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BUREAU OF RECLAMATION

DESIGN OF SMALL DAMS

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by a hyphen, such as GW–GC.

If the percentages of gravel and sand sizes in a coarse-grained soil are nearly equal, the classification procedure is to assume that the soil is a gravel and then continue on the chart until the final soil group, say GC, is reached. Since it could have been assumed that the soil is a sand, the correct field classification is GC–SC, because the criteria for the gravel and sand subgroups are identical. Similarly, within the gravel or sand groupings, boundary classifications such as GW–GP, GM–GC, GW–GM, SW–SP, SM–SC, and SW–SM, can occur.

Proper boundary classification of a soil near the borderline between coarse-grained and fine-grained soils is accomplished by classifying it first as a coarse-grained soil and then as a fine-grained soil. Such classifications as SM–ML and SC–CL are common.

Within the fine-grained division, boundary classifications can occur between low-liquid-limit soils and high-liquid-limit soils as well as between silty and clayey materials in the same range of liquid limits. For example, one may find ML–MH, CL–CH, and OL–OH soils; ML–CL, ML–OL, and CL–OL soils; and MH–CH, MH–OH, and CH–OH soils.

(c) *Laboratory Classification.*—Although most classifications of soil will be done visually and by simple hand tests, the Unified Soil Classification System has provided for precise delineation of the soil groups by mechanical analyses and Atterberg limits tests in the laboratory. Laboratory classifications are often performed on representative samples of soils which are being subjected to extensive testing and to verify field classifications when used in the design of small dams. Laboratory classification can be used to advantage in training the field classifier of soils to improve his ability to estimate percentages and degrees of plasticity.

The grain-size curve is used to classify the soil as being coarse-grained or fine-grained, and if coarse-grained, into gravel or sand by size, using the 50-percent criterion. Within the gravel or sand groupings, soils containing less than 5 percent finer than the No. 200 sieve size are considered "clean" and are then classified as well graded or poorly graded by their coefficients of uniformity and of curvature. In order for a clean gravel to be well graded (GW), it must have *both* a coefficient of uniformity, C_u, greater than 4 and a coefficient of curvature, C_c, between 1 and 3; otherwise, it is classified as a poorly graded gravel (GP). A clean sand having *both* C_u greater than 6 and C_c between 1 and 3 is in the SW group; otherwise, it is a poorly graded sand (SP).

Laboratory classification criteria for coarse-grained soils and for fine-grained soils are given in the Soil Classification Chart, figure 56.

94. *Engineering Characteristics of Soil Groups.* —(a) *General.*—Although there is no satisfactory substitute for actual testing to determine the important engineering properties of a particular soil, approximate values for typical soils of each classification group can be given as a result of statistical analysis of existing information. The attempt to put soils data into quantitative form involves the risk of (1) the data not being representative, and (2) use of the values in design without adequate safety factors. For the design of small dams, however, where investigation has disclosed no complex problems, expensive laboratory tests of permeability, shear, and consolidation of soils appear unwarranted and the use of average values of these properties is permissible. Since the values pertain to the soil groups, proper soil classification becomes of vital importance. Verification of field identification by laboratory gradation and Atterberg limits tests should be made on representative samples of each soil group encountered.

Table 8 is a summary of values obtained on more than 1,500 soil tests performed in the engineering laboratories of the Bureau of Reclamation in Denver, Colo., arranged according to the main soil classification groups and two frequently occurring boundary groups. The data for this table were obtained from reports for which laboratory soil classifications were available. The large majority of soils were from the 17 western States of the United States in which the Bureau operates; however, some foreign soils were included. Although the sampling area of the soils tested is limited, it is believed that the Unified Soil Classification System is relatively insensitive to geographical distribution. The procedure for determining which of many submitted samples should be tested is in itself conducive to obtaining a representative range of values, since samples were selected from the coarsest, finest, and average soil within a potential source.

