

R.N.YONG/B.P.WARKENTIN

SOIL PROPERTIES AND BEHAVIOUR

DEVELOPMENTS IN GEOTECHNICAL ENGINEERING VOL 5

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Developments in Geotechnical Engineering 5

SOIL PROPERTIES AND BEHAVIOUR

by

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PREFACE

Since publication of *Introduction to Soil Behaviour* by the authors a certain degree of formalization has been achieved in the study of soil behaviour. Whilst some aspects of soil behaviour are still in the stages of initial development, the subject of soil behaviour itself can now be considered to be a discipline standing on a base which draws from various allied fields. In this, it resembles most other disciplines. Considerable progress has been made in the development of various tools and techniques for evaluation of the specific interactions between soil particles and water, which allow the further development of fundamental concepts and mechanisms describing the behaviour of soil in response to external constraints.

The interaction of the various constituents in soil defines the integrity of the system. A proper modelling of the physics of the problem is required in order to provide adequate and meaningful analysis and prediction for application in the fields of geotechnical engineering where a knowledge of soil behaviour is needed to analyse or predict soil-response behaviour to external loads, of soil science and agronomy where soil water and the structure of soils are studied in relation to plant growth, and of agricultural engineering where response behaviour of surficial soils is required.

The material in the book is developed along the lines of the need for a fundamental appreciation of the physical constituents and their interactions which define structure of the soil-water system. Chapters 1 and 2 provide the background for an understanding of the nature of the mineral particles and the forces existing between the particles in the soil system. The structure and fabric of soil are developed in Chapter 3, and their relationship with water is examined in Chapter 4. The mechanisms involving water movement and soil performance are discussed in Chapters 5 and 6 in relation to the physics of soil-water movement and volume changes.

Application of the concepts developed for describing mechanisms of soil behaviour to the evaluation of mechanical properties of soil are provided in the subsequent chapters. No attempt is made in this book to provide design principles or specific parameters directly applicable for any one particular design problem. Rather, the concepts pertaining to the behaviour of soil, and the properties that are measured in relation to the response mechanisms evoked, are discussed. The central themes revolve around the need for an understanding of the physics of interaction,

the various factors defining the integrity of the soil-water system, and the properties that are measured which may be conditioned by experimental constraints in the test procedures used. The need to distinguish between analytical and mechanistic parameters cannot be overstressed, since this bears directly on interpretation of the physical performance of the material. It is with this kind of concern that the authors have sought to present the material, with the interpretations of performance based upon the fundamental mechanisms of particle and fabric unit interaction. The role of soil water is emphasized since this is fundamental to an understanding of soil properties and behaviour.

The authors have benefited considerably from discussions with many of their colleagues at various research centres and universities. Few concepts explaining soil properties and behaviour are developed completely* by one person. The concepts grow gradually in discussions and through studies of several research workers. The references cited in the book have been selected primarily with regard to ideas shown and information used. References are also given to articles in which original work can be found, and to state-of-the-art texts and research papers. Many of these were used in the development of the ideas in this book.

The authors are indebted to their colleagues and to their present and former graduate students for helpful discussions of the contents of various chapters. S.E. McKyes, J.C. Osler and D.E. Sheeran provided assistance at various times in the development of the book. The suggestions and input provided by Professor G.G. Meyerhof are especially acknowledged. In addition, the support obtained by grants for research from both the National Research Council of Canada and the Defence Research Board of Canada are acknowledged with gratitude. Finally the authors wish to thank N. Ahmed for preparation of illustrations, and Mrs. M. Powell who typed the manuscript.

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Chapter 1

NATURE OF SOILS

1.1 INTRODUCTION

Soil constituents exist in solid, liquid and gas states. The solid phase is represented by mineral and some organic particles with size variation from submicroscopic to visually discrete. The liquid phase is a solution of various salts in water. The gaseous phase tends toward the composition of air but with a high content of water vapour. The variability of any or all of these three phases together with corresponding variation in specific interaction of the three phases provides for non-uniformity in soil composition, characteristics, and properties. These microscopic interactions and reactions make it difficult to predict precisely the response of soil to a set of external constraints. Macroscopically, one attempts to sum up all the microscopic interactions and reactions into one or two representative measurable parameters to describe soil behaviour. This is the requirement for the development of insight into the physical behaviour of soil.

