

INTRODUCTION TO SOIL PHYSICS

S.W. Duiker and D.D. Fritton

The Department of Crop and Soil Sciences, Pennsylvania State University, Pennsylvania, USA.

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Summary

Soil physics is the study of the solid, liquid, and gaseous phases of soils and of fluxes of fluids and energy in soils. The solid phase consists of mineral and organic matter. The dominant liquid in soils is water, and the dominant gases are similar to those in the atmosphere, except that soils contain more CO₂ and water vapor and less O₂. Interactions between the three phases in soils determine the movement of fluids and energy. Soil physics established itself as a scientific discipline in the early 20th century. Much progress has been made since then in the characterization of the physical properties and processes in soils. Soil physics has been applied in studies of soil erosion, organic matter management, compaction, irrigation, drainage, and crop water use, to mention a few examples only.

Much progress has been made in soil physics by reducing studies to the physical aspects of soil only. Now seems to be the time to place this knowledge back into the context of the larger creation. It is proposed in this article that soil physics can make its greatest contribution to sustainable world development if more attention is given to how human

stewardship affects interactions between soil, water, atmosphere, plants, and animals. This will require collaboration between scientists of different disciplines. Some promising examples of cross-disciplinary collaboration of soil physicists with other scientists are given, including: crop growth simulation modeling and geographic information systems, a historical study of the human dimensions of soil rehabilitation, and soil quality studies.

1. The beginning of soil physics

The importance of soil physical properties has been recognized since the early days of agriculture, as evidenced by the use of tillage tools for land preparation, for example. It is, however, generally accepted that the scientific study of the physical properties of soils started in Europe in the early nineteenth century. Most of the early soil physics research focused on the effects of soil physical properties on crop growth, although the discovery of Darcy's law was a direct result of the application of soil physics to water pollution problems in France.

German scientists Schübler, Schumacher, and Wollny were among the first to study soil physical properties for crop production in the nineteenth century. Schübler determined specific gravity, bulk density, water-holding capacity, swelling/shrinkage, hygroscopic water content, heat capacity, latent heat of wetting, and electrical conductivity of soils. Schumacher's interest was more in the movement of air and water in the soil. Schumacher introduced the concept of capillary-saturation capacity (or 'field capacity') of soils, and suggested various management practices to improve the structure of soils.

Wollny studied the effects of plant growth and soil management on soil physical properties. He founded one of the first soil physics journals ('Forschungen auf dem Gebiete Agrikulturphysik' 1878-1898), and is therefore considered by many to be the father of soil physics in Europe. He did experiments to measure soil temperature, water and gaseous composition, how these properties were affected by soil management and earthworms, and how this affected crop productivity. Also in Europe, French scientist Schloesing and Dutch scientist Van Bemmelen wrote about the colloidal properties of clay in the late nineteenth century, including its ability to hold water when air-dry. Mitscherlich researched the heat of wetting of soil and refined the method to determine hygroscopic water content.

Darcy did his experiments in the nineteenth century in France that lead to the formulation of Darcy's law of saturated flow, published in 1856. Darcy worked for the city of Dijon that hired him to develop a treatment system for its surface water that was highly polluted by its famous mustard industry. Darcy's law was later independently derived by Hagen and Poiseuille from Newton's law of viscosity and the water flux in capillary tubes.

In America, scientists Hillgard, Johnson, King, and Slichter investigated various aspects of soil physics in the nineteenth century. Hillgard studied the particle size of soils and laid the foundations for modern soil survey. Johnson researched the effects of tillage on soil physical properties and capillary movement of water. King, considered to be the father of soil physics in the United States, researched the water holding capacity of

soils, the water requirements of different crops, air porosity, and the effects of tillage on soil. King published a book ‘Physics of Agriculture’ that remained the authoritative text on soil physics for several decades. Slichter did fundamental research into steady-state movement of water in soils and introduced the term ‘potential’ into soil physics literature.

