SOIL PHYSICS

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Contents

Biographical Sketch

Summary

Soil physics deals with the physical properties of the soil and their measurement, and the physical processes taking place in and through the soil. Soil consists of a mixture of mineral particles, organic substance, water, soluble components and gases. The individual mineral particles form the soil texture which is composed of sand, silt and clay with variable diameter. The clay fraction consists of several types of clay minerals with various physicochemical properties. The particle size distribution displays the relative amount of a range of size fractions, while the textural triangle shows the soil composition based on the relative amount of the three main soil fractions.

The aggregation of individual soil particles into clods or peds constitutes the soil structure in which the clay particles and the humus play a preponderant cementing role. Although characterized as single grained, massive or aggregated, there is no generally accepted method to define soil structure. This is also the case for aggregate stability which can only be described in subjective terms.

Soil physical and hydraulic properties such as specific soil surface, particle and bulk density, porosity and void ratio, water content, plasticity index, and saturated and unsaturated hydraulic conductivity are described. The significance of soil texture, structure and properties on agriculture is discussed briefly.

1. Introduction

Soil physics is the branch of soil science dealing with the physical properties of the soil, as well as with the measurement, prediction, and control of the physical processes taking place in and through the soil (Hillel, 1998). Soil physics involves both the understanding of soil behavior and its management and is, therefore, both a basic and an applied science.

The soil is a mixture of mineral particles, organic substances, soluble components, water and gases composing the bio-substrate. The mineral fraction consists of particles of different size, shape and composition. Organic matter includes plant and animal residues in various stages of decomposition, but also living organisms. The soluble components determine the chemical composition of the soil water filling part or all of the pores between the solid particles. Pores that do not contain water are filled with gases or vapor. The nature and properties of the solid, liquid and gaseous phases affect the chemical and physical interactions, and these are influenced themselves by temperature, pressure and light.

The mineral fraction of the solid phase may be completely dispersed or stick together to granules and/or aggregates. The total amount of individual particles is referred to as *soil texture* while the aggregation of individual particles to soil clods (or soil peds) is known as *soil structure*.

The soil as a whole is a dynamic entity and is constantly in search of an equilibrium

state, as it alternately wets and dries, swells and shrinks, disperses and flocculates, hardens and softens, warms and cools, freezes and thaws, compacts and cracks, absorbs and emits gases, adsorbs and releases exchangeable ions, precipitates and dissolves salts, becomes acidic or alkaline, and exhibits aerobic or anaerobic conditions leading to chemical oxidation or reduction (Hillel, 1998). The soil is a complex system that is idealized to understand and simulate some aspects of the soil behavior.

Soil interacts also with the ambient bodies and thus, absorbs energy and water from the atmosphere. The large soil pores drain the water downward while the fine pores retain moisture either for plant consumption or evaporation. In this respect, the soil serves as a medium for plant growth. Plant roots can penetrate and ramify in a loose, porous and well-aerated soil to achieve anchorage and to extract moisture and nutrients.

2. Soil Texture

Soil texture is an intrinsic attribute of the soil and it is, therefore, often used to specify its physical composition. Soil texture refers to the size range of the solid particles in the soil resulting from the weathering of parent rocks. The loose products may stay in place to form a residual soil, or may be transported by water, glacier or wind and be deposited at some distance from the original site.

The process of soil formation requires many thousands of years (see *Pedogenesis and Soil Forming Factors, and their Effect on Land Use*). The size and shape of the individual particles and their chemical and mineralogical composition are of particular interest because they affect the nature and properties of the soils involved, as for example hydraulic conductivity and natural fertility.

Soil particles are grouped into classes on the basis of size, and the relative proportions of these classes characterize the texture of the soil. These classes often differ also in mineral composition. Both particle size and mineral composition largely determine the nature and behavior of a soil like porosity, interactions with solutes, soil compaction, soil strength, etc.

The soil particle sizes are expressed in terms of an equivalent diameter because soil particles are not spherical but an-isometric. The equivalent diameter depends on the size of the particles. For larger soil particles that are separated by mechanical sieving (see below) it refers to the diameter of a sphere that passes through a given square opening size. For smaller particles sedimentation techniques are used to determine the sizes, and the equivalent diameter refers to the diameter of a sphere with the same density and velocity of settling in an aqueous medium. The largest soil particles are generally visible to the naked eye, whereas the smallest colloidal particles can only be observed with an electron microscope.

2.1. Mineral Soil Fractions

Soil particles are separated into three main classes: clay, silt and sand; these can still be subdivided depending on the classification system considered (Figure 1).

