CHARACTERIZATION OF GEOLOGIC MATERIALS

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Contents

Summary

Geologic materials include both soils and rocks. Soils are classified as coarse-grained (sands and gravels) and fine-grained soils (silts and clays) on the basis of particle size whereas rocks are divided into igneous, sedimentary, and metamorphic based on their origin. Void ratio, porosity, water content, degree of saturation, density, grain size distribution, and Atterberg limits are the index properties used for characterization of engineering behavior of soils.

Properties of soils used for design purposes include compaction characteristics, permeability, consolidation behavior, and shear strength parameters. Rocks are characterized on the basis of properties of intact rock and rock mass. Specific gravity, absorption, density, unconfined compressive strength, tensile strength, shear strength, Young's modulus, Poisson's ratio, and durability are used for characterization of intact rock as construction material.

Rock mass properties are important for design and stability of engineering structures, and are controlled by the nature of discontinuities present in a rock mass. Rock mass classification systems, which take into account the nature of discontinuities, are used to characterize the engineering behavior of rock masses.

1. Types of Geologic Materials

Geologic materials include both soils and rocks but a well-defined boundary between them does not exist. For example, a highly weathered rock shown as a rock on a geologic map may be considered soil by a civil engineer. For the purpose of this article, a soil is defined as a loose, unconsolidated aggregation of mineral particles that can be easily separated by hand pressure or agitation in water (Johnson and DeGraff, 1988) and that can be excavated without blasting (West, 1995).

A rock, on the other hand, is a hard and compact aggregation of minerals that remains intact in water and cannot be excavated without blasting (West, 1995). Between these two end members, there is a gradation zone (glacial tills, shales, claystones, mudstones, etc.) that exhibits properties of both soils and rocks.

1.1. Soils

Geologically, soils are the end products of mechanical and/or chemical weathering of rocks. Based on their mode of origin, soils can be categorized as residual or transported. Residual soils are those that remain at the place of their origin whereas transported soils are the ones that have been carried away from their place of origin by such agents as gravity (colluvial soils), water (alluvial soils), ice (glacial soils), and wind (aeolian soils).

Engineering properties of soils are closely related to their mode of origin. The residual soils are likely to exhibit a well-developed soil profile, colluvial soils are dominated by angular particles, alluvial soils are generally stratified, glacial soils can be highly heterogeneous with wide range in particle size, and aeolian soils are characterized by uniform particle size.

1.2. Rocks

Rocks are classified as igneous, sedimentary, and metamorphic on the basis of their origin. Igneous rocks are formed by solidification of molten rock material (lava or magma) upon cooling, sedimentary rocks are deposited in water in the form of layers, and metamorphic rocks are formed by the action of heat and pressure on pre-existing rocks. Detailed descriptions and classifications of these three types of rock can be found in books on physical geology. The International Association of Engineering Geology (IAEG) has also developed comprehensive classifications for igneous, sedimentary, and metamorphic rocks (IAEG, 1981) which can be useful for predicting their engineering behavior.

1.2.1 Igneous Rocks

As stated above, igneous rocks originate from the cooling of molten rock material that is termed magma when it lies below the ground surface and lava when it extrudes on the surface. Cooling below the earth's surface is slow and results in large crystals whereas cooling on the surface is rapid and results in small crystal size. Depending upon the place of cooling, igneous rocks are divided into extrusive or volcanic rocks (cool on the surface; fine-grained), hypabyssal rocks (cool a short distance below the surface; medium-grained), and intrusive or plutonic rocks (cool deep down inside the earth; coarse-grained).

Igneous rocks are usually classified on the basis of their texture (size, shape, and arrangement of grains) and mineral composition. Commonly encountered igneous rocks include granite, diorite, and gabbro as the coarse-grained varieties, rhyolite, andesite, and basalt as the fine-grained equivalents, and dolerite or diabase as the medium-grained equivalent of gabbro. Extrusive igneous rocks also include volcanic breccia and tuff that are made of pyroclastic material of varying sizes (material that is blown out in the air during volcanic eruptions).