For each soil property listed, the average and its 90 percent confidence limits are given where sufficient data were available to determine them. Since all laboratory tests, except large-sized permeability tests, were made on the minus No. 4 fraction of the soil, data on average values for the gravels are not available for most properties. However, an indication as to whether these average values will be greater than or less than the average values for the corresponding sand group is given in the table. The averages shown are subject to uncertainties that arise from sampling fluctuations, and they tend to vary from the true averages more widely if the number of observations is small. The plus or minus limits given are determined mathematically from the number of observations and from the standard deviation of the data used to determine the average. These limits imply that the true average, obtained by securing and testing more and more samples under the same essential conditions, lies within the plus or minus values 9 chances out of 10 [4].

The values for Proctor maximum dry density and optimum water content were obtained by tests described in section 120. The other properties are based on tests made on samples compacted to Proctor maximum dry density at optimum water content. The value of void ratio, e_o, is the ratio of the portion of the volume of the soil mass occupied by water and air to the volume of the soil grains. It is derived from the Proctor maximum dry density and the specific gravity of the grains. The MH and CH soil groups have no upper boundary of liquid limits in the classification; hence, it is necessary to give the range of those soils included in the table. The maximum liquid limits for the MH and the CH soils tested were 81 and 88 percent, respectively. Soils with higher liquid limits than these will have inferior engineering properties.

(b) *Permeability.*—The voids in the soil mass provide passages through which water may move. Such passages are variable in size and the paths of flow are tortuous and interconnected. If, however, a sufficiently large number of paths of flow are considered as acting together, an average rate of flow for the soil mass can be determined under controlled conditions that will represent a property of the

TABLE 8.—*Average properties of soils*

Soil classification group	Proctor compaction		Void ratio, e_o	Permeability, k, feet per year	Compressibility		Shearing strength		
	Maximum dry density in pounds per cubic foot	Optimum water content, percent			@ 20 p.s.i., percent	@ 50 p.s.i., percent	C_o p.s.i.	C_{sat} p.s.i.	tan ϕ
GW	>119	<13.3	(*)	27,000±13,000	<1.4	(*)	(*)	(*)	>0.79
GP	>110	<12.4	(*)	64,000±34,000	<0.8	(*)	(*)	(*)	>0.74
GM	>114	<14.5	(*)	>0.3	<1.2	<3.0	(*)	(*)	>0.67
GC	>115	<14.7	(*)	>0.3	<1.2	<2.4	(*)	(*)	>0.60
SW	119±5	13.3±2.5	0.37±*	(*)	1.4±*	(*)	5.7±0.6	(*)	0.79±0.02
SP	110±2	12.4±1.0	0.50±0.03	>15.0	0.8±0.3	(*)	3.3±0.9	(*)	0.74±0.02
SM	114±1	14.5±0.4	0.48±0.02	7.5±4.8	1.2±0.1	3.0±0.4	7.4±0.9	2.9±1.0	0.67±0.02
SM-SC	119±1	12.8±0.5	0.41±0.02	0.8±0.6	1.4±0.3	2.9±1.0	7.3±3.1	2.1±0.8	0.66±0.07
SC	115±1	14.7±0.4	0.48±0.01	0.3±0.2	1.2±0.2	2.4±0.5	10.9±2.2	1.6±0.9	0.60±0.07
ML	103±1	19.2±0.7	0.63±0.02	0.59±0.23	1.5±0.2	2.6±0.3	9.7±1.5	1.3±*	0.62±0.04
ML-CL	109±2	16.8±0.7	0.54±0.03	0.13±0.07	1.0±0.2	2.2±0.0	9.2±2.4	3.2±*	0.62±0.06
CL	108±1	17.3±0.3	0.56±0.01	0.08±0.03	1.4±0.2	2.6±0.4	12.6±1.5	1.9±0.3	0.54±0.04
OL	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)
MH	82±4	36.3±3.2	1.15±0.12	0.16±0.10	2.0±1.2	3.8±0.8	10.5±4.3	2.9±1.3	0.47±0.05
CH	94±2	25.5±1.2	0.80±0.04	0.05±0.05	2.6±1.3	3.9±1.5	14.9±4.9	1.6±0.86	0.35±0.09
OH	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)

The ± entry indicates 90 percent confidence limits of the average value. * Denotes insufficient data, > is greater than, < is less than.