Soil from a physical viewpoint

The most common physical properties of a body are probably those of weight and volume. The density of a soil is an important property. Another obvious physical property of the soil is the degree of wetness. Associated with this is water movement, swelling on wetting, and cracking on drying. The diffusion of air in the soil is regulated by the degree of wetness.

Soil consists of particles of different sizes, arranged in different ways, with voids or pore space between the particles. It has been described as a three phase (solid, liquid, gas) system in dynamic equilibrium; the equilibrium between these phases changes continuously. During a rainfall or during irrigation the liquid phase is increased and some of the gases are excluded. As a result of engineering construction, application of external stresses will cause particle movement.

Physically, the soil is made up of minerals of various sizes with some organic molecules strongly bonded to the minerals and some organic matter physically mixed in. The solid particles exist in a certain arrangement and the voids or pore spaces between these are partly filled with dilute solutions and partly with gases. The smallest particles, clay and silt, are not spread uniformly throughout the soil.

The clay particles are often arranged in parallel orientation and form coatings or clay skins around sand particles or soil fabric units, thus forming a boundary between sand and the voids or pore spaces. Many physical measurements are made on soil samples that are broken up or disturbed, i.e. not in their natural state. It should be remembered when the results of tests to determine these physical properties are evaluated that the particles in the soil have a definite arrangement upon which soil properties depend. The grain-size analysis, for example, gives only the proportion of different sized particles present, and not their arrangement with respect to each other.

Importance of physical properties

Physical properties of the soil often limit both agricultural and engineering use of soils. Since physical properties are much harder to alter than chemical properties, it is the physical properties which largely determine soil use.

The physical properties of importance in engineering are strength, compressibility, permeability, volume change, compactibility and frost susceptibility. Engineering structures may be designed with more confidence if one knows these properties and their changes with environment and time. Depth of soil, grain-size distribution, drainage, stability of soil crumbs, and water-holding capacity are among the common physical properties affecting cultivation of soil. These are also the properties which are considered in soil surveys, and land capability surveys, when soils are rated for crop production.

Physical properties of soils have been studied for many decades. The obvious differences in bearing capacity of soils and the necessity for tillage to prepare an adequate seed bed to allow germination of seed are two examples of practical reasons for this interest. In addition, there is the early interest of man in his physical surroundings. Physics, and the tools used in physics, were developed well before the tools used in chemistry. Thus many of the physical properties of soils, which are macroscopic, were realized before chemical and biological properties were considered.

1.2 ORIGIN OF SOIL

Soils are formed by the natural process of disintegration of rock and decomposition of organic matter. The minerals derived from parent rock material constitute the primary minerals of soils. The term "soils" bears different connotations depending upon the discipline in which the term is used. In its most general usage soil may be defined as finely-divided rock material. This can range from colloidal particles to boulders up to a few feet in diameter.

Weathering or disintegration of rock can be by physical or chemical processes. In physical weathering there is generally no alteration of the chemical or mineralogical composition of the rock material. This process involves the crushing of rock into smaller sizes. In chemical weathering, the decomposition of rock is by chemical changes with alteration of the minerals in the rock.

The forces associated with weathering and erosion constitute the chief agencies for production of soil from rock. Of these, water has by far the greatest effect. Other factors also contribute such as temperature, pressure from glaciers or other sources, wind, bacteria, and human activity. In the Mississippi River system for example, where the drainage area covers approximately one and a quarter million square miles, over 600,000,000 tons of soil are torn from the drainage area and carried downstream to the mouth of the river in the Gulf of Mexico in one calendar year.

The atmosphere absorbs at least 100,000 cubic miles of moisture a year, most of which returns to the earth in the form of rain, snow and other forms of moisture deposition. At least one third of this falls on land. A fair proportion of this will be used to erode the material on the surface.

After the breakdown of rock by forces associated with glaciers, temperature, rivers, wave action and other means, further particle breakdown may occur either chemically or physically. Water seeping through fissures in limestone, for example, can disintegrate limestone if the water contains acids. Weak carbonic acid may be formed by water passing through the atmosphere collecting carbon dioxide. Also in passing through vegetative cover, the pH of water may reach as low as 4. The percolation of weak carbonic acid through the limestone causes erosive action disintegrating and breaking it down into smaller particles.

