Soil Texture, Particle Size Distribution and Soil Classification

Hillel, pp. 63-69
Soil Texture

SOIL TEXTURE is defined by size distribution or mass fractions of soil primary particles (individual grains and particles).

- Primary mineral particles formed through physical and chemical weathering of parent material and refractory organic substances make up the solid phase.
- Particle size distribution and shape are the most important characteristics affecting:
  - pore geometry
  - total pore volume (porosity)
  - pore size distribution
  - solid surface area
Methods to Determine Particle Size Distribution

• **Sieving methods** – soil particles \( \geq 0.05 \text{ mm} \) (sand fraction) we use **Sieving** methods.

• **Sedimentation methods**
  - Pipette
  - Hydrometer
  - X-ray attenuation

• **Particle counting methods**
  - Light, SEM Microscopy
  - Coulter method

• **Laser/Light diffraction methods**
Sieving Methods

For particles $\geq 0.05$ mm (sand fraction) we apply SIEVING methods.

Results are expressed as particle diameters

Note - particles are rarely spherical, hence these diameters should be regarded as effective diameters based on sieve opening size.
Particle Size Distribution - Sedimentation

• For particles ≤ 0.05 mm (silt and clay fractions) sedimentation methods based on Stokes law are used to deduce particle size distribution.

• Soil particles settle in aqueous solution attaining terminal velocities proportional to their mass and size.

• The amount of suspended soil after a given settling time is used to determine particle size fractions.

• The amount of soil in suspension is determined by either extracting a sample by the *pipette* method or from a direct *hydrometer* reading.
Stokes Law

Three forces acting on a spherical particle:

- Buoyancy and drag forces act against the gravitational force.
- A spherical soil particle D=5 µm reaches 99% of its terminal velocity in aqueous solution within 0.017 ms, and for D=1 mm the time is 0.68 s.

Buoyancy Force (weight of displaced liquid)

\[ F_b = \rho_l (4\pi r^3 / 3) g \]

Drag Force (exerted by the surrounding liquid)

\[ F_d = 6\pi r \eta V \]

Gravitational Force

\[ F_g = \rho_s (4\pi r^3 / 3) g \]

\( \rho_l \) ... density liquid \([\text{kg/m}^3]\)
\( \rho_s \) ... density solid \([\text{kg/m}^3]\)
\( r \) ... radius sphere \([\text{m}]\)
\( g \) ... acceleration of gravity \([\text{m/s}^2]\)
\( V \) ... settling velocity \([\text{m/s}]\)
\( \eta \) ... dynamic viscosity \([\text{kg/m s}]\)
Stokes Law

The three forces acting upon the settling particle quickly equilibrate and the particle reaches a constant settling velocity.

We can solve the force balance equation to obtain the settling velocity

\[ \sum F_i = 0 = F_g - F_b - F_d \]

\[ 0 = \rho_s \left( \frac{4\pi r^3}{3} \right) g - \rho_1 \left( \frac{4\pi r^3}{3} \right) g - 6\pi r \eta V \quad \Rightarrow \quad V = \frac{(\rho_s - \rho_1) d^2 g}{18 \eta} \]

Since we know that velocity equals length per time we can calculate the time particles of a certain size need to settle through a distance \( h \):

\[ V = \frac{h}{t} = \frac{(\rho_s - \rho_1) d^2 g}{18 \eta} \quad \Rightarrow \quad t = \frac{18\eta h}{(\rho_s - \rho_1) d^2 g} \]

\( t \) is the time required for particles of a certain size to settle below a certain depth \( h \).
Stokes Law - Limitations

When applying STOKES law we need to be aware of a number of simplifying assumptions:

- Particles are large enough to be unaffected by the thermal (Brownian) motion of the fluid molecules
- All particles are rigid, spherical, and smooth
- All particles have the same density
- The suspension is dilute enough that particles do not interfere with each other
- Fluid flow around the particles is laminar. That means no particle exceeds the critical velocity for the onset of turbulence

In practice we know that soil particles are neither spherical nor smooth.

Hence the diameter calculated from STOKES law does not necessarily correspond to the actual dimensions of the particles.

