I. Physical properties of soils

1. Components of soils, consistency limits

Soil

According to an engineering approach, **soil** is the upper covering layer of the Earth's crust, on or in which engineering facilities are built or installed. It is also used as material of earthworks and it has an impact on stability, durability and proper use of buildings.

Soils are three-phase systems: the main components are solid, liquid and gaseous phases.

Rates of soil-components

Water content (or moisture content)

Water content shows the wetness of soils. Symbol: $w \quad [\%]$ or $w \quad [-]$.

Gravimetric water content is calculated as a ratio of the weight of water (m_v) and the weight of solid particles (m_s). It shows the weight percent of moisture compared to the mass of the solid phase of soil. The weight of water in a soil sample is determined by oven-drying at 105°C until reaching constant weight. At this temperature a strongly bounded water layer cannot evaporate from the soil sample.

As water content is a proportion of weights, its value is not affected by compaction of soils, thus it can be determined from disturbed soil samples. Water content values depend on surface phenomenon and surface stresses on soil particles.

The water content of sands is usually about 5% (the thickness of the water layer on the surface is small), that of clays is about 20-30%, while the water content of organic soils can be up to 100-300% in natural conditions.

Void ratio

Void ratio characterizes the compactness of soils. Symbol: $e \quad [\%]$ or $e \quad [-]$. It is defined as a (volumetric) ratio of the volume of void-space (fluids and air together) (V_k), and the volume of solids (V_s) (see Figure 1.1).

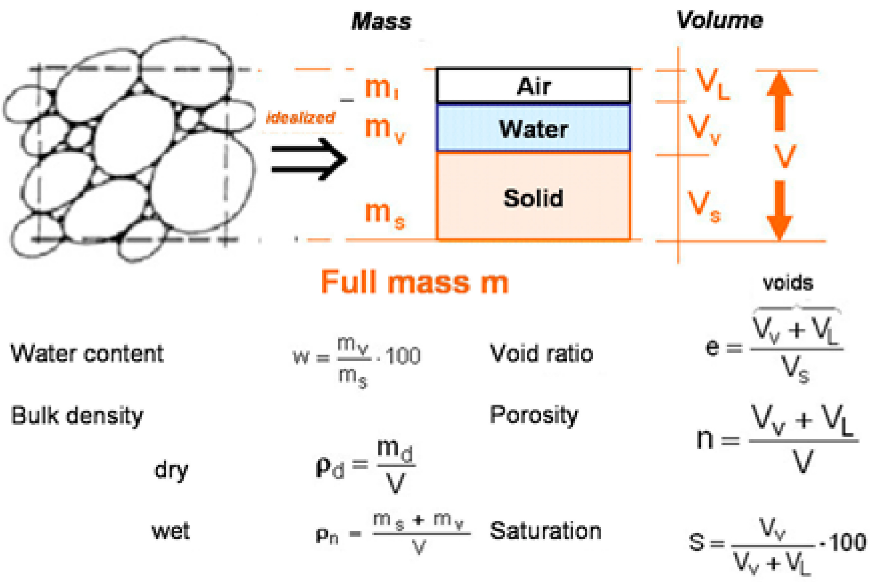

Figure 1.1: Interpretation of gravimetric and volumetric ratios of soils (Mecsi, 2009)

The value of the void ratio depends on volumetric changes of soils (the void ratio of loose soils is higher than that of dense soils), thus it can be determined only from undisturbed soil samples.

The void ratio of a dense sandy gravel soil is about 0.3, that of a loose sand is about 0.6, while the void ratio of clays (in natural conditions) varies between 0.5 and 1.0 and decreases with depth of the soil layers.

Porosity

Porosity is defined as a (volumetric) ratio of the volume of void-space (fluids and air together) (V_h), and the total or bulk volume of material (V), including the solid and void components (see Figure 1.1). Symbol: n $[\%]$ or n $[-]$.

The porosity of soils can vary widely. The porosity of loose soils can be about *n*=50%, while the porosity of compact soils is about *n*=30%. Porosity value depends on grain size distribution, and higher porosity follows smoother grain size distribution. When a soil sample consists of grains of various sizes, the smaller particles can be enclosed in the pores between larger grains. The porosity of granular soils mixed with clays can be smaller (*n*=20%) than the theoretical value.

The porosity of cohesive soils is usually higher, it can be *n*=50-70%.

Organic soils can have extremely loose structure. The porosity of fibrous peat can be as high as *n*=80-90%.