The derivation of rock fragments either physically or chemically is the first requirement for formation of soil. Rock fragments are broken down due to the action of glaciers or the forces exerted by flowing rivers and waves from the ocean. With time and continued action, the fragments are ground down to smaller and smaller particles. The product of the erosive forces whether by wind, water or glacier, find themselves deposited in lower regions such as deltas, valleys and plains.

Weathering is at its highest intensity where interfaces between the atmosphere, hydrosphere, biosphere and lithosphere overlap, e.g., the upper soil zone. The upper part of the regolith contains minerals which have been decomposed to less complex compounds. Some chemical weathering and other types of weathering also occur at the surface during erosion, transportation, etc.

The rate of weathering is influenced by many factors such as: size of rock particles, permeability of rock mass, position of groundwater table, topography, temperature, composition and amount of the groundwater, oxygen and other gases in the system, organic matter, wetting and drying, relative surface area of rock

exposed, relative solubilities of the original rocks and the weathered materials, environmental changes, etc.

Weathering is a spontaneous reaction involving geologic material and energy. It is a change in the direction of a decrease in the free energy of the system. Thus, it is possible to predict the thermodynamic susceptibility of minerals to weathering. The assemblages of minerals in soils and sedimentary rocks are a reflection of temporary equilibrium stages in the dynamic process of change from source material to final end-product.

The weathering sequence involved in the development of clay minerals from parent rocks may be represented in terms of a reaction series portraying sedimentary rocks and soils as equilibrium stages in a continuous progression from their ultimate source (common igneous rocks such as basalt and granite) to a final end-product such as laterite.

1.3 SOIL CLASSIFICATION

There are many methods available for classification of soils. The choice of method depends upon the specific use intended for the soil. Geological classifications of soils differ from those used in soil engineering and from those used in agriculture. Geologic classifications are mostly genetic but partly descriptive, mostly in terms of surficial deposits. The major sub-divisions in the geologic classification of surficial deposits are:

(a) Transported: (1) fluvial deposits; (2) alluvial deposits, such as alluvial fans and deltas; (3) aeolian deposits; (4) glacial fluvial deposits; (5) glacial deposits; (6) volcanic deposits; (7) marine deposits; (8) mass-wasting products, such as mud flows, slide rock, talus, rock glaciers, slope wash, etc.

(b) Residual: (1) Soils – zonal soils, azonal soils, intrazonal soils; (2) marine and lacustrine deposits; (3) organic-mineral complexes such as muskeg.

The pedologist, or soil scientist working in agriculture, regards soil not in terms of the complete unconsolidated material but in terms only of the weathered and altered upper part of the unconsolidated material. The term “horizon” is a general term used to define a stratum in the soil. A soil profile consists of a succession of horizons or strata. The surface horizons are formed by interaction of rock material with organic material and with the atmosphere. The “A” horizon denotes the top stratum that is altered by natural processes such as leaching and washing away of the material. The “B” horizon which lies below the “A” horizon represents the stratum of accumulation or deposition. The material that is leached or washed down from the “A” horizon accumulates in the “B” horizon. The “C” horizon lying below the “B” horizon contains soil that is unaltered by weathering

subsequent to deposition or formation. The development of A and B horizons in the soil profile is of primary importance. Soil formation or the development of the soil profile is determined by climate, vegetation, parent material, topography and time. Classification depends upon the complete description of the soil profile and relies to a large extent on profile development. Because of the complete description, this system serves a very useful purpose.

The other groups of soil classification methods of interest to us in the study of soil behaviour are the classifications of soils for engineering purposes. These classification methods rely primarily on the grain size and its gradation within the soil mass, its consistency, and probably its relation to frost penetration or its reaction to frost effects. These methods are outlined in various books on soil engineering.

While it is possible to infer from particle-size distribution an estimate of the water-holding capacity of soils, the strength and compressibility, etc., there is no substitute for actual measurement and evaluation of the properties of the soil. It is not possible, however, to include these actual measurements in classification methods, since they involve tedious laboratory studies. The purpose of classification is not to become involved in a long laboratory study programme but to provide a general description of the soil in a terminology for classification which is understood by all concerned. The present available classification systems for engineering purposes are meant specifically (and have been developed in general) for use in engineering projects involving highways and airport pavements. They concern themselves primarily with soils limited to the first few feet from the surface. Consequently, the properties measured and the descriptions of the soils are usually only those concerned with particle-size distribution and consistency. With a knowledge of clay mineralogy and the characteristics of clay–water interaction, it is possible to infer from a particle-size distribution curve the various properties of interest to the engineer. However, it is not generally possible for one to obtain a knowledge of the clay minerals present in the general classification of the system. Hence, for example, given a general grain-size distribution curve, it is frequently necessary to obtain consistency limits to give an idea of the clay–water interaction.