We rather receive an effective or equivalent settling diameter.
Soil particles are not spherical

- Relative settling velocities of triaxial ellipsoids (L=long, I=intermediate, & S=short axis) relative to spherical particle of equal volume (Matthews, 1991).
Sedimentation – Pipette Method

Typical experimental setup for the pipette method

\[ t = \frac{18\eta h}{(\rho_s - \rho_l) d^2 g} \]
Sedimentation – Hydrometer Method

The concentration (density) of suspended particles is measured directly with a calibrated Hydrometer at certain time intervals.

The hydrometer settling depth $h'$ is dependent on the concentration $R$ in g/l of the pure Sodium pyrophosphate solution and the shape and design of the hydrometer.

For the ASTM 152H Hydrometer $h'= -0.164R + 16.3$ [cm]. When $h'$ is known we can calculate settling times as:

$$t = \frac{18\eta h'}{\left(\rho_s - \rho_l\right) d^2 g}$$
Sedimentation – Hydrometer Method

All particles are in suspension

Only Silt and Clay particles are in suspension

Only Clay particles are in suspension

This hydrometer reading is: 1.008
Settling Times - Example

Use Stokes' law to calculate the time needed for: (a) sand particles (diameter >50µm) and (b) silt particles (>2µm) to settle to a depth of 0.2 m in an aqueous suspension at 25°C.

\[ t = \frac{18\eta h}{(\rho_s - \rho_l)d^2 g} \]

Sand \( d > 0.00005 \) m

\[
\begin{align*}
\eta &= 0.89 \text{ mPa s} = 0.00089 \frac{\text{kg}}{\text{ms}^2} \text{ s} \quad \text{at 25°C} \\
\rho_s &= 2650 \frac{\text{kg}}{\text{m}^3} \\
\rho_l &= 1000 \frac{\text{kg}}{\text{m}^3} \\
g &= 9.81 \frac{\text{m}}{\text{s}^2}
\end{align*}
\]

\[
t = \frac{18 \cdot 0.2 \cdot 0.00089}{(2650 - 1000)(0.00005)^2 \cdot 9.81} = 79 \text{ s}
\]

Units

- \( \left[ \frac{\text{kg}}{\text{m.s}^2} \right] \cdot \left[ \text{m} \right] = \frac{\text{kg}}{\text{s}} = \frac{\text{kg}}{\text{s}} \cdot \text{kg} = \text{s} \)
- \( \left[ \frac{\text{kg}}{\text{m}^3} \right] \cdot \left[ \text{m}^2 \right] \cdot \left[ \text{m} \right] = \frac{\text{kg}}{\text{s}^2} = \frac{\text{kg}}{\text{s}} \cdot \text{kg} = \text{s} \)

Dimensional Analysis

\[
\begin{align*}
\left[ \frac{\text{M}}{\text{L}^2 \cdot \text{t}^2} \right] \cdot \left[ \text{L} \right] = \frac{\text{M}}{\text{t}^2} \cdot \text{t}^2 = \text{M} = \frac{\text{M}}{\text{t} \cdot \text{M}} \cdot \text{t} = \text{M}
\end{align*}
\]

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Settling Times - Example

*Stokes Law*

\[
t = \frac{18 \eta h}{(\rho_s - \rho_l) d^2 g}
\]

Silt \( d > 0.000002 \) m

\[
t = \frac{18 \cdot 0.2 \cdot 0.00089}{(2650 - 1000) \cdot (0.000002)^2 \cdot 9.81} = 49485 \text{ s} = 13.74 \text{ hr}
\]
Modern methods for particle size analyses

New methods are now available (powder technology, etc.)

- Optical Microscopy
- Transmission/Scanning Electron Microscopy
- X-ray attenuation
- Particle counting (Coulter method)
- Light Scattering and Laser Diffraction Methods
Modern methods for particle size analyses (2)

Light Scattering and Laser Diffraction Methods:

- Particles of a given size diffract light at a certain angle that increases with decreasing particle size.

- Particle size distribution is inferred from light intensities measured at the detector as a function of the angle based on the Mie theory.
Modern methods for particle size analyses (3)

**X-ray attenuation (SediGraph)**

- A fine collimated x-ray beam passes through suspension
- The cell is lowered relative to the beam and relative solid concentrations at different levels and times is measured.
- Determines particles less than 1µm in 10 min.
**Coulter method**

- Counting particles passing through a sensing zone induce a perturbation.