Diameter of soil particles (mm)

| | 0.001 | 0.01 | 0.1 | 1.0 | 10.0 |

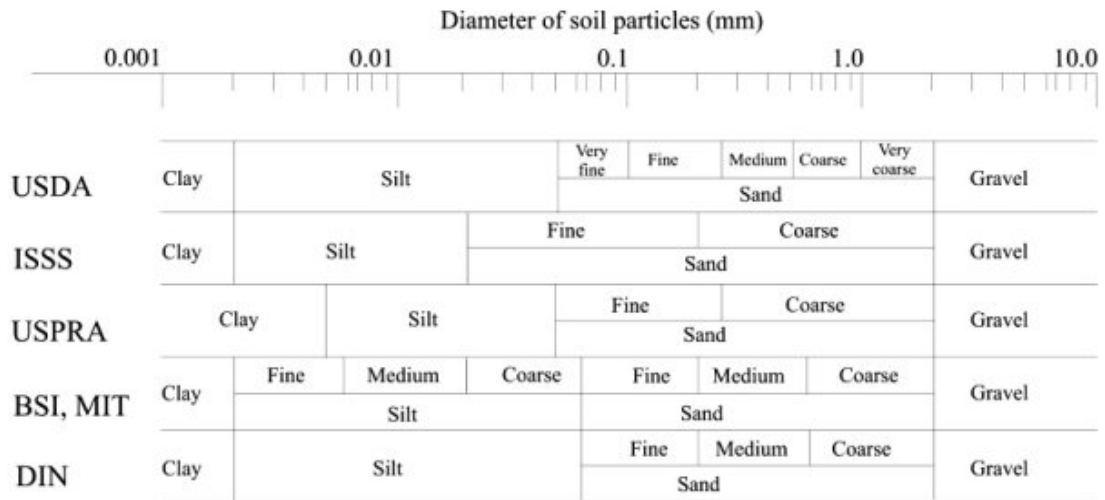|									
USDA	Clay	Silt	Very fine	Fine	Medium	Coarse	Very coarse	Gravel
			Sand					
ISSS	Clay	Silt	Fine		Coarse		Gravel
			Sand				
USPRA	Clay	Silt	Fine		Coarse		Gravel
			Sand				
BSI, MIT	Clay	Fine	Medium	Coarse	Fine	Medium	Coarse	Gravel
		Silt			Sand			
DIN	Clay	Silt		Fine	Medium	Coarse	Gravel
				Sand			

Figure 1. Classification of soil fractions by particle size diameter ranges as defined by: United States Department of Agriculture (USDA); International Soil Science Society (ISSS); United States Public Road Administration (USPRA); British Standards Institute (BSI); Massachusetts Institute of Technology (MIT); and German Standards (DIN) (after Hillel, 1998).

Two of these systems are used in agriculture: the USDA and the ISSS classifications. The other systems are mainly applied in geotechnical and construction works. In the first group, only the upper limit of the clay fraction, 0.002mm (2µm) is common to both classifications. This key particle size is based on the physical and chemical properties associated with the surface activity of clays.

Silt and sand fractions mainly consist of weathering-resistant primary minerals of the parent material. They do not display a distinct physical or chemical activity and are, therefore, considered the skeleton of the soil. Clay, on the other hand, contains secondary minerals formed in the soil itself from the decomposition of the primary minerals.

2.1.1. Sand

The conventional definition of soil material includes particles up to 2mm in diameter and excludes larger particles such as gravel, stones, cobbles and even boulders with a diameter of several centimeters. The connotation of soil texture in agricultural studies involves therefore only the particle size distribution of the fine soil fraction.

The largest group of soil particles is sand with sizes ranging from 2000µm (2mm) to 50µm (USDA-classification) or to 20µm (ISSS-classification). This fraction is generally subdivided into coarse, medium and fine sand (Figure 1). Sand particles usually consist of quartz but may also contain fragments of other minerals such as feldspar, mica and occasionally heavy minerals such as zircon, tourmaline and hornblende, although the latter is rather rare (Mack and Leistikow, 1996).

2.1.2. Silt

The silt fraction comprises particles between 2 and 50µm (USDA-classification) or between 2 and 20µm (ISSS-classification). Silt particles have similar mineralogical and physical properties as sand, but because they are much smaller, they have a greater surface area per unit mass and are often coated with strongly adhered clay particles. Therefore, (fine) silt may exhibit to a limited extent some physicochemical properties of clay.

2.1.3. Clay

Clay particles range in diameter from 2µm downward and constitute the colloidal soil fraction; they are plate- or needle-like and belong mineralogically to the aluminosilicates. The clay fraction strongly affects soil behavior because of its great surface area per unit mass and physicochemical activity. A clay soil will usually exhibit a plastic behavior, is sticky when moist and hard when dry.