Engineering properties of igneous rocks are related to their texture and mineral composition (West, 1995; Tugrul and Zarif, 1999). Fine-grained acid igneous rocks containing volcanic glass, opal, and chalcedony can result in alkali-silica reaction, when used as aggregate in Portland cement concrete, leading to volumetric expansion and cracking.

Coarse-grained igneous rocks have generally lower strength and abrasion resistance than fine-grained igneous rocks and are, consequently, less suitable for engineering applications (West, 1995). The mode of emplacement of intrusive igneous rocks is also significant in terms of engineering characterization (Johnson and DeGraff, 1988). Massive plutonic rocks (stocks and batholiths) tend to be more isotropic with respect to engineering properties and less problematic in engineering construction than tabular plutons (dikes and sills).

Among the extrusive rocks, those formed of lava flows are expected to be more homogeneous and closely jointed than the pyroclastic rocks that are heterogeneous with widely spaced jointing.

1.2.2. Sedimentary Rocks

Sedimentary rocks comprise about 75% of the rocks exposed at the earth surface. These rocks are deposited as sediments in water that are later lithified through the processes of compaction, cementation, and crystallization to form the rock. Layering or stratification is the single most characteristic feature of sedimentary rocks. Based on their origin, sedimentary rocks are divided into clastic sedimentary rocks, comprised of material broken down from pre-existing rocks, and chemical sedimentary rocks resulting from chemical precipitation, both inorganic and biochemical. Breccias, conglomerates, sandstones, shales, clystones, mudstones, and siltstones are examples of clastic sedimentary rocks.

Limestones, dolomites, and evaporates belong to the family of chemical, crystalline, sedimentary rocks of inorganic nature while chalk and coal are good examples of organic sedimentary rocks. According to West (1995), the three rock types that comprise 99% of all sedimentary rocks are shales (46%), sandstones (32%), and limestones (22%).

Sedimentary rocks are extremely diverse in their texture and mineral composition. The source rock, agent of transportation, duration and distance of transportation, depositional environment, lithification processes, and type and amount of cementation all contribute to the diversity of sedimentary rocks. The diverse nature of sedimentary rocks is manifested by the extreme variation in their engineering properties.

Alkali-carbonate reaction, low abrasion resistance of coarse limestone aggregate, susceptibility of argillaceous carbonates, shales, and cherts to pitting and popouts during freeze-thaw cycles, low strength and high swelling potential of some shales, claystones, and mudstones, and presence of solution cavities and open fractures in limestone, are some of the problems posed by sedimentary rocks in engineering works.

1.2.3. Metamorphic Rocks

Metamorphic rocks form by the action of heat and pressure on pre-existing rocks within the earth's crust. Metamorphism, which results in textural, structural, and mineralogical changes in the parent rock, can take place near igneous intrusions (contact metamorphism) or over very large areas associated with plate movements (regional metamorphism). Most regionally metamorphosed rocks exhibit foliated texture that results from arrangement of minerals in parallel planes under the influence of pressure. The foliated metamorphic rocks include slates, phyllites, schists, and gneisses. The non-foliated metamorphic rocks include marble (metamorphosed limestone) and quartzite (metamorphosed sandstone).

Foliated metamorphic rocks exhibit directional properties. Strength, permeability, and seismic velocity are strongly affected by direction of foliation (West, 1995). Since foliation represents planes of weakness in metamorphic rocks, serious stability problems can arise in projects involving slopes, tunnels, and foundations.

2. Engineering Characterization of Soils

Soils constitute one of the most widely encountered materials in engineering construction. Many engineering structures are either made of soil material or they are founded on soils. The design and stability of these structures depends on the engineering properties of soils involved that, in turn, are greatly influenced by their geologic characteristics. Because of their heterogeneity, anisotropic nature, and non-linear stress-strain curves, characterization and prediction of the engineering behavior of soils is a challenging job that requires experience and good judgment. For characterization purposes, engineering properties of soils are commonly grouped into index properties and design properties.