Porosity values are significantly affect by the past or present loads (e.g. geological preload) on soils.

Saturation

Saturation shows the rate of fluids and air in the void-space, and it is defined as a (volumetric) ratio of the volume of fluids (V_v) and the volume of void-space (V_h). Symbol: S $[\%]$ or S $[-]$.

$$S = \frac{V_v}{V_h} \cdot 100 \quad [\%] \text{ or } S = \frac{V_v}{V_h} \quad [-]$$

Saturation can be determined only from undisturbed soil samples. The theoretical value of saturation can range from 0 to 1. The saturation of soils under groundwater level is *S*=1.0, saturation of sands above groundwater level is about *S*=0.2-0.4 , but clays above groundwater level can be almost saturated (*S*=0.8-0.9).

Two parameters from the four above can describe clearly the condition of soils, e.g. *e* and *S*, which means there is a connection between these parameters:

$$S = \frac{w \cdot \rho_s}{e \cdot \rho_v}$$

Volumetric rates of soil components

Volumetric rate of solids (s) characterizes compactness, and is defined as a (volumetric) ratio of the volume of solids (V_s), and the total or bulk volume of material (V):

$$s = \frac{V_s}{V}$$

Volumetric rate of fluids (v) characterizes soil moisture, and is defined as a (volumetric) ratio of the volume of fuids (V_v), and the total or bulk volume of material (V):

$$v = \frac{V_v}{V}$$

Volumetric rate of air (l) is defined as a (volumetric) ratio of the volume of air (V_l), and the total or bulk volume of material (V):

$$l = \frac{V_l}{V}$$

Description of soil condition requires only two independent parameters; clearly, from these the third can be calculated:

$$s\% + l\% + v\% = 100\%$$

Soil condition can be characterized by one point in a ternary diagram, as seen in Figure 1.2. Changes in soil condition can be illustrated as vectors connecting the characteristic points of different soil conditions.

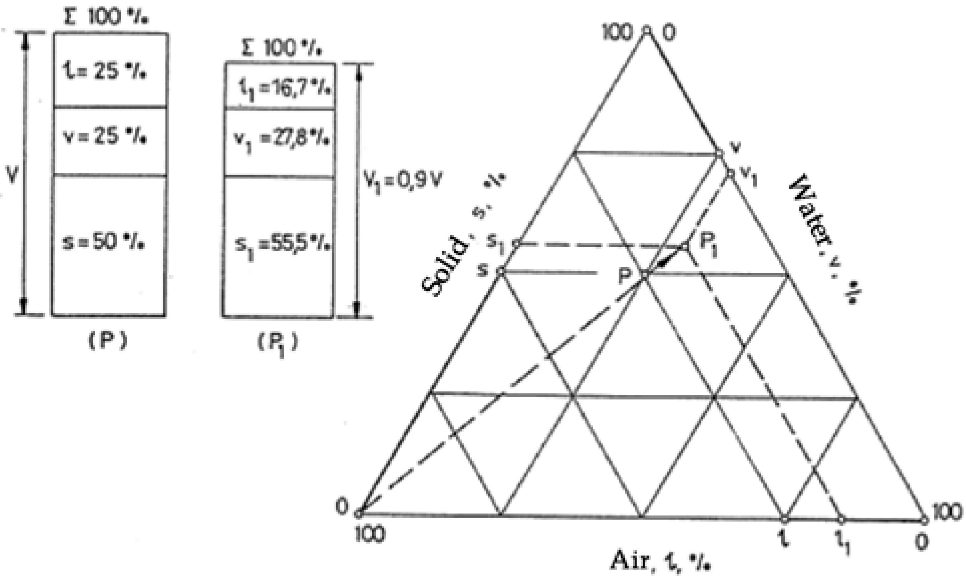

Figure 1.2: Characterization of volumetric rates of soil components in ternary diagram

Density and bulk density

Density (particle density or bulk density) $\rho \left[\frac{kg}{m^3}\right]$ or $\rho \left[\frac{g}{cm^3}\right]$ is defined as the mass of particles of the material (m) divided by the total volume they occupy (V): $\rho = \frac{m}{V}$

The particle density or true density of a particulate solid or powder is the density of the particles that make up the powder, in contrast to the bulk density, which measures the average density of a large volume of the powder in a specific medium (usually air). The total volume includes particle volume, inter-particle void volume and internal pore volume.