Briggs and Shantz developed the concept of maximum available moisture, defined as the difference between wilting coefficient (‘wilting point’) and moisture equivalent (roughly ‘field capacity’). Their study ‘The wilting coefficient for different plants and its indirect determination’ was published in 1912. Buckingham, in 1907, published ‘Studies on the Movement of Soil Moisture’, in which he recognizes that water flow in unsaturated soils is proportional to matric potential. Unfortunately, the importance of this work was only recognized many years later.

By the 1920s, soil physics had become a recognized discipline. Probably the first soil physics course was taught in 1899 at the Ohio State University. Finally, scientific journals were initiated in which soil physical studies were published, e.g. The British Journal of Agricultural Science (1865-), Discussions of the Faraday Society (1903-), the Proceedings of the American Society of Agronomy (1907-), Soil Science (1916-), and Hilgardia (1925-).

2. Contemporary soil physics

2.1. Theory of soil physics

2.1.1. Solid phase

A large fraction of the solid phase of the soil consists of a size distribution of inorganic particles. Various scientific disciplines have classified inorganic particles into groups, called soil separates, based on their size. One common classification, used by the USDA in the United States, is shown in Table 1. Soil texture is defined as the relative proportion of sand, silt, and clay in the < 2.0-mm inorganic fraction of the soil.

Soil Separate	Size Range (mm)	Shape	Surface Area (m ² g ⁻¹)
Rock Fragments	> 2.0	Irregular, rounded, to thin and flat	up to 0.001
Sand	0.05 – 2.0	rounded, irregular	0.001 to 0.04
Clay	0.002 – 0.05	rounded, irregular	0.04 to 1.0
Silt	< 0.002	platelike	5 to 870

Table 1. The USDA classification of soil particles and selected properties.

The organic fraction of the solid phase of the soil typically represents 10 to 50 g kg⁻¹ of solids in the A horizon of an inorganic soil. Lower horizons in the soil profile typically contain < 10 g of organic matter per kg of solids. Soils are classified as organic soils if the proportion of organic materials exceeds 200 g kg⁻¹ of solids. Organic matter in a soil ranges from relatively inert particles of plant and animal material to their decomposition residues, called humus. Most of the humus, the active fraction of the organic matter, is

bonded to the inorganic fraction of the soil. Humus decomposes very slowly and some of it has been in the soil over 1000 years.

The < 0.002-mm fraction of the soil, the clay and humus portion, is the physically and chemically active part of the soil. The mineralogy and the proportion of the < 0.002-mm fraction of the soil determine to a large extent the physical and chemical properties of a soil. Most of the < 0.002-mm fraction of the soil is composed of sheets of layer silicates. The properties of these minerals are shown in Table 2.

The solid phase is not a completely disorganized jumble of materials. We know that in the top meter or so, most of the material that is smaller than 2.0 mm in size is usually organized into units, called peds or soil structural units, as shown in Figure 1. These units are formed from numerous adjacent particles that are weakly glued together by the highly active clay and humus material. Normally only one of these shapes is dominant in any one horizon of the soil. The genesis of peds is not completely understood, but it involves the types of layer silicate clays, iron and aluminum oxides, shrinking and swelling of the solid phase, the wetting and drying of the particles, the activity of animals and plants, and the availability of organic exudates and decay products.

Layer Silicate	Surface Area ($\text{m}^2 \text{g}^{-1}$)	Cation Exchange Capacity ($\text{cmol}_c \text{kg}^{-1}$)
Kaolinite	10 – 20	3 - 15
Illite	65 – 100	0 - 40
Vermiculite	40 – 870	100 - 150
Smectite	50 – 840	80 - 150
Chlorite	80	10 – 40

Table 2. Properties of some common layer silicate clays.

