

## CHAPTER 4

# Soil Formation and Characteristics

The term “soil,” as used by the US Army, refers to the entire unconsolidated material that overlies and is distinguishable from bedrock. Soil is composed principally of the disintegrated and decomposed particles of rock. It also contains air and water as well as organic matter derived from the decomposition of plants and animals. Bedrock is considered to be the solid part of the earth’s crust, consisting of massive formations broken only by occasional structural failures. Soil is a natural conglomeration of mineral grains ranging from large boulders to single mineral crystals of microscopic size. Highly organic materials, such as river bottom mud and peat, are also considered soil. To help describe soils and predict their behavior, the military engineer should understand the natural processes by which soils are formed from the parent materials of the earth’s crust. As soils are created, by the process of rock weathering and often by the additional processes of transportation and disposition, they often acquire distinctive characteristics that are visible both in the field and on maps and photographs.

### Section I. Soil Formation

#### WEATHERING

Weathering is the physical or chemical breakdown of rock. It is this process by which rock is converted into soil. Weathering is generally thought of as a variety of physical or

chemical processes that are dependent on the environmental conditions present.

#### Physical Processes

Physical weathering is the disintegration of rock. Physical weathering processes break rock masses into smaller and smaller pieces without altering the chemical composition of the pieces. Therefore, the disintegrated fragments of rock exhibit the same physical properties as their sources. Processes that produce physical weathering are—

- Unloading.
- Frost action.
- Organism growth.
- Temperature changes.
- Crystal growth.
- Abrasion.

**Unloading.** When rock layers are buried under the surface, they are under compressive stress from the weight of overlying materials. When these materials are removed, the resulting stress reduction may allow the rock unit to expand, forming tensional cracks (jointing) and causing extensive fracturing.

**Frost Action.** Most water systems in rocks are open to the atmosphere, but freezing at the surface can enclose the system. When the enclosed water freezes, it expands nearly one-tenth of its volume, creating pressures up to

4,000 pounds per square inch (psi). The expanding ice fractures the rock.

**Organism Growth.** Trees and plants readily grow in the joints of rock masses near the surface. The wedging action caused by their root growth hastens the disintegration process.

**Temperature Changes.** Daily or seasonal temperature changes can cause differential expansion and contraction of rocks near the earth's surface. This results in a tensional failure called spalling or exfoliation. As the rock's surface heats up, it expands; as it cools, it contracts. The jointing patterns of igneous rock are often the result of temperature changes.

**Crystal Growth.** The growth of minerals precipitating from groundwater can apply pressure similar to that of expanding ice. Soluble minerals, such as halite (salt), readily crystallize out of solution.

**Abrasion.** Sediments suspended in wind or fast-moving water can act as abrasives to physically weather rock masses. Rock particles carried by glacial ice can also be very abrasive.

### Chemical Processes

Chemical weathering is the decomposition of rock through chemical processes. Chemical reactions take place between the minerals of the rock and the air, water, or dissolved or suspended chemicals in the atmosphere. Processes that cause chemical weathering are—

- Oxidation.
- Hydration.
- Hydrolysis.
- Carbonation.
- Solution.

**Oxidation.** Oxidation is the chemical union of a compound with oxygen. An example is rusting, which is the chemical reaction of oxygen, water, and the iron mineral pyrite ( $\text{FeS}_2$ ) to form ferrous sulfate ( $\text{FeSO}_4$ ). Oxidation is responsible for much of the red

and yellow coloring of soils and surface rock bodies. This type of reaction is important in the decomposition of rocks, primarily those with metallic minerals.

**Hydration.** Hydration is the chemical union of a compound with water. For example, the mineral anhydrite ( $\text{CaSO}_4$ ) incorporates water into its structure to form the new mineral gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ).

**Hydrolysis.** This decomposition reaction is related to hydration in that it involves water. It is a result of the partial dissociation of water during chemical reactions that occur in a moist environment. It is one of the types of weathering in a sequence of chemical reactions that turns feldspars into clays. An example of hydrolysis is the altering of sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) to sodium hydroxide ( $\text{NaOH}$ ) and carbonic acid ( $\text{H}_2\text{CO}_3$ ).

**Carbonation.** This is the chemical process in which carbon dioxide from the air unites with various minerals to form carbonates. A copper penny eventually turns green from the union of copper with carbon dioxide in the air to form copper carbonate. Carbonate rocks, in turn, are susceptible to further weathering processes, namely solution.

**Solution.** Carbon dioxide dissolved in water forms a weak acid called carbonic acid ( $\text{H}_2\text{CO}_3$ ). Carbonic acid acts as a solvent to dissolve carbonates, such as limestone, and carry them away. This creates void spaces, or caves, in the subsurface. Areas that have undergone extensive solutioning are known as karst regions.

### DISCONTINUITIES AND WEATHERING

Jointing and other discontinuities increase the surface area of the rock mass exposed to the elements and thereby enhance chemical weathering. Discontinuities, such as joints, faults, or caverns, act as conduits into the rock mass for the weathering agents (air and water) to enter. Weathering occurs on exposed surfaces, such as excavation walls, road cuts, and the walls of discontinuities. The effect of weathering along discontinuities is a

general weakening in a zone surrounding the wall surface.

### EFFECTS OF CLIMATE

The climate determines largely whether a type of rock weathers mostly by chemical or mostly by physical processes. Warm, wet (tropical or subtropical) climates favor chemical weathering. In such climates, there is abundant water to support the various chemical processes. Also, in warm, wet climates, the temperature is high enough to allow the chemical reactions to occur rapidly. Cold, dry climates discourage chemical weathering of rock but not physical weathering. The influence of climate on the weathering of the many rock types varies; however, most rock types weather more rapidly in warm, wet climates than in cold and/or dry climates.

### EFFECTS ON RELIEF FEATURES

Weathering combined with erosion (the transportation of weathered materials) is responsible for most of the relief features on the earth's surface. For example, the subsurface cavities so predominant in karst regions develop along the already existing joints and bedding planes and commonly form an interlacing network of underground channels. If the ceiling of one of these subterranean void spaces should collapse, a sinkhole forms at the earth's surface. The sinkhole may range in size from a few feet to several miles in diameter. It may be more than a hundred feet deep, and it may be dry or contain water. Extensive occurrences of sinkholes result in the formation of karst topography, which is characterized by a pitted or pinnacle ground surface with numerous depressions and a poorly developed drainage pattern. Other features associated with karst topography include:

- Lost or disappearing streams where surface streams disappear or flow underground.
- Rises where underground streams suddenly reappear at the surface to form springs.

Solution cavities and sinkholes can be detrimental to foundations for horizontal and vertical construction and should be identified and evaluated for military operations.

### SOIL FORMATION METHODS

Soils may be divided into two groups based on the method of formation—residual soils and transported soils.

#### Residual Soils

Where residual soils are formed, the rock material has been weathered in place. While mechanical weathering may occur, chemical weathering is the dominant factor. As a result of this process, and because the rock material may have an assorted mineral structure, the upper layers of soils are usually fine-grained and relatively impervious to water. Under this fine-grained material is a zone of partially disintegrated parent rock. It may crumble easily and break down rapidly when exposed to loads, abrasions, or further weathering. The boundary line between soil and rock is usually not clearly defined. Lateritic soils (highly weathered tropical soils containing significant amounts of iron or iron and aluminum) are residual. Residual soils generally present both drainage and foundation problems. Residual soil deposits are characteristically erratic and variable in nature. *Figure 4-1, page 4-4*, shows a typical residual soil.

