ratio and dry density.

Solution

For saturated soil, $S_r = 1$

Void ratio:

$$e = w \cdot G_s = 36\% \times 2.7 = 3.67$$

Dry density:

$$m_s = G_s \times \rho_w = 2.70 \times 1 = 2.70 \text{ g}$$

$$V = 1 + e = 1 + 3.672 = 4.67 \text{ cm}^3$$

$$\rho_d = \frac{m_s}{V} = \frac{2.7}{4.672} = 0.58 \text{ g/cm}^3$$