1.4 PROCEDURE FOR THE MINERALOGICAL ANALYSIS OF SOILS

It has become customary to recognize two particle categories in soils:

- (1) Granular particles (gravel, sand and silt).
- (2) Colloidal particles (clay-size particles).

The boundary between these is taken to be at 4 microns by geologists using the

Wentworth scale, or 2 microns by engineers. This division is convenient also for mineralogical soil analysis, and the list of methods is divided accordingly.

(A) *Grain-size analysis and fractionation.*

1. Sieving methods.
2. Sedimentation methods (wet analysis).
3. Infra-sizer method (air elutriation).

(B) *Methods for coarse particles.*

1. Chemical analysis.
2. Microscope studies.
 - (a) Binocular microscope (> 0.25 mm).
 - (b) Polarizing microscope (> 5.0 microns).
 - Refractive indices by immersion.
 - Determination of minerals by their optical properties.
 - (c) Staining methods.
 - (d) Particle shape, size, sphericity, angularity, statistical counts of particles, composition and texture studies.
3. Specific gravity determinations.
4. Heavy-liquid analysis.
5. Electromagnetic separation.


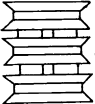



(C) *Methods for clay-size fraction.*



1. X-ray diffraction and fluorescence.
2. Differential thermal analysis.
3. Optical (microscope) study of aggregates.
4. Electron microscopy.
5. Chemical methods.
 - (a) Bulk chemical analysis.
 - (b) Chemical treatment for removal of specific substances.
 - (c) Organic content analysis.
 - (d) Cation-exchange capacity determination.
 - (e) Potash determination.
 - (f) Glycol or glycerol retention.
6. Surface area determination.
7. Infrared methods.

Certain methods used for characterizing the clay-size fraction are also applicable to the coarser fraction, particularly the X-ray diffraction and differential thermal analysis methods. The methods for examination of clay-size fractions are given in Chapters 2 and 3.

TABLE 1.1

Summarized properties of clay-mineral groups (From Soderman and Quigley, 1965)*

Clay type	Symbol ¹	Negative charge per unit cell	Cation exchange capacity ² (m.eq./100 g)	Glycol retention (mg/g)	Basal spacing		Liquid limit w_L	Plasticity index I_p	Activity a_c	Compression index C_c	Friction angle Drained
					glycol (Å)	dry (Å)					
Kaolin	 strong H + bond	-0.01	3	20	7	7	50	20	0.2 av	0.2	20–30°
Illite	 strong K + bond	-1.0	25	80	10	10	100 to 120	50 to 65	0.6 av	0.6–1	20–25°
Chlorite	 strong bond Al, Mg or Fe hydroxide sheet	-0.5 to -1.0	10–40	30	14	14	Probably like illite				
Vermiculite	 weak Mg bond	-0.5 to -0.7	150	150	14	10	Probably between illite and montmorillonite				
Montmorillonoid	 very weak bond	-0.3	100	260	16 to 18	10	150 to 700	100 to 650	1–6	1–3	12–20°

¹  silica sheet;  hydroxide sheet.

² m.eq./100g = milliequivalents/100 grams of dry soil.

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Most of the methods used in mineral analysis of the coarser grain fraction of soils are the standard chemical and geological methods. Mechanical analyses and sedimentation methods are discussed in the standard laboratory texts on soil mechanics. The infra-sizer such as that designed by Hultain, is useful for separating the finer fractions using air elutriation rather than liquid sedimentation, as the basis for separation. It is more rapid and convenient than the liquid separation methods.

Microscope studies and identification of minerals are discussed in standard texts on optical mineralogy and petrography. Of the methods listed, microscope techniques and electromagnetic separation are the quickest methods for mineralogical analysis of granular soils. Magnetic or electromagnetic separators use the small difference in the magnetic susceptibility of minerals. Rapid separation of feldspars, carbonates or any other mineral, is possible. Weighing the various separated mineral fractions gives a quick quantitative mineral analysis of the soil.