- **Coulter method** is based on passage of particles suspended in an electrolyte through a small orifice with electrodes on each side.

- Changes in electrical impedance are proportional to the volume of particles.

- Measurement range of 0.6 to 1200\(\mu\)m.
Particle-Size Diagram

- Particle size distribution (PSD) is often expressed as particle diameter as a function of soil mass fraction of smaller particles.
- The curve is equivalent to cumulative statistical distribution of particle diameters in the sample (note log scale for particle sizes).
Comparison of methods for PS analyses

- Six methods for particle size analysis were compared in recent study by Wu et al. (1993).
- The agreement between the various methods in the data depicted is surprising considering the different physical principles and interpretation techniques behind each method.
Particle Size Distribution - Classification

- Soils are classified according to their particle size distributions.
- Classification schemes lump detailed information on particle size distributions into fractions of clay, silt, sand, and gravel.
- A commonly used scheme is the USDA classification scheme that defines the following fraction limits:

  - Particles < 0.002 mm
    - CLAY
  - Particles ≥ 0.002 mm and < 0.05 mm
    - SILT
  - Particles ≥ 0.05 mm and < 2 mm
    - SAND
  - Particles ≥ 2 mm
    - GRAVEL
Particle Size Distribution - Classification

**USDA CLASSIFICATION**

- Particles < 0.002 mm: **CLAY**
- Particles ≥ 0.002 mm and < 0.05 mm: **SILT**
- Particles ≥ 0.05 mm and < 2 mm: **SAND**
- Particles ≥ 2 mm: **GRAVEL**
From available particle size diagrams we can determine the particle fractions as shown for the clay soil above.
After the fractions (sand, silt, and clay) are determined we use the USDA textural triangle to determine the soil textural class.

Sand = 100-93 = 7%
Silt = 93-61 = 32%
Clay 61%
Field Determination of Soil Texture

Soil textural classification may be completed in the field for applications that do not require accurate quantitative determinations.

The basic approach is to hand-evaluate soil properties including the ability to form a “ribbon”, grittiness, stickiness, plasticity, and behavior of “casts” formed by squeezing.

Experienced individuals may often resolve textural classes (sand, silt, clay) to within only a few percent of those derived from other techniques, and samples can be processed rather rapidly.
Field Determination of Soil Texture

Flow chart for the “texture-by-feel” method.
Why do we need to classify soil types?

- To compress detailed PSD information into an informative “index”.
- To aggregate and create map units with similar soil properties for land use planning - farming, irrigation, construction, etc.
- Develop predictive capabilities for hydrological and other applications.
Particle Size Distribution - Example

One kilogram of soil was passed through the following series of sieves with the weights found on each sieve:

<table>
<thead>
<tr>
<th>Sieve no.</th>
<th>#4</th>
<th>#10</th>
<th>#20</th>
<th>#40</th>
<th>#60</th>
<th>#100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening size [mm]</td>
<td>4.760</td>
<td>2.000</td>
<td>0.840</td>
<td>0.420</td>
<td>0.250</td>
<td>0.147</td>
</tr>
<tr>
<td>Weight [g]</td>
<td>45</td>
<td>115</td>
<td>40</td>
<td>10</td>
<td>100</td>
<td>70</td>
</tr>
</tbody>
</table>

The soil that did not pass through the largest sieve was collected in a pan. 40 g of the original sample was then tested by the sedimentation method at 25°C. Hydrometer readings in a 1 liter aqueous suspension (after subtracting the blank reading of 2 g/l) were converted to effective diameters (µm) as shown in the following table:

<table>
<thead>
<tr>
<th>Time [sec]</th>
<th>30</th>
<th>60</th>
<th>180</th>
<th>5400</th>
<th>16200</th>
<th>43200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective diameter [µm]</td>
<td>66.5</td>
<td>47.6</td>
<td>28.0</td>
<td>5.3</td>
<td>3.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Hydrometer reading [g/l]</td>
<td>19</td>
<td>17</td>
<td>15</td>
<td>8</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

1. Find the soil’s Sand, Silt, and Clay contents, and its USDA textural class.

2. Use all the information to draw a particle size distribution diagram (use semi-log scale)
The first step is to convert the weight in g that passes a certain “sieve” to cumulative %.