The density of solid particles, water and air must be known for practical calculations. The solid part of soils consists of many different mineral particles, and their density can vary. Gravel and sand soils consist of mainly quartz grains, while clays consist of mineral particles of higher density.

Based on experience, we find that the particle density of solid granules of soils varies within narrow limits ($2.65 - 2.85 \ \frac{g}{cm^3}$), therefore average density values or values from tables of standards can be taken into account.

Natural (or wet) bulk density (ρ_n) is defined as the full (wet) mass of particles of the material (m_n) divided by the total volume they occupy (V): $\rho_n = \frac{m_n}{V}$

Typical values of natural density of soils vary within $1.8 - 2.1 \ \frac{g}{cm^3}$. This value is usually applied for calculations of soil mass (net weight, geostatic pressure, earth pressure).

Dry bulk density (ρ_d) is defined as the dry (dried) mass of particles of the material (m_d) divided by the total volume they occupy (V): $\rho_d = \frac{m_d}{V}$

It is used as a compactness indicator in earthwork construction.

Saturated bulk density (ρ_t) is defined as the total mass of particles of the saturated soil material (m_t) divided by the total volume they occupy (V): $\rho_t = \frac{m_t}{V}$

Underwater bulk density (ρ') is a derived value for calculations of density of soils underwater:

$\rho' = \rho_t - \rho_v$, where ρ_v is the density of water.

Consistency limits

The strength of connections between soil particles changes with water content in soils containing clay minerals. Therefore, these soils behave differently with different water content depending on the (quantitative and qualitative) clay mineral content.

The original condition of soils changes in contact with water. Higher water content makes soils liquid, drying soils slowly leads to plastic consistency, reaching at the end the firm condition of constant volume. These transitions are continual.

Water contents where soils show specific properties are called **consistency limits**. For determination of consistency limits disturbed, kneaded soil samples are used. An interpretation of consistency limits is shown in Figure 1.3.

The determination of consistency limits is performed on saturated soil samples by equipment and methods described in international standards.

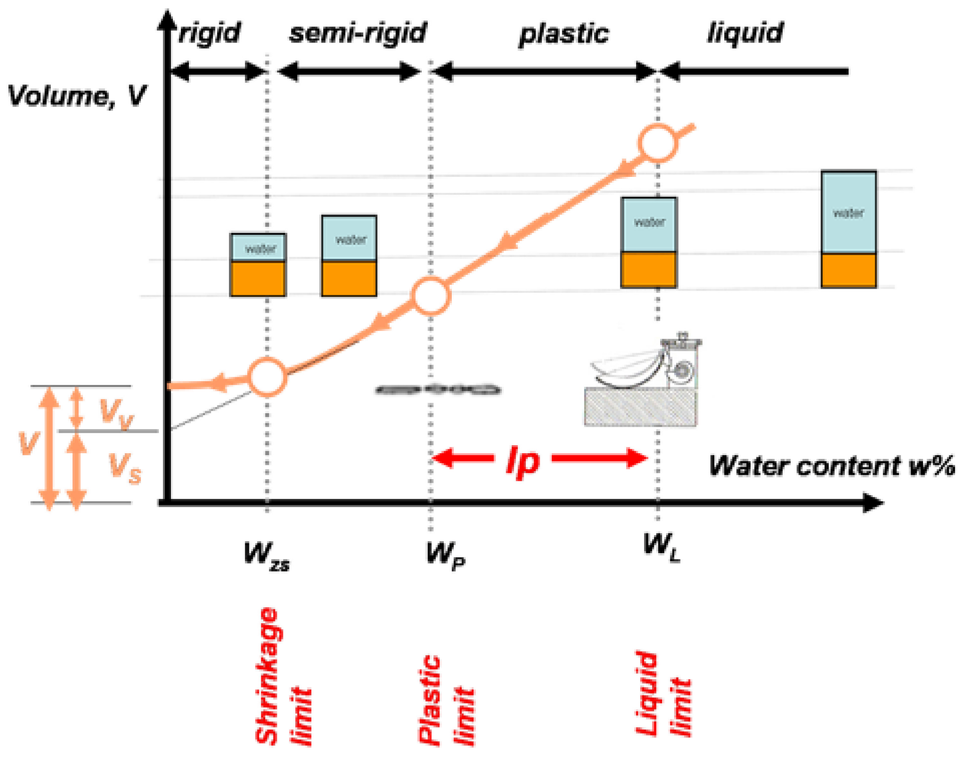

Figure 1.3: Interpretation of consistency limits (Mecsi, 2009)

Liquid limit

Liquid limit (w_L) is the water content separating liquid and plastic condition. The practical meaning of liquid limit is that soils at the consistency of liquid limit slip down a slope of approximately 10°.