A general knowledge of the chemical and physical nature of clay is needed to understand its physical behavior. Chemically, the clay is usually composed of SiO_2, Al_2O_3, Fe_2O_3 and H_2O along with varying amounts of MgO, CaO, Na_2O and P_2O_3. Physically, clays are distinctly crystalline minerals, yet also certain amounts of non-crystalline material may be present. The main building stones of clay are aluminum and silicon (see also *Soil Mineralogy*).

The alumina units consist of two sheets of closely packed oxygen atoms or hydroxyl groups, held together by an aluminum atom forming an octahedron of six oxygen atoms or hydroxyl groups, three in each sheet, surrounding one aluminum atom. The silica units consist of a sheet of oxygen atoms that are held together by silicon atoms. A tetrahedron of four oxygen atoms, three in the sheet and one above, surrounds the silicon atom. The oxygen atom above the sheet provides the possibility to link a silica unit with an alumina unit since it can serve as one of the six oxygen atoms surrounding the aluminum in the alumina unit. The interlinking of a number of specific sheets into various layer-lattice structures along with the origin and nature of the isomorphous substitution of representative atoms in the crystal result in several types of crystalline clay minerals. Isomorphous substitution within a crystal lattice creates a negative structural charge and, thus, attracts positively charged (exchangeable) cations.

In a dry state, colloidal particles attach the neutralizing counter-ions close to their surface, but upon wetting some of these ions dissociate from the surface and enter into solution. The hydrated colloidal clay or humus particles form a micelle in which the adsorbed ions are spatially separated, to a greater or lesser extent, from the negatively charged particle thus forming an *electrostatic double layer*. The thickness of this layer depends on the valence of the cations and is twice as thick for monovalent cations as for divalent cations. The concentration affects the thickness as well, in the sense that higher concentrations reduce the double layer thickness compared to lower ones. Other cations introduced in the solution can replace (exchange) the cations in the double layer.

The total number of exchangeable cations is nearly constant under chemically neutral conditions and is independent of the cations present. It is an intrinsic property of the soil material commonly called the called the *Cation Exchange Capacity* (CEC) and (in the

older literature) expressed in milli-equivalents/100 g (me/100 g) or (in more recent work) in centimoles/kg (cmol$_c$/kg) of dry soil. The CEC of a soil ranges from nil in sands to 100 me/100 g and more in clayey and/or organic soils. It does not only depend on the clay content but also on the clay type. Several types of clay minerals can be recognized:

- The *kaolinite group* has one silica and one alumina unit stacked in alternating fashion (1:1 lattice type). No ions or water molecules can enter the adjacent layers, and only the external surfaces determine their colloidal properties. Owing to its relatively large particles and low specific surface, kaolinite exhibits less plasticity, cohesion and swelling as compared to other clay minerals. The CEC is less than 10-15 me/100 g of clay.
- The *illite group* belongs to the hydrated micas within the 2:1 lattice type and consists of two silica and one single alumina unit. Aluminum (Al) replaces the silicon (Si) in the silica units and the negative charges are compensated by potassium (K) atoms which are partially embedded within the units and bind them firmly together, so the expansion of the lattice is effectively prevented. The CEC ranges between 20 and 40 me/100 g.
- The *vermiculite group* is similar to the illite group, except that magnesium (Mg) rather than K is the exchangeable cation of the interlayer. As Mg ions are highly hydrated, both an interlayer of exchangeable cations and water hold the units of the 2:1 lattice together. The lattice exhibits therefore only a relatively limited expansion capacity depending on the size of exchangeable ions present in the interlayer. The CEC varies between 100 and 150 me/100 g and includes both external and internal surfaces.
- The *montmorillonite or smectite group* is a 2:1 lattice clay type and contains minerals like montmorillonite, beidellite and nontronite. Some substitution of Al for Si has occurred in the silica unit and of Fe and Mg for Al in the alumina unit. The layers are not tightly bound, so that water, ions and even organic compounds can enter between them. This causes interlayer swelling and expansion of the crystal lattice, contrary to the hydrated micas. The CEC of montmorillonite varies between 80 and 150 me/100g, and the high expansion of the crystal lattice results in a pronounced swelling and shrinking with varying moisture conditions in the soil, as well as in a high soil plasticity and cohesion. On drying, montmorillonite clays tend to crack and form unusually hard clods.
- The *chlorite group* has a 2:2 lattice type wherein Mg rather than Al is the predominant ion in the alumina unit. Essentially, the chlorite structure consists of two silica, one alumina and one magnesia unit. Substitution of Al for Si in the silica unit and of Al and Fe for Mg in the magnesia unit results in electrostatic binding of the structural units. The CEC ranges between 10 and 40 me/100 g and, therefore, chlorite behaves like illite.
- The *attapulgite* or *palygorskite group* has a 2:1 lattice that extends in only one direction, thus resulting in needle or chain-like minerals. Two silica units enclose the magnesia unit because Mg predominates over Al. Isomorphous substitution of Al for Si in the silica unit is rather small but isomorphous substitution of Al and some other cations such as iron (Fe) and manganese (Mn) in the magnesia unit is high. The amount of exchangeable ions is rather low and, consequently, the CEC ranges only between 5 and 30 me/100 g. This type of mineral is common in arid soils.