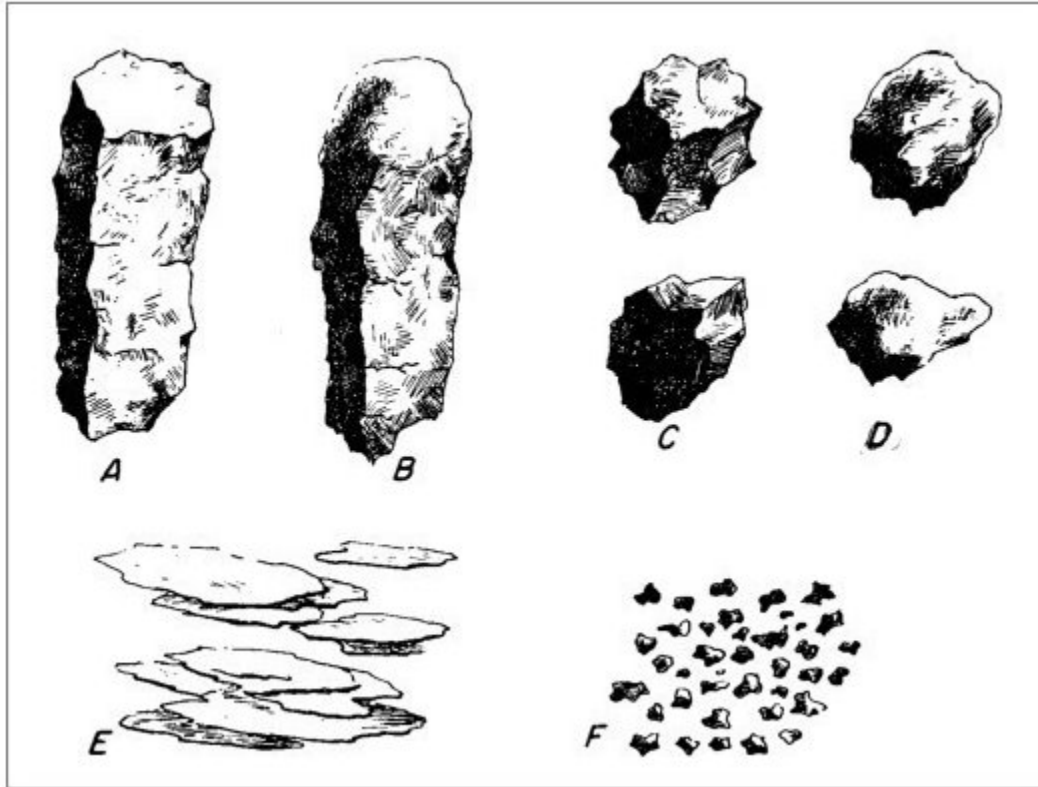


Figure 1. Drawings illustrating some of the types of soil structure: A. prismatic, B. columnar, C. angular blocky, D. subangular blocky, E. platy, and F. granular. From USDA (1951). *Soil Survey Manual*. USDA Agriculture Handbook No 18.

The solid phase of the soil is characterized as well by its density. Individual particles have a density similar to their primary minerals ranging from 1.3 Mg m^{-3} for organic particles to 3.5 Mg m^{-3} or greater for soils with high iron content. The average density of all particles in the soil is called the particle density.

Most soils have a particle density close to that of quartz and a value of 2.65 Mg m^{-3} is frequently used. Since soils contain pore space as well as solid-filled space, a second density, the bulk density, is used to represent the mass of solids divided by the total volume occupied by the solids and pores. Soils vary widely in this property, but values of bulk density typically are between 1.0 and 2.0 Mg m^{-3} with values in the range of 1.2 to 1.5 Mg m^{-3} being optimum for most plant growth.

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Biographical Sketches

Daniel D. Fritton is professor of soil physics at the Department of Crop and Soil Sciences, The Pennsylvania State University, USA, where he teaches courses in soil science and soil physics. He and his students have performed research on the effect of soil physical properties on soil compaction, soil profile modification, corn root growth, on-site effluent disposal, nitrate pollution, macropore flow, and hydraulic conductivity. He is an author or co-author of numerous publications on these subjects.

Sjoerd W. Duiker is assistant professor of soil management and applied soil physics at the Department of Crop and Soil Sciences, The Pennsylvania State University, USA. His expertise is in soil management for sustainable crop production. Areas he has worked and published in include: carbon sequestration, soil erosion, soil compaction, no-tillage agriculture, weed management in pearl millet, and cassava in East Africa.

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