2.1. Index Properties

2.1.1. Phase Relationships

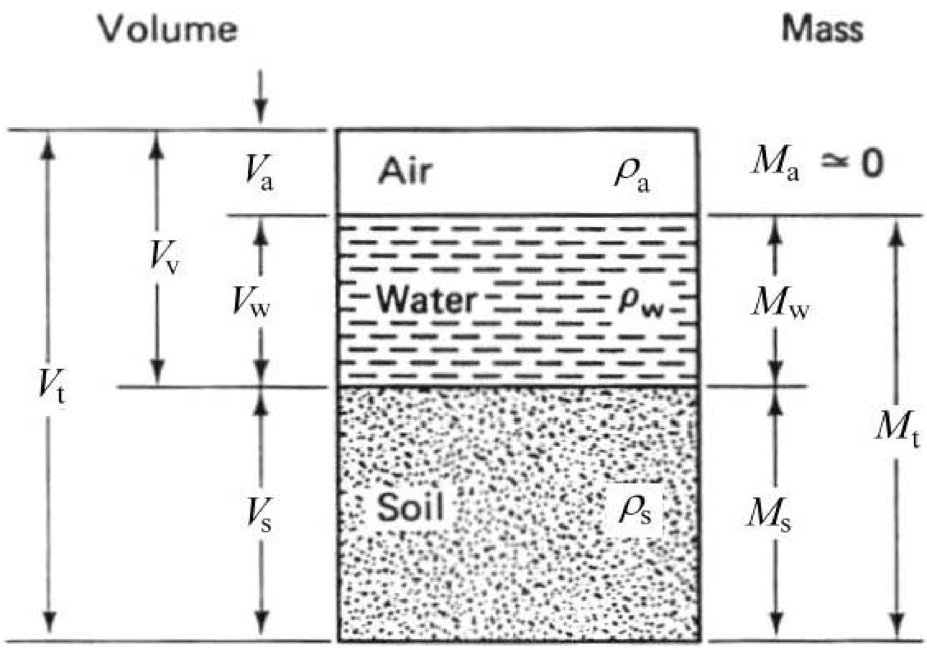

Figure 1. Phase diagram showing mass-volume relationships for soils (taken from Holtz and Kovacs, Introduction to Geotechnical Engineering, © 1981. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ).

A mass of soil commonly consists of three phases: solid mineral particles, water, and air. For a completely saturated and a completely dry soil, all voids (open spaces between solid particles) are filled with water and air respectively, and the soil mass reduces to a two-phase system. Figure 1 shows a schematic representation of the masses and volumes of various phases involved. The inter-relationships between these phases define some important index properties used for soil characterization. The symbols used in defining various properties described below are given in Figure 1.

Void Ratio (e): Void ratio is defined as the ratio of the volume of voids to the volume of solids, expressed as a decimal $\left(e = V_{\mathrm{v}}/V_{\mathrm{s}}\right)$. The higher the void ratio, the more compressible is the soil. Typical values of void ratio can range from 0.4-1.0 for sands, from 0.3-1.5 for clays, and much higher for organic soils (Holtz and Kovacs, 1981).

Porosity (n): Porosity is the ratio of the volume of voids to the total volume of a soil mass, expressed as a percentage $\left\{n = \left(V_{\mathrm{v}}/V_{\mathrm{t}}\right)100\right\}$. Theoretically, porosity can range from 0-100%. Clayey soils tend to have higher porosity values (30-70%) than sandy soils (20-50%). Void ratio and porosity are related to each other as follows:

$$e = n/1 - n \tag{1}$$

$$n = e/1 + e \tag{2}$$

Degree of Saturation (S): Degree of saturation relates to the amount of water in the voids. It is the ratio of the volume of water to the volume of voids, expressed as a percentage $\left\{S = \left(V_{\mathrm{w}}/V_{\mathrm{v}}\right)100\right\}$. The degree of saturation ranges from 0% for a completely dry soil to 100% for a completely saturated soil. The lower the degree of saturation of an expansive clayey soil, the more will it expand upon the addition of water.