#### Transported Soils

By far, most soils the military engineer encounters are materials that have been transported and deposited at a new location. Three major forces—glacial ice, water, and wind—are the transporting agents. These forces have acted in various ways and have produced a wide variety of soil deposits. Resulting foundations and construction problems are equally varied. These soils may be divided into glacial deposits, sedimentary or water-laid deposits, and eolian or wind-laid deposits. Useful construction material can be located by being able to identify these features on the ground or on a map (see *Chapter 3*).



Figure 4-1. Residual soil forming from the in-place weathering of igneous rock.

### SOIL PROFILES

As time passes, soil deposits undergo a maturing process. Every soil deposit develops a characteristic profile because of weathering and the leaching action of water as it moves downward from the surface. The profile developed depends not only on the nature of the deposit but also on factors such as temperature, rainfall amounts, and vegetation type. Under certain conditions, complex profiles may be developed, particularly with old soils in humid regions. In dry regions, the profile may be obscured.

Typical soil profiles have at least three layers, known as horizons (see *Figure 4-2*). They are-

- A horizon.
- B horizon.
- C horizon.

The A horizon, or upper layer, contains a zone of accumulation of organic materials in its upper portion and a lower portion of lighter color from which soil colloids and other soluble constituents have been removed. The B horizon represents the layer where soluble materials accumulate that have washed out of the A horizon. This layer frequently contains much clay and may be several feet thick. The C horizon is the weathered parent material. The development of a soil profile depends on the downward movement of water. In arid and semiarid regions, the movement of water may be reversed and water may be brought to the surface because of evaporation. Soluble salts may thus be brought to the surface and deposited.

The study of the maturing of soils and the relationship of the soil profile to the parent

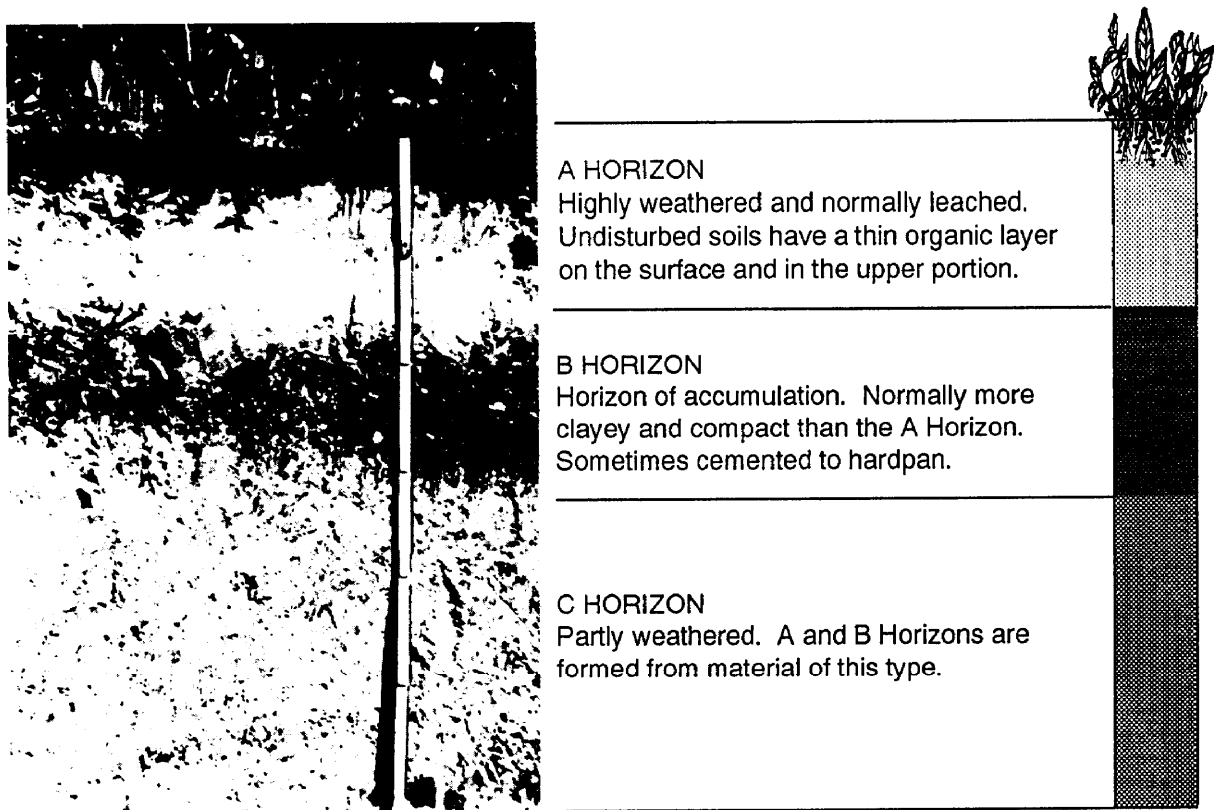


Figure 4-2. Soil profile showing characteristic soil horizons.

material and its environment is called pedology. As will be explained later, soils may be classified on the basis of their soil profiles. This approach is used by agricultural soil scientists and some engineering agencies. This system is of particular interest to engineers who are concerned with road and airfield problems.

Soils not only characteristically vary with depth, but several soil types can and often do exist within a relatively small area. These variations may be important from an engineering standpoint. The engineering properties of a soil are a function not only of the kind of soil but also of its conditions.

## Section II. Soil Characteristics

### PHYSICAL PROPERTIES

The engineering characteristics of soil vary greatly, depending on such physical properties as—

- Grain or particle size.

- Gradation.
- Particle shape.
- Structure.
- Density.
- Consistency.

These properties are defined, in most cases numerically, as a basis for the systematic classification of soil types. Such a classification system, used in connection with a common descriptive vocabulary, permits the ready identification of soils that may be expected to behave similarly.

The nature of any given soil can be changed by manipulation. Vibration, for example, can change a loose sand into a dense one. Therefore, the behavior of a soil in the field depends not only on the significant properties of the individual constituents of the soil mass but also on properties due to particle arrangement within the mass.

Frequently, the available laboratory equipment or other considerations only permit the

military engineer or the engineer's soil technician to determine some of the soil's properties and then only approximately. Hasty field identification often permits a sufficiently accurate evaluation for the problem at hand. However, the engineer cannot rely solely on experience and judgment in estimating soil conditions or identifying soils. He must make as detailed a determination of the soil properties as possible and subsequently correlate these identifying properties with the observed behavior of the soil.

### Grain or Particle Size

In a natural soil, the soil particles or solids form a discontinuous mass with spaces or voids between the particles. These spaces are normally filled with water and/or air. Organic material may be present in greater or lesser amounts. The following paragraphs are concerned with the soil particles themselves. The terms "particle" and "grain" are used interchangeably.

**Detemination.** Soils may be grouped on the basis of particle size. Particles are defined according to their sizes by the use of sieves, which are screens attached to metal frames. *Figure 4-3* shows sieves used for the Unified Soil Classification System (USCS). If a particle will not pass through the screen with a particular size opening, it is said to be "retained on" that sieve. By passing a soil mixture through several different size sieves, it can be broken into its various particle sizes and defined according to the sieves used. Many different grain-size scales have been proposed and used. Coarse gravel particles are comparable in size to a lemon, an egg, or a walnut, while fine gravel is about the size of a pea. Sand particles range in size from that of rock salt, through table salt or granulated sugar, to powdered sugar. Below a Number 200 sieve, the particles (fines) are designated as silts or clays, depending on their plasticity characteristics.