With the microscope, especially the polarizing microscope, a visual examination of the particles, together with observation of their birefringence and determination of their optical sign, is usually sufficient to identify most minerals. It is not usually important to determine the exact composition of the minerals in soil analysis. A general grouping into quartz, feldspars, micas, pyroxenes, amphiboles, and the accessory minerals such as zircon, iron oxides, sphene and apatite is sufficient. Should a more detailed analysis be desirable, the refractive indices of the minerals by the immersion method, as well as their other optical properties, may be determined.

Different clay minerals result in different soil properties, so a mineral analysis is often necessary to an understanding of soil behaviour. This is discussed further in Chapter 2. Table 1.1 summarizes some of the different properties of common clay minerals.

1.5 PARTICLE-SIZE COMPOSITION OF SOILS

The particle-size distribution of a soil influences chemical, physical and biological properties of soils. Separates consisting of larger particles, the sands and gravels, form the skeleton of the soil and determine many of its mechanical properties. The finest separate, consisting of clay particles, has a large surface area and determines most of the chemical and physical-chemical properties of the soils. Particle-size distribution in soils influences type and weight of cultivation machines required, the susceptibility of soils to erosion, the water-holding capacity and hence the water supply to plants, and spacing of irrigation and drainage ditches and types of drainage and irrigation systems required. It also influences the strength and compressibility of soils, both of which are important in the consideration of bearing

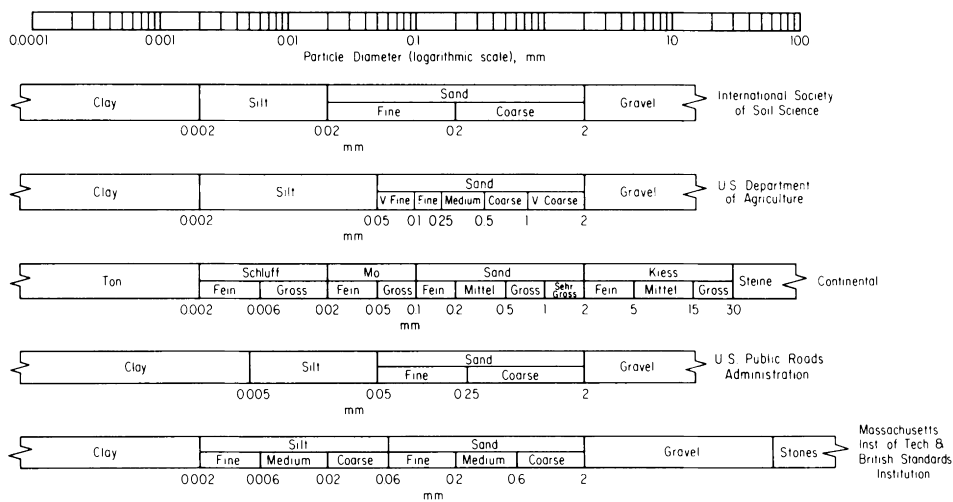


Fig.1.1. Principle particle-size scales. (From Anonymous, 1954: Soil Mechanics for Road Engineers, Chapters 3 and 4.)

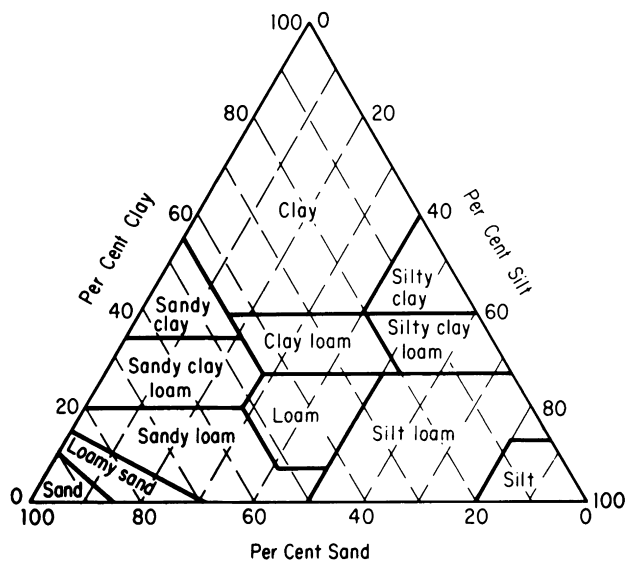


Fig.1.2. Chart showing per cent clay, silt, and sand in the soil textural classes of U.S. Department of Agriculture.