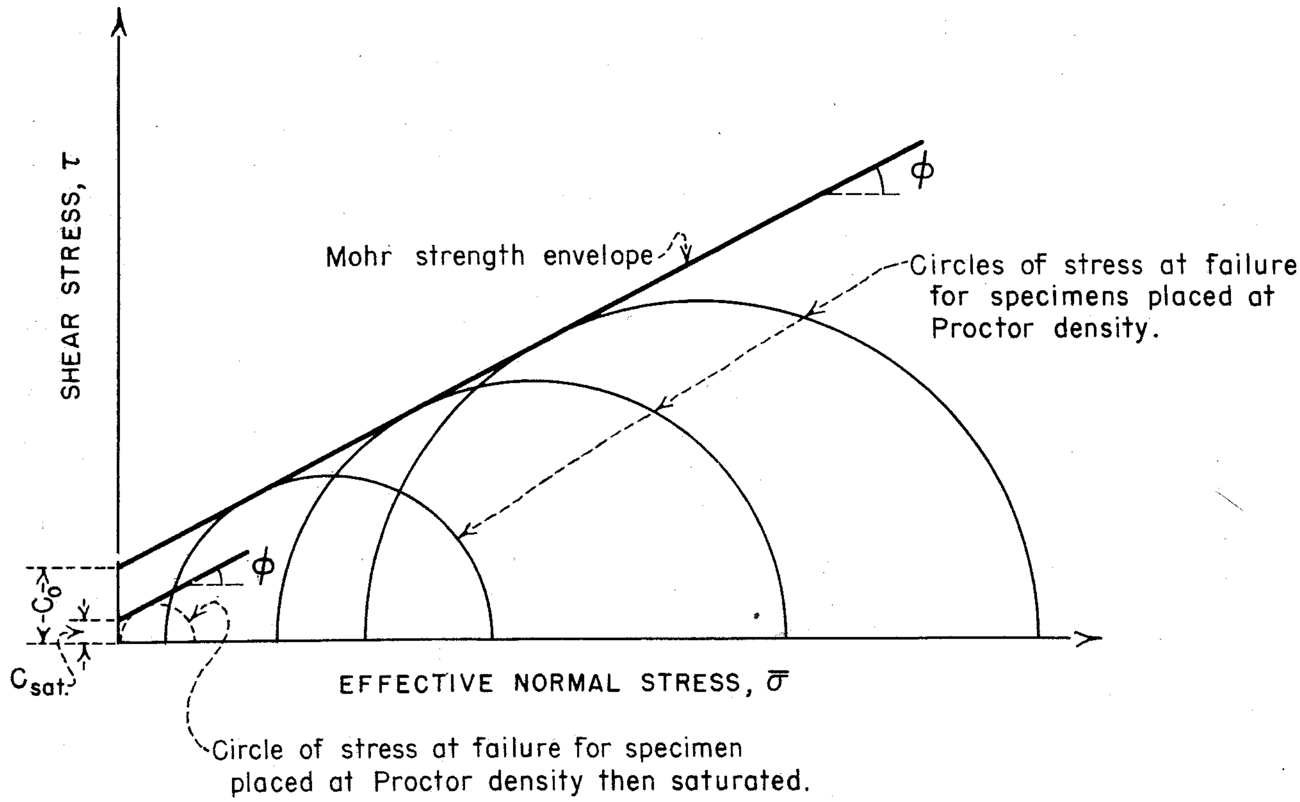

Figure 57. Shear strength of compacted soils. 288—D—2474.

soil. The water movement is called percolation; the measure of it is called permeability; and the factor relating permeability to unit conditions is called the coefficient of permeability, *k,* which represents the discharge through a unit area at unit hydraulic gradient. The use of *k* in estimating flow through soils is discussed in section 130(b). There are many units of measurement in common use for expressing the coefficient of permeability. The one used in table 8 is feet per year, or cubic feet per square foot per year at unit gradient. One foot per year is virtually equal to 10^{-6} centimeters per second.