Water Content (w): Water content is the ratio of the mass of water to the mass of solids, expressed as a percentage $\left\{w = \left(M_{\mathrm{w}}/M_{\mathrm{s}}\right)100\right\}$. The water content for natural soils can range from 0% for a completely dry soil to several hundred percent for some marine organic clays. The higher the natural water content of a soil, the more undesirable are its engineering properties.

Density (ρ): Density connects the two sides of the phase diagram in Figure1. Density is the ratio of the mass to the volume of a soil. Different types of density are used in engineering practice such as bulk density $\left(\rho = M_{\mathrm{t}}/V_{\mathrm{t}}\right)$, solid density $\left(\rho_{\mathrm{s}} = M_{\mathrm{s}}/V_{\mathrm{s}}\right)$, dry density $\left(\rho_{\mathrm{d}} = M_{\mathrm{s}}/V_{\mathrm{t}}\right)$, saturated density $\left\{\rho_{\mathrm{sat}}\left(M_{\mathrm{s}} + M_{\mathrm{w}}\right)/V_{\mathrm{t}}, \text{ with } M_{\mathrm{w}} \text{ at } S = 100\%\right\}$, and submerged density $\left(\rho' = \rho_{\mathrm{sat}} - \rho_{\mathrm{w}}\right)$.

2.1.2. Soil Texture

Soil texture relates to particle sizes and shapes as well as distribution of various sizes (gradation) in a soil mass. Based on soil texture, soils are subdivided into coarse-textured and fine-textured categories. Sands and gravels are considered coarse-textured soils and silts and clays fine- textured; the distinction between the two groups being whether the grains can be seen with the naked eye or not. Texture controls the behavior of coarse-grained or granular soils and water controls the behavior of fine-grained or cohesive soils.

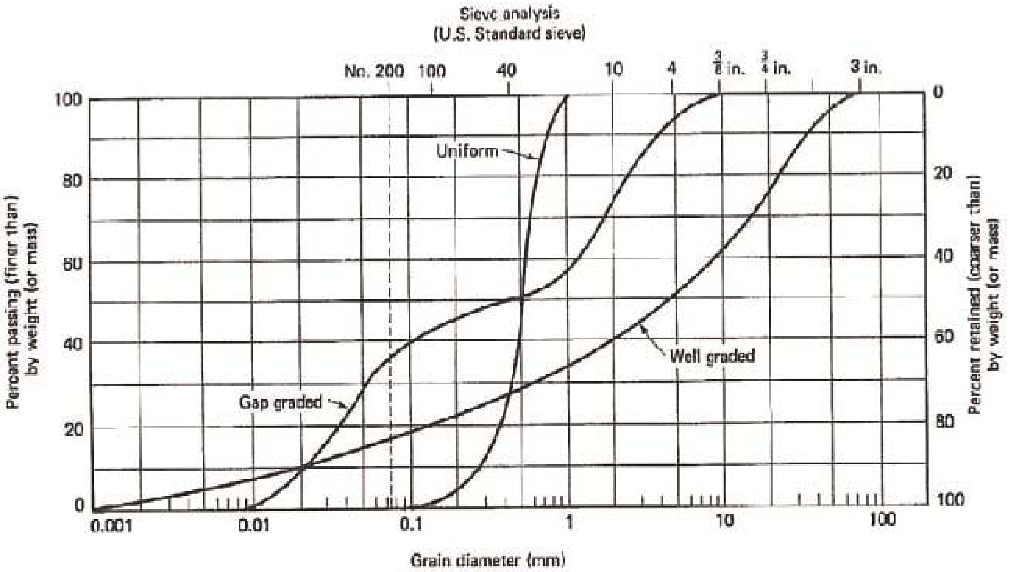

Figure 2. Grain size distribution curves (taken from Holtz and Kovacs, Introduction to Geotechnical Engineering, © 1981. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ).