Other grain-size scales apply other limits of size to silts and clays. For example, some civil engineers define silt as material less than 0.05 mm in diameter and larger than 0.005 mm. Particles below 0.005 mm are clay sizes.

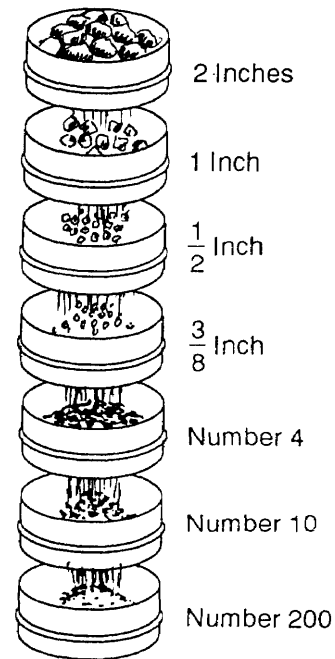


Figure 4-3. Dry sieve analysis.

A particle 0.07 mm in diameter is about as small as can be detected by the unaided eye. It must be emphasized that below the Number 200 sieve (0.074-mm openings), particle size is relatively unimportant in most cases compared to other properties. Particles below 0.002 mm (0.001 mm in some grain-size scales) are frequently designated as soil colloids. The organic materials that may be present in a soil mass have no size boundaries.

Several methods may be used to determine the size of soil particles contained in a soil mass and the distribution of particle sizes. Dry sieve analysis has sieves stacked according to size, the smallest being on the bottom. Numbered sieves designate the number of openings per lineal inch. Dimensioned sieves indicate the actual size of the opening. For example, the Number 4 standard sieve has four openings per lineal inch (or 16 openings per square inch), whereas the  $\frac{1}{4}$ -inch sieve has a sieve opening of  $\frac{1}{4}$  inch.

The practical lower limit for the use of sieves is the Number 200 sieve, with 0.074 - millimeter-square openings. In some instances, determining the distribution of

particle sizes below the Number 200 sieve is desirable, particularly for frost susceptibility determination. This may be done by a process known as wet mechanical analysis, which employs the principle of sedimentation. Grains of different sizes fall through a liquid at different velocities. The wet mechanical analysis is not a normal field laboratory test. It is not particularly important in military construction, except that the percentage of particles finer than 0.02 mm has a direct bearing on the susceptibility of soil to frost action. A field method for performing a wet mechanical analysis for the determination of the percentage of material finer than 0.02 mm is given in Technical Manual (TM) 5-530. The procedure is called decantation.

The procedures that have been described above are frequently combined to give a more complete picture of grain-size distribution. The procedure is then designated as a combined mechanical analysis.

Other methods based on sedimentation are frequently used in soils laboratories, particularly to determine particle distribution below the Number 200 sieve. One such method is the hydrometer analysis. A complete picture of grain-size distribution is frequently obtained by a combined sieve and hydrometer analysis. This method is described in TM 5-530 (Section V).

**Reports.** Test results may be recorded in one of the following forms:

- Tabular (see *Figure 4-4, page 4-8*).
- Graphic (see *Figure 4-5, page 4-9*).

The tabular form is used most often on soil consisting predominantly of coarse particles. This method is frequently used when the soil gradation is being checked for compliance with a standard specification, such as for a gravel base or a wearing course.

The graphic form permits the plotting of a grain-size distribution curve. This curve affords ready visualization of the distribution and range of particle sizes. It is also particularly helpful in determining the soil

classification and the soil's use as a foundation or construction material.

### Gradation

The distribution of particle sizes in a soil is known as its gradation. Gradation and other associated factors, primarily as applicable to coarse-grained soils, are discussed in the following paragraphs.

**Effective Size.** The grain size corresponding to 10 percent passing on a grain-size distribution curve (see *Figure 4-5, page 4-9*) is called Hazen's effective size. It is designated by the symbol  $D_{10}$ . For the soil shown,  $D_{10}$  is 0.13 mm. The effective sizes of clean sands and gravels can be related to their permeability.

**Coefficient of Uniformity.** The coefficient of uniformity ( $C_u$ ) is defined as the ratio between the grain diameter (in millimeters) corresponding to 60 percent passing on the curve ( $D_{60}$ ) divided by the diameter of the 10 percent ( $D_{10}$ ) passing. Hence,  $C_u = D_{60}/D_{10}$ .

For the soil shown on *Figure 4-5, page 4-9*—

$$D_{60} = 2.4 \text{ mm and } D_{10} = 0.13 \text{ mm}$$

$$\text{then } C_u = 2.4/0.13 = 18.5$$

The uniformity coefficient is used to judge gradation.

**Coefficient of Curvature.** Another quantity that may be used to judge the gradation of a soil is the coefficient of curvature, designated by the symbol  $C_c$ .

$$C_c = \frac{(D_{30})^2}{(D_{60} \times D_{10})}$$

$D_{10}$  and  $D_{60}$  have been defined, while  $D_{30}$  is the grain diameter corresponding to 30 percent passing on the grain-size distribution curve. For the soil shown in *Figure 4-5, page 4-9*:

$$D_{30} = 0.3 \text{ mm}$$

$$\text{and } C_c = \frac{(0.3)^2}{(2.4)(0.13)} = .29$$

**Well-Graded Soils.** A well-graded soil is defined as having a good representation of all

SIEVE ANALYSIS DATA					1. DATE STARTED 22 FEB 91	
2. PROJECT BRAVO AIRFIELD			3. EXCAVATION 1+00		4. DATE COMPLETED 28 FEB 91	
5. SAMPLE DESCRIPTION  LIGHT BROWN SANDY SOIL					6. SAMPLE NUMBER 1A	
					7. PREWASHED (x one)	
8. ORIGINAL SAMPLE WEIGHT 2459		9. + #200 SAMPLE WEIGHT 2359			10. -#200 SAMPLE WEIGHT 100	
11. SIEVE SIZE	12. WEIGHT OF SIEVE	13. WEIGHT OF SIEVE + SAMPLE	14. WEIGHT RETAINED	15. CUMULATIVE WEIGHT RETAINED	16. PERCENT RETAINED	17. PERCENT PASSING
1½	202					
1	231					
¾	210	210	0	0	0	100.0
½	230	624	394	394	16.0	84.0
#4	205	332	127	521	5.2	78.8
#8	225	691	466	987	19.0	59.8
#20	215	612	397	1384	16.2	43.6
#60	235	581	346	1730	14.1	29.5
#100	250	612	362	2092	14.7	14.8
#200	260	515	255	2347	10.4	4.4
18. TOTAL WEIGHT RETAINED IN SIEVES (Sum Column 14)				2347	19. ERROR (8 - 23)  2459-2457 = 2	
20. WEIGHT SIEVED THROUGH #200 (Weight in pan) 270-260				10		
21. WASHING LOSS (8 - 19 + 10) 2459-(2359+100)				0		
22. TOTAL WEIGHT PASSING #200 (20 + 10) 10+100				110		
23. TOTAL WEIGHT OF FRACTIONS (18 + 22)				2457		
24. REMARKS  USCS <u>SP</u> PERCENT - G <u>21.2</u> PERCENT - S <u>74.4</u> PERCENT - F <u>4.4</u>					25. ERROR (Percent)  $\frac{\text{ERROR (19)}}{\text{ORIGINAL WT (8)}} \times 100 =$  $\frac{2}{2459} \times 100 = .08$	
26. TECHNICIAN <i>Joe Blob PVZ</i>			27. COMPUTED BY (Signature) <i>Joe Blob PVZ</i>		28. CHECKED BY (Signature) <i>Fred Jones SSG</i>	

DD Form 1206, DEC 86

Previous editions are obsolete.