The coefficient of permeability of natural soil deposits ranges from 1 million feet to 0.001 foot per year. In many soil deposits the permeability parallel to the bedding planes may be 100 or even 1,000 times as large as the permeability at right angles to the bedding planes. Permeability in some soils is very sensitive to small changes in density, water content, or gradation. Because of the possible wide variation in permeability, a numerical value of *k* should be considered only as an order of magnitude. It is customary to describe soils with permeabilities less than 1 foot per year as impervious; those with permeabilities between 1 and 100 feet per year as semipervious; and soils with permeabilities greater than 100 feet per year as pervious. These values, however, are not absolute for the design of dams. Successful structures have been built whose various zones were constructed of soils with permeabilities not within these respective ranges.

(c) *Compressibility.*—Two values are given for compressibility: the value at 20 pounds per square inch effective stress, and the value at 50 pounds per square inch effective stress. These values are for confined compression with drainage permitted. In the confined compression test the soil is prevented from moving laterally by the sides of the container. Porous stones on the top and the bottom permit the water and air in the compacted specimens to drain under the load. The value recorded is the percentage reduction of initial volume at equilibrium under the applied vertical stress. The phenomenon of compressibility is associated with changes in volume in the voids and only to a very limited extent with changes in the solid particles. If the voids are to a large extent filled with air, the addition of a load on the soil mass will result in compression almost immediately. If, on the other hand, the voids are very nearly or completely filled with water, very little or no compression will take place immediately upon application of the load, and only as the water drains from the soil mass will consolidation take place. If the water can drain readily from the soil mass, consolidation may take place in a relatively short period of time, but if the soil is very impervious and the soil mass is large, complete consolidation may require many years.

(d) *Shear Strength.*—Three different values are given for the soil groups under this heading: C_o, C_{sat}, and tan ϕ. The values of C_o and tan ϕ are the vertical intercept and the slope, respectively, of the Mohr strength envelope on an effective stress basis. The Mohr plot is shown in figure 57. The Mohr strength envelope is obtained by testing several sealed specimens of soil, at the Proctor maximum dry density and optimum water content, in a triaxial shear machine in which pore-water pressures developed during the test are measured. The effective stresses are obtained by subtracting the measured pore-water pressures in the specimen from the stresses applied by the machine. No drainage is permitted during the tests; hence, they are sometimes called unconsolidated quick tests. The value C_{sat} was obtained by preparing a specimen at Proctor maximum dry density and optimum water content, saturating it, and shearing it to failure to obtain the small circle shown in figure 57. The value C_{sat} is the intercept on the vertical axis of a line tangent to the circle having an inclination ϕ.

These values for shear strength are applicable for use in Coulomb's equation:

$$s=C+(\sigma-u)\tan\phi \qquad (1)$$

where:

s=shear strength per unit of area,
u=pore-water pressure,
σ=applied normal stress,
tan ϕ is as previously defined, and
C is either C_o or C_{sat}, depending on the water content of the soil.

A discussion of the significance of pore-water pressure in the laboratory tests is beyond the scope of this text. The application of pore pressure measurements to the shear strength of cohesive soils is discussed in reference [17]. The effective-stress principle, which takes the pore-water pressures into account, was used in arriving at recommended slopes given in chapter VI.

D. ROCK CLASSIFICATION

(Adapted from the Army publication, "Geology and its Military Applications" [5])

95. Rocks and Minerals.—(a) *Definition and Types.*—In a broad sense, rocks are aggregates of minerals. The principal exceptions to this definition are the products of organic decay such as coal, and volcanic glasses such as obsidian. To the engineer the term "rock" signifies firm and coherent or consolidated substances that cannot normally be excavated by manual methods alone. Based on the principal mode of origin, rocks are grouped into three large classes: igneous, sedimentary, and metamorphic. These are discussed in more detail in sections 96, 97, and 98.

(b) *Mineral Identification.*—The physical properties characteristic of a mineral, controlled by its chemical composition and molecular structure, are valuable aids in its rapid field identification. Those characteristics which can be determined by simple field tests are introduced to aid in the identification of minerals and indirectly in the identification of rocks.

Hardness.—The hardness of a mineral is a measure of its ability to resist abrasion or scratching. A simple scale based on empirical tests for hardness has been universally accepted. The 10 minerals selected to form the