Particle size can vary from boulders (10^3mm) to colloidal size clay material (10^{-5}mm). Different grain size ranges are used for classification purposes by American Society for Testing and Materials (ASTM), American Association of State Highway and Transportation Officials (AASHTO), British Standards, and Unified Soil Classification System (USCS) details of which can be found in most soil mechanics books. Particle size distribution for coarse-grained soils is determined by performing a sieve analysis, using a set of standardized sieves.

The method has been standardized by ASTM and is designated as D 422 (ASTM, 1996). For the material passing the No. 200 sieve (0.074mm) and for fine-grained soils, the hydrometer analysis (ASTM D 422), based on Stokes' Law, is used. A grain size distribution curve is obtained by plotting the cumulative percent passing against the corresponding sieve sizes using a semi-log paper. Figure 2 shows the grain size distribution curves for three different soils.

A well-graded soil is the one in which all particle sizes are well represented, a gap-graded soil has certain sizes missing, and a uniformly-graded or poorly-graded soil consists predominantly of one size particles. In engineering practice, a well-graded soil is expected to exhibit the best engineering properties whereas uniformly graded soils can be problematic.

Two quantitative indices, as defined below, are commonly used to describe the soil gradation:

$$\text{Coefficient of uniformity} = C_u = D_{60}/D_{10} \quad (3)$$

$$\text{Coefficient of curvature} = C_c = (D_{30})^2/(D_{10})(D_{30}) \quad (4)$$

where D_{10}, D_{30}, and D_{60} are particle sizes corresponding to 10%, 30%, and 60% of the soil finer than the corresponding diameter respectively (on cumulative weight percent basis).

The smaller the C_u, the more uniformly graded the soil is. Well-graded soils have C_u values greater than 15. Alternatively, a soil will be well graded if its C_c is between 1 and 3, and C_u is greater than 4 for gravels and greater than 6 for sands.

2.1.3. Atterberg Limits

Atterberg limits, also referred to as consistency limits, represent water contents at which marked changes in physical state and engineering behavior of fine-grained soils occur. By comparing the natural water content of a soil with its Atterberg limits, one can predict its engineering behavior. Important Atterberg limits include liquid limit (LL), plastic limit (PL), and shrinkage limit (SL).

Liquid limit is the minimum water content at or above which a soil behaves as a viscous liquid and plastic limit is the minimum water content at which a soil behaves as a plastic material. Liquid and plastic limits for fine-grained soils can be determined by ASTM method D 4318 (ASTM, 1996). The numerical difference between the liquid and plastic limits is referred to as the plasticity index (PI).

It indicates the range of water content over which a soil behaves as a plastic material. Volume of a soil continues to decrease upon drying. Shrinkage limit is the minimum water content beyond which no further reduction in volume occurs upon further drying.

Although Atterberg limits are index properties, they are extremely important in characterization of fine-grained soils as they can be correlated with almost all other engineering properties. Soils with low SL and high PI values are most prone to detrimental volume change with changes in water content.

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Biographical Sketch

Abdul Shakoor, professor of engineering geology at the Kent State University, Ohio, U.S.A., received his MS and Ph.D. degrees in engineering geology from Purdue University. Prior to joining Purdue University, he obtained an M.Sc. in Geology from Punjab University, Pakistan and an M.Sc. in engineering geology from Leeds University, England. He started his professional career as a site Geologist at Mangla Dam, Pakistan, and in a teaching position at Punjab University. In 1982, Professor Shakoor joined Kent State University where he is currently in charge of the graduate program in engineering geology. He is Co-Editor of Environmental and Engineering Geoscience (1998-present), a joint publication of the Association of Environmental and Engineering Geologists and the Geological Society of America. His research interests include engineering behavior of mudrocks, stability of slopes, evaluation of construction materials, and engineering applications of waste materials. In addition to his teaching and research responsibilities, Professor Shakoor has worked on a variety of consulting projects including slope stability, blasting-related damage, expansive soils, construction materials, and dam engineering.