Figure 4-4. Data sheet, example of dry sieve analysis.



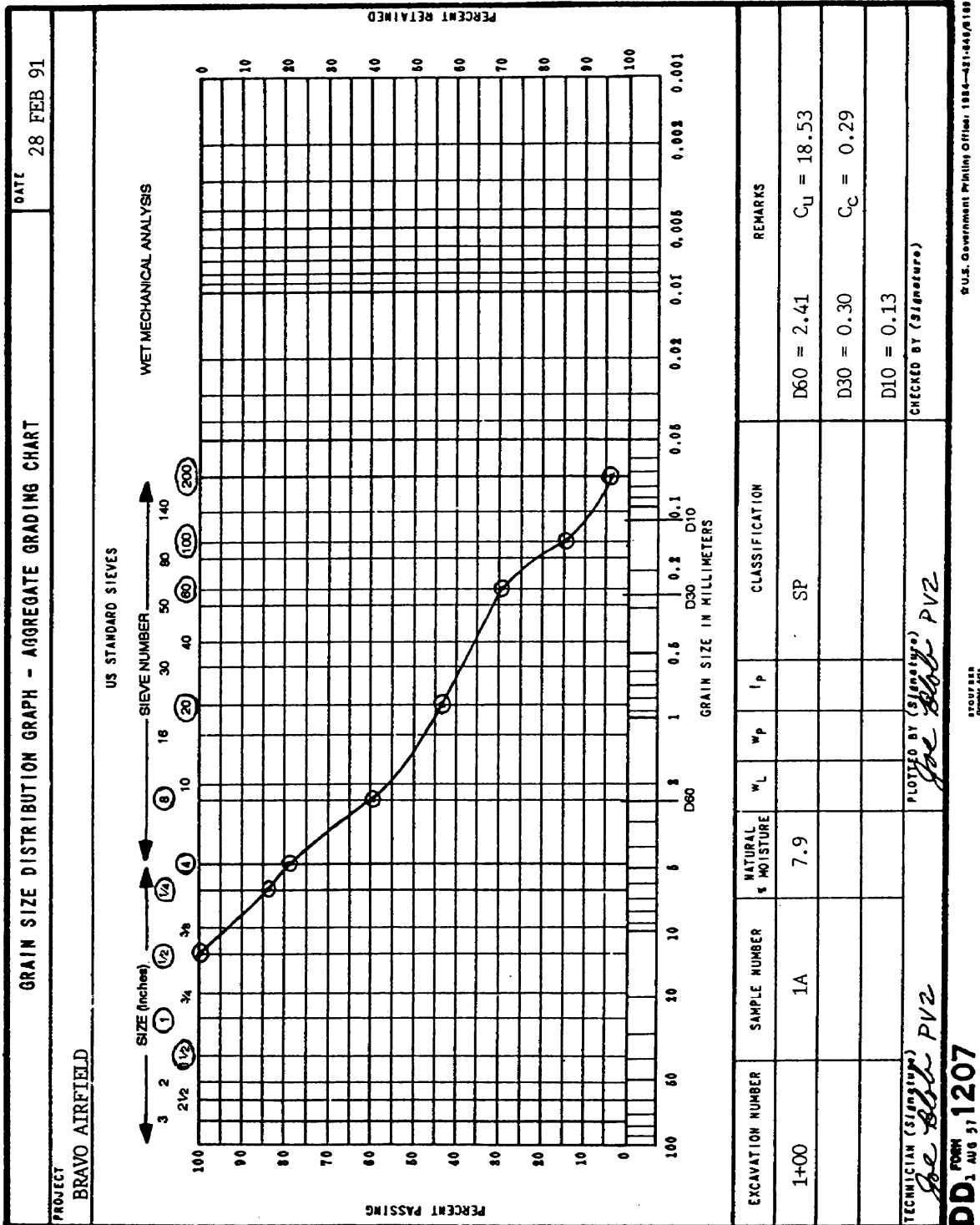
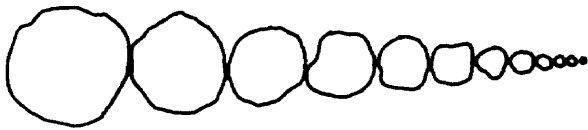


Figure 4-5. Grain-size distribution curve from sieve analysis.

particle sizes from the largest to the smallest (see *Figure 4-6*), and the shape of the grain-size distribution curve is considered “smooth.” In the USCS, well-graded gravels must have a  $C_u$  value  $>4$ , and well-graded sands must have a  $C_u$  value  $>6$ . For well-graded sands and gravels, a  $C_c$  value from 1 to 3 is required. Sands and gravels not meeting these conditions are termed poorly graded.



**Figure 4-6. Well-graded soil.**

**Poorly Graded Soils.** The two types of poorly graded soils are—

- Uniformly graded.
- Gap-graded.

A uniformly graded soil consists primarily of particles of nearly the same size (see *Figure 4-7*). A gap-graded soil contains both large and small particles, but the gradation continuity is broken by the absence of some particle sizes (see *Figure 4-8*).

*Figure 4-9* shows typical examples of well-graded and poorly graded sands and gravels. Well-graded soils ((GW) and (SW) curves)



**Figure 4-7. Uniformly graded soil.**



**Figure 4-8. Gap-graded soil.**

would be represented by a long curve spanning a wide range of sizes with a constant or gently varying slope. Uniformly graded soils ((SP) curve) would be represented by a steeply sloping curve spanning a narrow range of sizes; the curve for a gap-graded soil ((GP) curve) flattens out in the area of the grain-size deficiency.

**Bearing Capacity.** Coarse materials that are well-graded are usually preferable for bearing from an engineering standpoint, since good gradation usually results in high density and stability. Specifications for controlling the percentage of the various grain-size groups required for a well-graded soil have been established for engineering performance and testing. By proportioning components to obtain a well-graded soil, it is possible to provide for maximum density. Such proportioning develops an “interlocking” of particles with smaller particles filling the voids between larger particles, making the soil stronger and more capable of supporting heavier loads. Since the particles are “form-fitted”, the best load distribution downward will be realized. When each particle is surrounded and “locked” by other particles, the grain-to-grain contact is increased and the tendency for displacement of the individual grains is minimized.