The hydrometer readings are related to 40 g of the original sample of 1 kg. E.g. a hydrometer reading of 17 g/l gives $\frac{17 \cdot 100}{40} = 42.5\%$.
# Particle Size Distribution - Example

<table>
<thead>
<tr>
<th>Equivalent Particle Diameter [mm]</th>
<th>Weight Passing [g]</th>
<th>Weight Passing [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 4.760</td>
<td>1000</td>
<td>100.0</td>
</tr>
<tr>
<td>4.760</td>
<td>955</td>
<td>95.5</td>
</tr>
<tr>
<td>2.000</td>
<td>840</td>
<td>84.0</td>
</tr>
<tr>
<td>0.840</td>
<td>800</td>
<td>80.0</td>
</tr>
<tr>
<td>0.420</td>
<td>790</td>
<td>79.0</td>
</tr>
<tr>
<td>0.250</td>
<td>690</td>
<td>69.0</td>
</tr>
<tr>
<td>0.147</td>
<td>620</td>
<td>62.0</td>
</tr>
<tr>
<td>Silt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.067</td>
<td>19 (475)</td>
<td>47.5</td>
</tr>
<tr>
<td>0.048</td>
<td>17 (425)</td>
<td>42.5</td>
</tr>
<tr>
<td>0.028</td>
<td>15 (375)</td>
<td>37.5</td>
</tr>
<tr>
<td>0.005</td>
<td>8 (200)</td>
<td>20.0</td>
</tr>
<tr>
<td>0.003</td>
<td>6 (150)</td>
<td>15.0</td>
</tr>
<tr>
<td>0.002</td>
<td>5 (125)</td>
<td>12.5</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.002</td>
<td></td>
<td>12.5</td>
</tr>
</tbody>
</table>

Sand [%] = 84.0 - 42.5 = 41.5

Silt [%] = 42.5 - 12.5 = 30.0

Clay [%] = 12.5
Particle Size Distribution - Example

**USDA textural class**
The USDA classification only considers particle fractions smaller than 2 mm. Since 16% of the particles of our sample are larger 2 mm, we have to modify the values calculated on the previous slide.

Sand [%] = 41.5 * (100 / 84) = 49.4
Silt [%] = 30.0 *(100 / 84) = 35.7
Clay [%] = 12.5 *(100 / 84) = 14.9
Particle Size Distribution - Example

Particle Size Diagram

- Sieving
- Hydrometer

Log-Scale
Specific Surface Area of Soil Particles

Hillel, pp. 69-72

CE/ENVE 320 – Vadose Zone Hydrology/Soil Physics
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Surface Area

- The large interfacial area per unit volume in soils give rise to liquid-solid interactions and adsorption of water & chemicals.
- The soil clay fraction dominates soil specific surface area.

Clay $\sim 800 \text{ m}^2/\text{g}$

Sand $\sim 0.01-10 \text{ m}^2/\text{g}$

Effect of soil particle size and shape on soil surface area
Specific Surface Area of Soil Particles

Specific surface area is a fundamental and intrinsic property of soils that correlates with important phenomena like:

- Cation exchange
- Adsorption and Release of Chemicals
- Swelling
- Water Retention
- Soil Plasticity, Cohesion, and Strength
Specific Surface Area of Particles - Definitions

The specific surface area of soil particles may be defined as:

- Total Surface Area per Unit of Mass of Particles

\[ A_m = \frac{A_s}{M_s} \quad [m^2/g] \]

- Total Surface Area per Unit of Volume of Particles

\[ A_v = \frac{A_s}{V_s} \quad [m^2/m^3] \]

- Total Surface Area per Unit of Volume of Soil

\[ A_b = \frac{A_s}{V_t} \quad [m^2/m^3] \]

Specific surface area depends primarily on size, shape, and surface roughness of particles.
Specific surface area of regular particles

The shape of sand and silt-sized particles is commonly idealized with smooth spheres. The specific surface of a spherical particle \([\text{Surface Area/Mass}]\) is calculated as:

\[
A_m = \frac{a}{m} = \frac{a}{V \cdot \rho_s} = \frac{4 r^2 \pi}{\left(\frac{4 \pi r^3}{3}\right) \cdot \rho_s} = \frac{3}{\rho_s r}
\]