The liquid limit can be determined using the so-called Casagrande method – see Figure 1.4 and Video 1.1.

A groove is made with a standardized tool in the soil sample placed into the metal cup of this equipment and the cup is repeatedly dropped onto a hard rubber base, during which the groove closes up gradually as a result of the impact. The number of blows for the groove to close for 10 mm is recorded, and the water content of the soil is determined. The test must be repeated at higher water content (by adding water to the soil sample). A relationship between the number of blows and water contents can be graphed, and the liquid limit can be read from this graph. The moisture content at which it takes 25 drops of the cup to cause the groove to close is defined as the liquid limit.

This value of water content is considered as liquid limit – very typical of soil types and of connections between soil particles and water - and it varies usually between 35% and 100%.

The physical background of determination of liquid limit is looking for the moisture content at which soils show definite deformation against certain impact.

Experience shows that the number of blows–water content curves (the so-called liquid lines) of soils of different plasticity are parallel lines drawn in a semilogarithmic coordinate system.

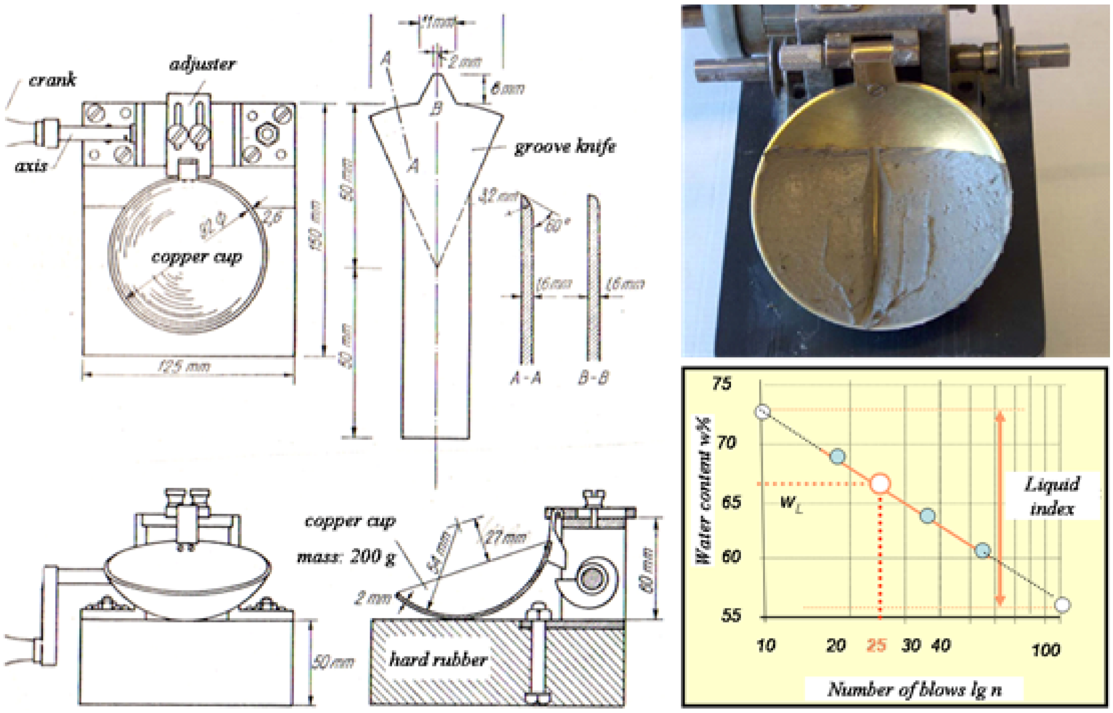

Figure 1.4: Determination of liquid limit using Casagrande equipment

VIDEO 1.1

Video 1.1: Determination of liquid limit using Casagrande equipment

New European standards recommend another method: the so-called cone penetrometer test (Figure 1.5). It is based on the measurement of penetration into the pulpy soil of a standardized cone of specific mass in 5 seconds time. Liquid limit is the water content where this penetration is equal to 10 or 20 mm. It can be determined by the graphing method already known from Casagrande method. Practical experiences show that cone penetrometer tests give more accurate results for low plasticity soils. An additional advantage is that the liquid limit can be theoretically determined based on one point (one test)

Plastic limit

Plastic limit (w_p) is the water content at which soil starts to transform from plastic to rigid condition, in other words from kneadable to brittle. The plastic limit is defined as the water content of soil when the soil sample can be rolled to a diameter of 3 mm and it just begins to crumble.