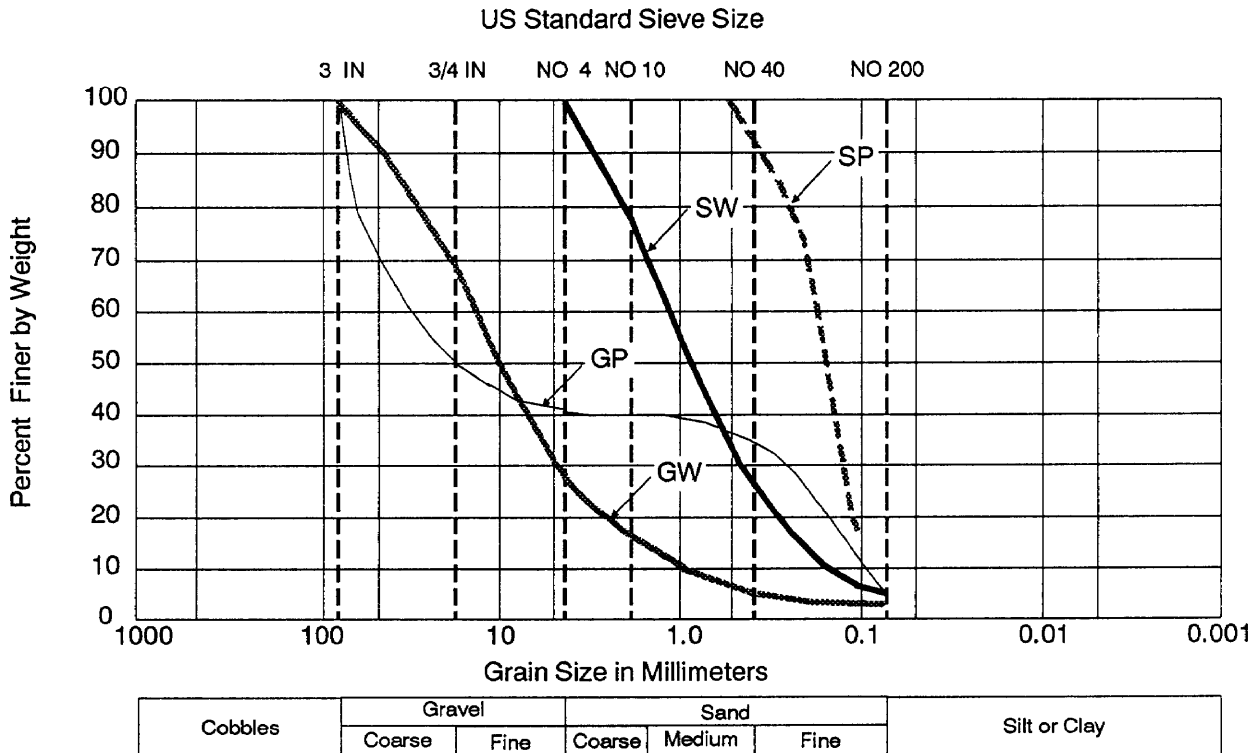
### Particle Shape

The shape of individual particles affects the engineering characteristics of soils. Three principal shapes of soil grains have been recognized. They are—

- Bulky.
- Scalelike or platy.
- Needlelike.

**Bulky.** Bulky grains are nearly equal in all three dimensions. This shape characterizes sands and gravels and some silts. Bulky grains may be described by such terms as—

- Angular.
- Subangular.
- Subrounded.
- Well-rounded.



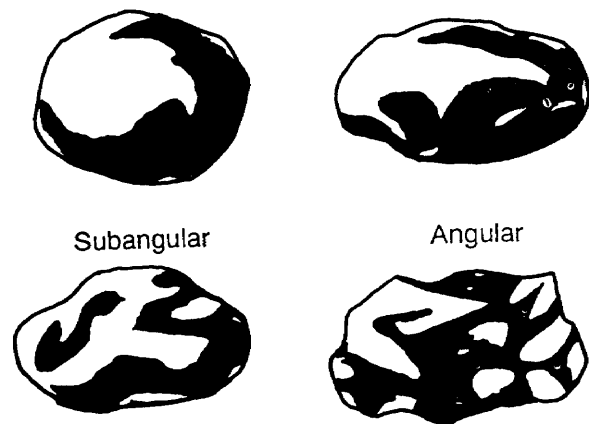
**Figure 4-9.** Typical grain-size distribution curves for well-graded and poorly graded soils.

These four subdivisions of the bulky particle shape depend on the amount of weathering that has occurred (see *Figure 4-10*). These subdivisions are discussed in the order of desirability for construction.

Angular particles are particles that have recently been broken up. They are characterized by jagged projections, sharp ridges, and flat surfaces. The interlocking characteristics of angular gravels and sands generally make them the best materials for construction. Such particles are seldom found in nature because weathering processes normally wear them down in a relatively short time. Angular material may be produced artificially by crushing, but because of the time and equipment required for such an operation, natural materials with other grain shapes are frequently used.

Subangular particles have been weathered until the sharper points and ridges of their original angular shape have been worn off. The particles are still very irregular in shape with some flat surfaces and are excellent for construction.

Subrounded particles are those on which weathering has progressed even further. Still somewhat irregular in shape, they have no sharp corners and few flat areas. Subrounded particles are frequently found in stream beds. They may be composed of hard, durable particles that are adequate for most construction needs.



**Figure 4-10.** Bulky grains.

Rounded particles are those in which all projections have been removed and few irregularities in shape remain. The particles approach spheres of varying sizes. Rounded particles are usually found in or near stream beds, beaches, or dunes. Perhaps the most extensive deposits exist at beaches where repeated wave action produces almost perfectly rounded particles that may be uniform in size. Rounded particles also exist in arid environments due to wind action and the resulting abrasion between particles. They are not desirable for use in asphalt or concrete construction until the rounded shape is altered by crushing.

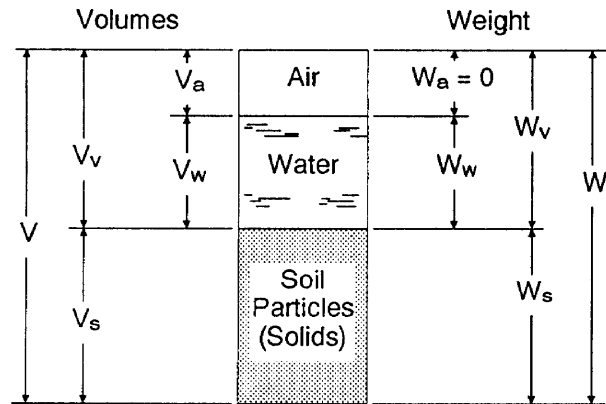
**Platy.** Platy grains are extremely thin compared to their length and width. They have the general shape of a flake of mica or a sheet of paper. Some coarse particles, particularly those formed by the mechanical breakdown of mica, are flaky or scalelike in shape. However, most particles that fall in the range of clay sizes, including the so-called clay minerals, have this characteristic shape. As will be explained in more detail later, the presence of these extremely small platy grains is generally responsible for the plasticity of clay. This type of soil is also highly compressible under static load.

**Needlelike.** These grains rarely occur.

### Structure

Soils have a three-phase composition, the principal ingredients being the soil particles, water, and air. Organic materials are also found in the surface layer of most soils. Basic concepts regarding volume and weight relationships in a solid mass are shown in *Figure 4-11*. These relationships form the basis of soil testing, since they are used in both quantitative and qualitative reporting of soils. It must be recognized that the diagram merely represents soil mass for studying the relationships of the terms to be discussed. All void and solid volumes cannot be segregated as shown.

**Specific Gravity.** The specific gravity, designated by the symbol  $G$ , is defined as the



**Figure 4-11. Volume-weight relationships of a soil mass.**

ratio between the weight per unit volume of the material at a stated temperature (usually 20 degrees Celsius (C)) and the weight per unit volume of water.