- The *interstratified* or *mixed-layer* group consists of a mixed stacking of various units, instead of a uniform stack of the same units, which all have, with the exception of the fibrous clay group, a layered structure with oxygen atoms or hydroxyl ions around Al, Si, Fe and Mg. This holds true for the kaolinite, illite, vermiculite, montmorillonite and chlorite minerals. Differences in the structure of the crystal lattice of the clay minerals will affect their physical and chemical properties, particularly the CEC and hydration properties.
- The *allophanes* are non-crystalline (amorphous) colloids composed of poorly structured silica and alumina components found in volcanic ashes. They have a large specific surface area, high cation and anion exchange capacities, and hold tremendous quantities of water.

Typical properties of some clay minerals are given in Table 1. The imbalance of proton and hydroxyl charges on the exposed edges of broken clay lattice bonds engenders surface charges that may even become positive at low pH-values. Consequently, pH-sensitive clay minerals may display a capacity for anion adsorption that was specifically noticed in kaolinite. Anion adsorption is selective: silicate and phosphate ions are more strongly adsorbed than sulfate, nitrate or chloride ions.

Properties	Clay mineral				
	Kaolinite	Illite	Montmorillonite	Chlorite	Allophane
Planar diameter (µm)	0.1-4	0.1-2	0.01-1	0.1-2	
Basic layer thickness (nm)	0.72	1	1	1.4	
Particle thickness (nm)	50	5-30	1-10	10-100	
Specific surface (m²/g)	5-20	80-120	700-800	80	
CEC (me/100 g)	3-15	15-40	80-100	20-40	40-70
Area per charge (nm²)	0.25	0.5	1	0.5	1.2

Table 1. Typical properties of selected clay minerals (Hillel, 1998).

2.2. Organic Soil Fraction

The organic soil fraction, or humus, contributes only indirectly to soil texture, but affects other soil properties, including texture, in many ways. This dark material is found in the surface soil and characterizes the more or less stable soil organic matter fraction remaining after the major portion of added plant and animal residues have decayed. Humus does not include undecomposed or partially decomposed organic residues such as recent stubble or dead roots.

Humus particles are, like clay, negatively charged and form micelles capable to hydrate and to adsorb cations among other organic and inorganic constituents. Their charge results from the dissociation of organic carboxylic and phenolic groups, and their cation exchange capacity (CEC) is due to the replacement of hydrogen, and thus pH dependent. The CEC increases at higher pH-values. The CEC of humus is much greater per unit mass than of clay. Humus can, therefore, store and slowly release large amounts of nutrients for plant uptake.

The humus content of a soil varies from as high as 10% and more in typical black prairie soils to almost 0% in the desert soils; it is of the order of 1-3% in most temperate soils. Humus content normally decreases with depth and is negligible at the bottom of the root zone. Organic soils like peat or muck may contain more than 50% organic matter, which is not all humus if the strict definition of humus is considered. Humus coagulates with clay and serves as a cementing agent, binding and stabilizing soil aggregates and improving soil structure.

2.3. Particle Size Distribution

The major method to measure the particle size distribution of a soil is the mechanical analysis. The results of this analysis can be presented as a particle size distribution curve which displays the complete array and distribution of the particle sizes, or in a textural triangle based on the relative amounts of the clay, silt and sand fractions.

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Biographical Sketch

Willy Dierickx is a senior research officer retired from the Institute for Agricultural and Fisheries Research, Technology and Food, Agricultural Engineering, of the Ministry of the Flemish Community, Merelbeke, Belgium. He holds a M.Sc. in Agricultural Engineering, with specialization in Drainage and Irrigation Engineering, from the University of Ghent (1966), and a Ph.D. in Agricultural Science from the University of Wageningen, The Netherlands (1980).

He has been active for more than thirty years in agricultural water management research. His research topics were the hydraulics of drainage materials and geotextiles both in the laboratory and in the field. He participated in many international conferences taking responsibilities as session chairman or keynote lecturer. He is author/co-author of numerous scientific papers, and co-author of a FAO Drainage and Irrigation paper on subsurface drainage materials and an ILRI-book on subsurface drainage envelopes. As a scientist, he carried out several scientific and technical advisory missions (Egypt; Pakistan, India and Suriname) by order of the Dutch government, UNDP and development companies. Currently, he is joint Editor-in-Chief of the scientific journal 'Agricultural Water Management' edited by Elsevier.