The shape of clay particles is commonly idealized with smooth disk-shaped platelets with specific surface area given as:

\[
A_m = \frac{a}{m} = \frac{2 r^2 \pi + 2 r \pi x}{r^2 \pi x \rho_s} = \frac{2 r \pi (r + x)}{r^2 \pi x \rho_s} = \frac{2 (r + x)}{r x \rho_s} \approx \frac{2}{x \rho_s}
\]

\(r \gg x\)
Calculated specific surface areas for idealized soil particles

Table 1-3: Specific surface area of soil particles \( (\rho_s=2700 \ \text{kg/m}^3) \) (Jury et al., 1992)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Idealized Shape</th>
<th>Effective Diameter ([\text{cm}])</th>
<th>Mass ([\text{g}])</th>
<th>Area ([\text{cm}^2])</th>
<th>Specific Surface Area ([\text{cm}^2/\text{g}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>Sphere</td>
<td>(2 \times 10^{-1})</td>
<td>(1.13 \times 10^{-2})</td>
<td>(1.26 \times 10^{-1})</td>
<td>11</td>
</tr>
<tr>
<td>Sand</td>
<td>Sphere</td>
<td>(5 \times 10^{-3})</td>
<td>(1.77 \times 10^{-7})</td>
<td>(7.85 \times 10^{-5})</td>
<td>444</td>
</tr>
<tr>
<td>Silt</td>
<td>Sphere</td>
<td>(2 \times 10^{-4})</td>
<td>(1.13 \times 10^{-11})</td>
<td>(1.26 \times 10^{-7})</td>
<td>11100</td>
</tr>
<tr>
<td>Clay*</td>
<td>Disk</td>
<td>(2 \times 10^{-4})</td>
<td>(8.48 \times 10^{-15})</td>
<td>(6.28 \times 10^{-8})</td>
<td>7400000</td>
</tr>
</tbody>
</table>

\* Thickness \(\approx 10^{-7}\) cm
Calculations for Smooth and Spherical Particles

Specific surface area calculations assuming smooth and spherical particles may lead to serious underestimation of actual surface area as shown by Borkovec et al. [1993].

- Methylene Blue Adsorption (Particle Size Distribution - Sedimentation)
- Nitrogen Adsorption (PSD - Sedimentation)
- Nitrogen Adsorption (PSD - Microsieving)
- Nitrogen Adsorption (PSD - Sieving)
- Calculated Assuming Smooth and Spherical Particles
Small particles dominate soil SA

Comparison of particle size distribution and associated contribution to soil surface area (Borkovec et al., 1993)
Specific surface can be estimated from the clay fraction and mineralogy (Or and Wraith, 1999).
For Montmorillonite-Kaolinite dominated clay fractions we can estimate specific surface area according to:

\[ A_m [m^2/g] = 5.65 \text{ Clay}\% - 18.9 \]

For Kaolinite-Illite dominated clay fractions:

\[ A_m [m^2/g] = 1.87 \text{ Clay}\% + 6.0 \]
Specific Surface Area – Measurement Methods

Gas adsorption isotherms are measured with automated surface area analyzers.

Nitrogen gas $N_2$ is commonly used for gas adsorption.
First we saturate an oven-dry soil sample with EGME. Then we evaporate excess EGME in an evacuated system.

The evaporation rate decreases when all free EGME is gone and only that adsorbed monolayer is left.

From measurements and theoretical considerations for pure Montmorillonite we know that 0.000286 g EGME is required to cover 1 m² of clay with one monolayer.

From weighing the dry sample and the EGME treated sample in consecutive time steps until it attains a constant mass we can determine the mass of adsorbed EGME.

\[ A_m = \frac{\text{Adsorbed EGME after Evaporation}}{\text{Weight of Dry Sample}} \cdot 0.000286 \text{[g/m}^2\text{]} \]
Specific Surface Area – Measurement Methods

Non-polar ($N_2$) probe molecules measure only external surface area because they are not able to access crystallographic planes of expandable clay minerals or complex organic structures.

Polar molecules penetrate interlayer surfaces providing a measure of both internal and external surface area.