Specific gravity =

$$\frac{\text{weight of sample in air (grams)}}{\text{weight of sample in air (grams) — weight of sample in water (grams)}}$$

Test procedures are contained in *TM 5-530*. The specific gravity of the solid substance of most inorganic soils varies between 2.60 and 2.80. Tropical iron-rich laterite soils generally have a specific gravity of 3.0 or more. Clays can have values as high as 3.50. Most minerals, of which the solid matter of soil particles is composed, have a specific gravity greater than 2.60. Therefore, smaller values of specific gravity indicate the possible presence of organic matter.

**Volume Ratios.** The total volume ( $V$ ) of a soil mass consists of the volume of voids ( $V_v$ ) and the volume of solids ( $V_s$ ). The volume of voids in turn consists of the volume of air ( $V_a$ ), and the volume of water ( $V_w$ ) (see *Figure 4-11*). The most important volume ratio is the void ratio ( $e$ ). It is expressed:

$$e = \frac{V_v}{V_s}$$

The volume of solids is the ratio of the dry weight ( $W_d$ ) of a soil mass, in pounds, to the

product of its specific gravity ( $G$ ) and the unit weight of water (62.4 pounds per cubic foot (pcf)). It is expressed:

$$V_s = \frac{W_d \text{ (lb)}}{62.4 \times G}$$

The volume of the water is the ratio of the weight of the water ( $W_w$ ), in pounds, to the unit weight of the water. It is expressed:

$$V_w = \frac{W_w}{62.4}$$

The degree of saturation ( $S$ ) expresses the relative volume of water in the voids and is always expressed as a percentage. It is expressed:

$$S = \frac{V_w}{V_v} \times 100 \text{ percent}$$

A soil is saturated if  $S$  equals 100 percent, which means all void volume is filled with water.

**Weight Ratios.** The total weight ( $W$ ) of a soil mass consists of the weight of the water ( $W_w$ ) and the weight of the solids ( $W_s$ ), the weight of the air being negligible. Weight ratios widely used in soil mechanics are moisture content, unit weight, dry unit weight, and wet unit weight.

Moisture content ( $w$ ) expressed as a percentage is the ratio of the weight of the water to the weight of the solids. It is expressed:

$$w \text{ (percent)} = \frac{W_w}{W_s} \times 100$$

The moisture content may exceed 100 percent. By definition, when a soil mass is dried to constant weight in an oven maintained at a temperature of  $105 \pm 5$  degrees C,  $W_w = 0$ , and the soil is said to be oven dry or dry. If a soil mass is cooled in contact with the atmosphere, it absorbs some water. This water absorbed from the atmosphere is called hygroscopic moisture. *TM 5-530* contains testing procedures for determining moisture content.

Unit weight ( $\gamma$ ) is the expression given to the weight per unit volume of a soil mass. It is expressed:

$$\gamma = \frac{W}{V}$$

In soils terminology, the terms “unit weight” and “density” are used interchangeably.

Wet unit weight ( $\gamma_m$ ), also expressed as wet density, is the term used if the moisture content is anything other than zero. The wet unit weight of natural soils varies widely. Depending on denseness and gradation, a sandy soil may have a wet unit weight or density of 115 to 135 pcf. Some very dense glacial tills may have wet unit weights as high as 145 pcf. Wet unit weights for most clays range from 100 to 125 pcf. Density of soils can be greatly increased by compaction during construction. In foundation problems, the density of a soil is expressed in terms of wet unit weight.

Dry unit weight ( $\gamma_d$ ), also expressed as dry density, is the term used if the moisture content is zero. Since no water is present and the weight of air is negligible, it is written:

$$\gamma_d = \frac{W_s}{V}$$

Dry unit weight normally is used in construction problems. The general relationship between wet unit weight and dry unit weight is expressed:

$$\gamma_d = \frac{\gamma}{1 + w/100}$$

A numerical example of volume-weight relationships follows:

GIVEN:

A soil mass with:

wet unit weight = 125 pcf  
 moisture content = 18 percent  
 specific gravity = 2.65  
 volume = 1 cubic foot (cu ft)

FIND:

- $\gamma_d$  dry unit weight
- (2)  $e$ , void ratio

SOLUTION:

- Find dry unit weight

$$\gamma_d = \frac{\gamma_m}{1 + w/100}$$

$$\gamma_d = \frac{125}{1 + 18/100}$$

$$= 125/1.18$$

$$= 105.9 \text{ pcf}$$

- Find the void ratio using the formula:

$$e = V_v/V_s$$

$$V_s = W_d/62.4 \text{ G}$$

$$V_s = 105.9/62.4 \text{ (2.65)}$$

$$= 0.64 \text{ cu ft}$$

If  $V_v = V - V_s$ , then

$$V_v = 1.00 - 0.64 = 0.36 \text{ cu ft}$$

Thus, if  $e = V_v/V_s$ , substituting computed values, then

$$e = 0.36/0.64 = 0.56$$

The relationships discussed previously are used in calculations involved in soil construction work. They are used along with the necessary soil tests to classify and to help determine engineering characteristics of soil.

### Relative Density

Use of the void ratio is not very effective in predicting the soil behavior of granular or unrestricted soils. More useful in this respect is the term relative density, expressed as  $D_r$ . Relative density is an index of the degree to which a soil has been compacted. Values range from 0 ( $e = e_{max}$ ) to 1.0 ( $e = e_{min}$ ). It is written:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

where

$e_n$  = the natural, in-place, void ratio

$e_{max}$  = the void ratio in the loosest possible condition

$e_{min}$  = the void ratio in the most dense condition possible.

The limiting ranges of  $e_{max}$  may be found by pouring the soil loosely into a container and determining its weight and volume. The limiting ranges of  $e_{min}$  may be found by tamping and shaking the soil until it reaches a minimum volume and recording its weight and volume at this point. Relative density is important for gravels and sands.

### Soil-Moisture Conditions

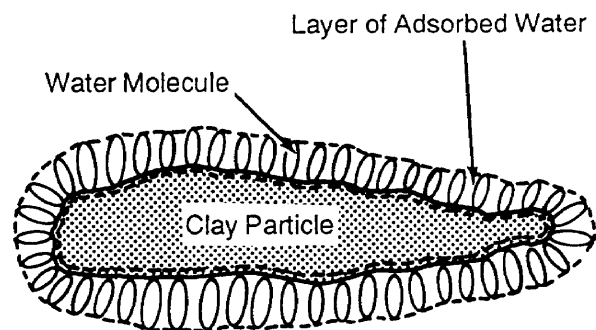
Coarse-grained soils are much less affected by moisture than are fine-grained soils. Coarser soils have larger void openings and generally drain more rapidly. Capillarity is no problem in gravels having only very small amounts of fines mixed with them. These soils will not usually retain large amounts of water if they are above the ground water table. Also, since the particles in sandy and gravelly soils are relatively large (in comparison to silt and clay particles), they are heavy in comparison to the films of moisture that might surround them. Conversely, the small, sometimes microscopic, particles of a fine-grained soil weigh so little that water within the voids has a considerable effect on them. The following phenomena are examples of this effect:

- Clays frequently undergo very large volume changes with variations in moisture content. Evidence of this can be seen in the shrinkage cracks that develop in a lake bed as it dries.
- Unpaved clay roads, although often hard when sunbaked, lose stability and turn into mud in a rainstorm.
- In general, the higher the water content of a clay or silt, the less is its strength and hence its bearing capacity.