Determination of the plastic limit is based on this definition: we try to roll the soil sample to a thread of 3 mm. If the sample is about to break up, the water content of the soil sample is exactly on the plastic limit (**Figure** 1.6, **Video** 1.2), so the plastic limit can be determined by the calculation of the water (moisture) content of this thread.

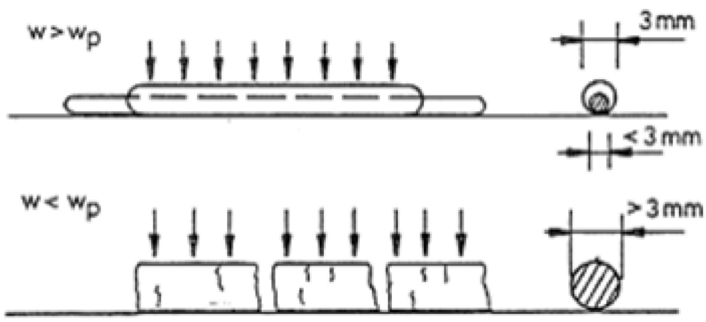

Figure 1.6: Determination of plastic limit

VIDEO 1.2

Video 1.2: Determination of plastic limit

The plastic limit is of great importance in engineering aspects. Performing soil tillage or earthworks is the most economical and the simplest in this condition, when both manual and mechanical grading require the least amount of power. Dirt roads are passable, and embankments can be most easily compacted (reaching the smallest possible void ratio) when the water content of the soil is at its plastic limit.

Plasticity index

The plasticity index (I_p) is the difference between the water content of the liquid limit and the plastic limit.

$$I_p = w_L - w_p$$

A small plasticity index refers to water-sensitive soils while a higher I_p value means higher water absorbent capacity, and thus the quantity and quality of clay minerals can be characterized indirectly.

The plasticity index is also a measure of the cohesion ability of soils. A higher plasticity index usually means a higher expected value of cohesion (by the same compactness).

The plasticity index has an important role both in soil classification and in empirical formulas.

Experience obtained during determination of the value of plasticity index result in several empirical correlations.

Shrinkage limit

When drying a liquid or plastic soil mass, reduction of volume occurs to the same extent as water leaves. Shrinkage is caused by the capillary forces acting on the surface of the soil clod. At a certain water content these forces can not cause further volume reduction, volume ceases to change, the saturated soil becomes slowly unsaturated, and air phase substitutes moisture phase in the pores (see Figure 1.3).

The water content where further loss of moisture will not result in any more volume reduction is called the **shrinkage limit** (w_{zs}) or (w_s).

The finer-grained soil and the higher content of clay minerals results in the higher value of shrinkage. The quality of clay mineral content (Na-montmorillonite vs. Ca-montmorillonite), the lattice structure of clay minerals, and the thickness of the diffuse double layer are particularly important to the measure of shrinkage.

Activity

As above, consistency limits are highly influenced by clay mineral content. Soils with the same clay content can show different behaviour, thus we have to distinguish between clay content and clay mineral content. Clay content is the rate of the particles smaller than 0.002 mm ($clay\ fraction[\%]$), while clay mineral content is the quantity of clay minerals in the soil sample. Determination of the clay mineral content of a soil sample is not enough to draw conclusions about the behaviour of the soil, because there is a difference in its behaviour depending on the principal clay mineral (e.g. montmorillonite, illite, kaolinite). This property is particularly important in environmental protection for the determination of water and contamination retention capability. **Skempton's Activity value** (S), is especially useful for evaluating this behaviour. Skempton's Activity is not a consistency parameter, but affects the values of consistency limits.

The value of activity can be calculated from the plasticity index (I_p) and $clay\ fraction[\%]$:

$$S = \frac{I_p}{clay\ fraction[\%]}$$

Skempton's Activity value of the most important clay minerals:

- Kaolinite: $S = 0.25$;
- Illite: $S = 0.40$;
- Montmorillonite: $S \geq 1.25$.

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