These effects are very important to an engineer and are functions of changing water content. The Army's emphasis on early achievement of proper drainage in horizontal construction stems from these properties of cohesive soils.

**Adsorbed Water.** In general terms, adsorbed water is water that may be present as thin films surrounding the separate soil particles. When the soil is in an air-dry condition, the adsorbed water present is called hygroscopic moisture. Adsorbed water is present because the soil particles carry a negative electrical charge. Water is dipolar; it is attracted to the surface of the particle and bound to it (see *Figure 4-12*). The water films are affected by the chemical and physical structure of the soil particle and its relative surface area. The relative surface area of a particle of fine-grained soil, particularly if it has a flaky or needlelike shape, is much greater than for coarse soils composed of bulky grains. The electrical forces that bind adsorbed water to the soil particle also are much greater. Close to the particle, the water contained in the adsorbed layer has properties quite different from ordinary water. In the portion of the layer immediately adjacent to the particle, the water may behave as a solid, while only slightly farther away it behaves as a viscous liquid. The total thickness of the adsorbed layer is very small, perhaps on the order of 0.00005 mm for clay soils. In coarse soils, the adsorbed layer is quite thin compared with the thickness of the soil particle. This, coupled with the fact that the contact area between adjacent grains is quite small, leads to the conclusion that the presence of the adsorbed water has little effect on the physical properties of coarse-grained soils. By contrast, for finer soils and particularly in clays, the adsorbed water film is thick in comparison with particle size. The effect is very pronounced when the particles are of colloidal size.

**Plasticity and Cohesion.** Two important aspects of the engineering behavior of fine-grained soils are directly associated with the



**Figure 4-12.** Layer of adsorbed water surrounding a soil particle.

existence of adsorbed water films. These aspects are plasticity and cohesion.

Plasticity is the ability of a soil to deform without cracking or breaking. Soils in which the adsorbed films are relatively thick compared to particle size (such as clays) are plastic over a wide range of moisture contents. This is presumably because the particles themselves are not in direct contact with one another. Plastic deformation can take place because of distortion or shearing of the outside layer of viscous liquid in the moisture films. Coarse soils (such as clean sands and gravels) are nonplastic. Silts also are essentially nonplastic materials, since they are usually composed predominantly of bulky grains; if platy grains are present, they may be slightly plastic.

A plasticity index (PI) is used to determine if soils are cohesive. Not all plastic soils are cohesive; soil is considered cohesive if its PI is 5. That is, they possess some cohesion or resistance to deformation because of the surface tension present in the water films. Thus, wet clays can be molded into various shapes without breaking and will retain these shapes. Gravels, sands, and most silts are not cohesive and are called cohesionless soils. Soils of this general class cannot be molded into permanent shape and have little or no strength when dry and unconfined. Some of these soils may be slightly cohesive when damp. This is attributed to what is sometimes called apparent cohesion, which is also

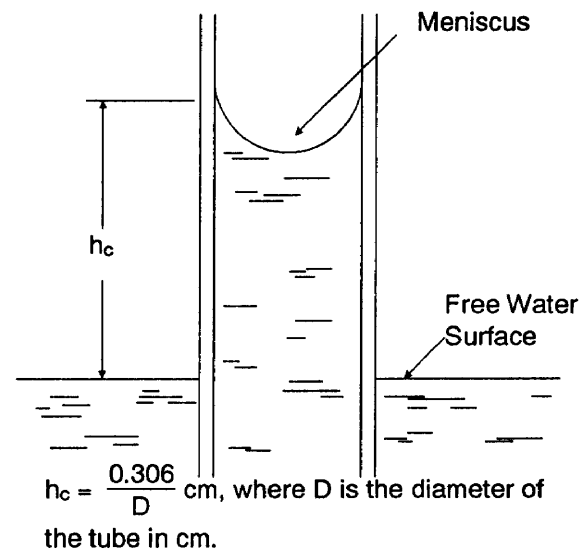
due to the surface tension in the water films between the grains.

**Clay Minerals and Base Exchange.** The very fine (colloidal) particles of clay soils consist of clay minerals, which are crystalline in structure. These minerals are complex compounds of hydrous aluminum silicates and are important because their presence greatly influences a soil's physical properties. X rays have been used to identify several different kinds of clay minerals that have somewhat different properties. Two extreme types are kaolinite and montmorillonite. Both have laminated crystalline structures, but they behave differently. Kaolinite has a very rigid crystalline structure, while montmorillonite can swell by taking water directly into its lattice structure. Later, the flakes themselves may decrease in thickness as the water is squeezed out during drying, the flakes are thus subject to detrimental shrinkage and expansion. An example of this type of material is bentonite, largely made up of the montmorillonite type of clay mineral. Because of its swelling characteristics, bentonite is widely used commercially in the construction of slurry walls and temporary dam cores. Most montmorillonites have much thicker films of adsorbed water than do kaolinites. Kaolinites tend to shrink and swell much less than montmorillonites with changes in moisture content. In addition, the adsorbed water film may contain disassociated ions. For example, metallic cations, such as sodium, calcium, or magnesium, may be present. The presence of these cations also affects the physical behavior of the soil. A montmorillonite clay, for example, in which calcium cations predominate in the adsorbed layer may have properties quite different from a similar clay in which sodium cations predominate. The process of replacing cations of one type with cations of another type in the surface of the adsorbed layer is called base (or cation) exchange. It is possible to effect this replacement and thereby alter the physical properties of a clay soil. For example, the soil may swell, the plasticity may be reduced, or the permeability may be increased by this general process.

**Capillary Phenomena.** Capillary phenomena in soils are important for two reasons. First, water moves by capillary action into a

soil from a free-water surface. This aspect of capillary phenomena is not discussed here but is covered in *Chapter 8*. Second, capillary phenomena are closely associated with the shrinkage and expansion (swelling) of soils.

The capillary rise of water in small tubes is a common phenomenon, which is caused by surface tension (see *Figure 4-13*). The water that rises upward in a small tube is in tension, hanging on the curved boundary between air and water (meniscus) as if from a suspending cable. The tensile force in the meniscus is balanced by a compressive force in the walls of the tube. Capillary phenomena in small tubes can be simply analyzed and equations derived for the radius of the curved meniscus, the capillary stress (force per unit of area), and the height of capillary rise (see  $h_c$  in *Figure 4-13*). A soil mass may be regarded as being made up of a bundle of small tubes formed by the interconnected void spaces. These spaces form extremely irregular, tortuous paths for the capillary movement of water. An understanding of capillary action in soils is thus gained by analogy. Theoretical analyses indicate that maximum possible compressive pressure that can be exerted by capillary forces is inversely proportional to the size of the capillary openings.



**Figure 4-13. Capillary rise of water in small tubes.**



**Shrinkage.** Many soils undergo a very considerable reduction in volume when their moisture content is reduced. The effect is most pronounced when the moisture content is reduced from that corresponding to complete saturation to a very dry condition. This reduction in volume is called shrinkage and is greatest in clays. Some of these soils show a reduction in volume of 50 percent or more while passing from a saturated to an oven-dry condition. Sands and gravels, in general, show very little or no change in volume with change in moisture content. An exception to this is the bulking of sands, which is discussed below. The shrinkage of a clay mass may be attributed to the surface tension existing in the water films created during the drying process. When the soil is saturated, a free-water surface exists on the outside of the soil mass, and the effects of surface tension are not important. As the soil dries out because of evaporation, the surface water disappears and innumerable menisci are created in the voids adjacent to the surface of the soil mass. Tensile forces are created in each of these boundaries between water and air. These forces are accompanied by compressive forces that, in a soil mass, act on the soil structure. For the typical, fairly dense structure of a sand or gravel, the compressive forces are of little consequence; very little or no shrinkage results. In fine-grained soils, the soil structure is compressible and the mass shrinks. As drying continues, the mass attains a certain limiting volume. At this point, the soil is still saturated. The moisture content at this stage is called the shrinkage limit. Further drying will not cause a reduction in volume but may cause cracking as the menisci retreat into the voids. In clay soils, the internal forces created during drying may become very large. The existence of these forces also principally accounts for the rocklike strength of a dried clay mass. Both silt and clay soils may be subject to detrimental shrinkage with disastrous results in some practical situations. For example, the uneven shrinkage of a clay soil may deprive a concrete pavement of the uniform support for which it is designed; severe cracking or failure may result when wheel loads are applied to the pavement.

**Swelling and Slaking.** If water is again made available to a still-saturated clay soil mass that has undergone shrinkage, water enters the soil's voids from the outside and reduces or destroys the internal forces previously described. Thus, a clay mass will absorb water and expand or swell. If expansion is restricted, as by the weight of a concrete pavement, the expansion force may be sufficient to cause severe pavement cracking. If water is made available to the soil after it has dried below the shrinkage limit, the mass generally disintegrates or slakes. Slaking may be observed by putting a piece of dry clay into a glass of water. The mass will fall completely apart, usually in a matter of minutes. Construction problems associated with shrinkage and expansion are generally solved by removing the soils that are subject to these phenomena or by taking steps to prevent excessive changes in moisture content.

**Bulking of Sands.** Bulking is a phenomenon that occurs in dry or nearly dry sand when a slight amount of moisture is introduced into the soil and the soil is disturbed. Low moisture contents cause increased surface tension, which pulls the grains together and inhibits compaction. As a result, slightly moist sands can have lower compacted densities than totally dry or saturated sands. Commonly in sands, this problem is made worse because a slight addition of moisture above the totally dry state increases the sliding coefficient of the particles. The U-shaped compaction curve, with characteristic free-draining soils (sands and gravels), illustrates the concept of bulking. Adding sufficient water to saturate the sand eliminates surface tension, and the sand can be compacted to its densest configuration (see *Figure 4-14, page 4-18*).

#### CONSISTENCY (ATTERBERG) LIMITS

A fine-grained soil can exist in any one of several different states, depending on the amount of water in the soil. The boundaries between these different soil states are moisture contents called consistency limits. They are also called Atterberg limits after the Swedish soil scientist who first defined them in 1908. The shrinkage limit is the boundary

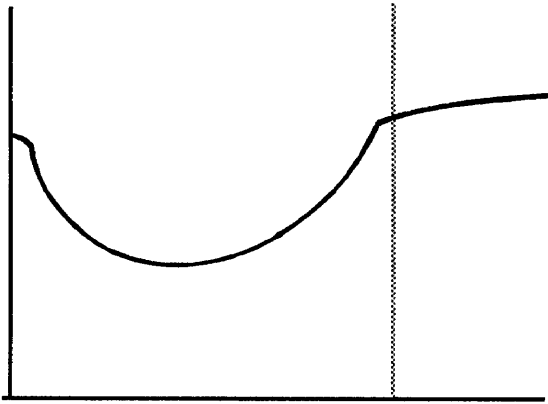


Figure 4-14. U-shaped compaction curve.

between the semisolid and solid states. The plastic limit (PL) is the boundary between the semisolid and plastic states. The liquid limit (LL) is the boundary between the plastic and liquid states. Above the LL, the soil is presumed to behave as a liquid. The numerical difference between the LL and the PL is called the PI and is the range of moisture content over which the soil is in a plastic condition. The Atterberg limits are important index properties of fine-grained soils. They are particularly important in classification and identification. They are also widely used in specifications to control the properties, compaction, and behavior of soil mixtures.

### Test Procedures

The limits are defined by more or less arbitrary and standardized test procedures that are performed on the portion of the soil that passes the Number 40 sieve. This portion of soil is sometimes called the soil binder. *TM 5-530* contains detailed test procedures to be used in determining the LL and the PL. The tests are performed with the soil in a disturbed condition.

**Liquid Limit.** The LL (or  $w_L$ ) is defined as the minimum moisture content at which a soil will flow upon application of a very small shearing force. With only a small amount of energy input, the soil will flow under its own weight. In the laboratory, the LL is usually determined by use of a mechanical device (see *Figure 4-15*). The detailed testing procedure is described in *TM 5-530*.

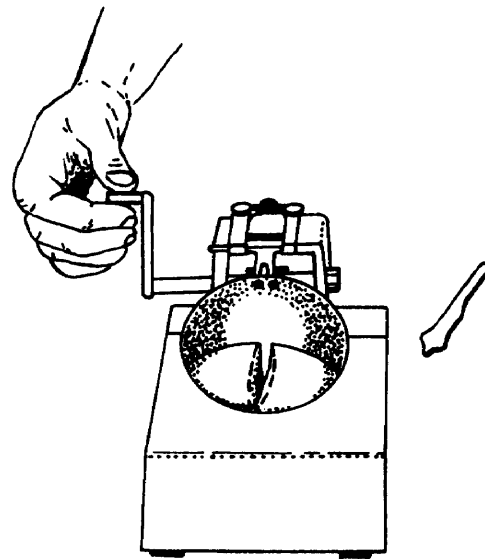


Figure 4-15. Liquid limit test.

**Plastic Limit.** The PL (or  $w_p$ ) is arbitrarily defined as the lowest moisture content at which a soil can be rolled into a thread 1/8 inch in diameter without crushing or breaking. If a cohesive soil has a moisture content above the PL, a thread may be rolled to less than 1/8 inch in diameter without breaking. If the moisture content is below the PL, the soil will crumble when attempts are made to roll it into 1/8-inch threads. When the moisture content is equal to the PL, a thread can be rolled out by hand to 1/8 inch in diameter; then it will crumble or break into pieces 1/8 to 3/8 inch long when further rolling is attempted. Some soils (for example, clean sands) are nonplastic and the PL cannot be determined. A clean sand or gravel will progress immediately from the semisolid to the liquid state.

### Plasticity Index

The PI (or  $I_p$ ) of a soil is the numerical difference between the LL and the PL. For example, if a soil has a LL of 57 and a PL of 23, then the PI equals 34 ( $PI = LL - PL$ ). Sandy soils and silts have characteristically low PIs, while most clays have higher values. Soils that have high PI values are highly plastic and are generally highly compressible and highly

cohesive. The PI is inversely proportional to the permeability of a soil. Soils that do not have a PL, such as clean sands, are reported as having a PI of zero.

Relationships between the LLs and PIs of many soils were studied by Arthur

Casagrande of Harvard University and led to the development of the plasticity chart. The chart's development and use in classifying and identifying soils and selecting the best of the available soils for a particular construction application are discussed in *Chapter 5*.