WRP Technical Note SG-RS-1.2
May 1994

Engineering Properties of Wetland Soils

PURPOSE: This technical note provides guidance for evaluating the engineering properties of wetland soils required for wetland engineering. Mass properties are also included to complete evaluation of the engineering properties. Engineering of wetland soils includes development and application of efficient procedures for the design, establishment and construction, restoration, operation, and maintenance of wetlands. This information supplements material outlined in WRP Technical Note WG-RS-3.1.

BACKGROUND: Engineering properties are strength, compressibility, and permeability. These properties influence the critical soil processes that govern the performance of a wetland when a force is applied to the soil.

Critical soil processes include the compaction characteristics of fill materials used to construct dikes, slope stability, and settlement of earth dikes containing water and soils in wetlands; compaction characteristics of wetland soils, sedimentation, and erosion characteristics of wetland soils, and the flow of water through wetlands and dikes. These processes influence water and sediment storage capacity, water quality and flow, and erosion from and collection of sediments on the surface of submerged wetland soils. The strategy for determining procedures for construction or restoration, operation, and maintenance of wetlands is based on the critical soil processes evaluated from the engineering properties of wetland soils.

Preliminary or approximate engineering properties of wetland soils may be evaluated from classification data with some information on mass properties such as density, void ratio, and water content. The engineering classification of wetland soils may be determined by field expedient and laboratory procedures given in WRP Technical Note SG-RS-1.1, *Engineering Description of Wetland Soils.*

Information required to determine engineering properties for final design, restoration, construction, and maintenance of wetlands may be provided from results of detailed site evaluation and soil survey. The survey should include in-situ soil tests such as cone penetration (CPT) and standard penetration (SPT) and laboratory tests performed on undisturbed soil samples. Hand-operated piston, Shelby push tubes, rotary, and samplers are available for retrieving disturbed and undisturbed soil samples as outlined in EM 1110-2-1907.

IDENTIFICATION OF MASS PROPERTIES: Mass properties are the density, void ratio, and water content of the soil.

- Density, g/cc. Mass per unit volume of material:

  Wet density γ - in-place total mass per unit total volume of material. γ may be determined by ASTM D1556, D2167, or portable field methods given in Appendix E of EM 1110-2-1907.

  Dry density γ_d - mass of solid particles per total volume of material. γ_d may be determined from $\gamma/(1 + w/100)$ where "w" is the water content on a dry weight basis in percent.

Saturation density γ_{sat} - wet density at which the pore water pressure of a normally consolidated undisturbed soil is zero. γ_{sat} of a freshly deposited (normally consolidated) sediment may be estimated by $(G_s + e_{SL})\gamma_w/(1 + e_{SL})$ where e_{SL} = void ratio at the saturation limit, $\approx 1.0 + 0.0589PI$. $\gamma/\gamma_{sat} < 1.3$ indicates possible wetland soils. γ_w = unit mass of water, 1 g/cc. G_s = specific gravity of solids.

- Dessication limit e_{DL}. Least void ratio of soil caused by desiccation. $e_{DL} \approx 1.6 + 0.0106PI$ and it occurs approximately at a degree of saturation of 60 percent. Void ratios near e_{DL} indicate an overconsolidated, desiccated soil.

- Liquidity index LI, percent. Ratio of water content w minus PL to PI, (w - PL)/PI. LI close to and exceeding unity indicate normally consolidated soils, recently deposited sediments, and a potential of being wetland soils. LI exceeding unity indicates soil on the verge of being a viscous liquid. LI close to or less than zero indicates overconsolidated, desiccated soil and soil with high foundation strength.

- Void Ratio, e. Ratio of the volume of void space to the volume of solid particles in a given soil mass. $e = (G_s/\gamma_d)\gamma_w - 1.0$ where G_s = specific gravity, γ_d = dry density, g/cc, and γ_w= unit mass of water, 1 g/cc.

- Water content w, percent. Ratio of the mass of water contained in the pore spaces of soil to the mass of solid dry material expressed as a percentage. Soil water content may be evaluated in the laboratory by ASTM D2216 or microwave oven method D4643. The natural water content of in situ soil can indicate drainage characteristics and nearness to a water table. The optimum water content of compacted fill materials allows compaction to the greatest density and strength.

  Field expedient natural water content test. A piece of undisturbed soil is tested by squeezing it between the thumb and forefinger to determine its consistency; i.e., hard, stiff, brittle, friable, sticky, plastic or soft. The soil is then remolded by working it in the hands, and changes, if any, are observed. Clays which turn almost liquid on remolding are probably near or above the liquid limit. If the clay remains stiff and crumbles upon being remolded, the natural water content is below the plastic limit.

  Field expedient optimum water content (OMC) test. A golf ball size of soil is molded by hand and squeezed between the thumb and forefinger. If the ball shatters into several fragments of rather uniform size, the soil is near or at OMC. If the ball flattens out without breaking, the soil is wet of the OMC. If the soil is difficult to roll into a ball or crumbles under very little pressure, the soil is dry of the OMC.

IDENTIFICATION OF ENGINEERING PROPERTIES: Engineering properties are the strength, compressibility, and permeability parameters of the soil.

- Strength properties. Strength parameters define the ability of soil to support dikes, retaining walls, pavements, and other structures and to resist erosion from flowing water. The shear strength τ is given by Coulomb's equation in terms of strength parameters c and ϕ, $\tau = c + \sigma_n \tan\phi$ where σ_n is the component of stress normal to the shear plane. The shear stress τ is tangent to the shear plane.

c, cohesion, kPa - shear resistance at zero normal stress or the intrinsic shear strength. A perfectly cohesive soil has strength only from cohesion where $\phi = 0$. The shear strength of a clay when undrained is $c = C_u$ where C_u is the undrained shear strength. The compressive strength q_u is twice the undrained shear strength. q_u is usually determined on specimens not confined by any applied stress.

ϕ, friction angle, degrees - The angle of internal friction or angle of shear resistance is the angle between the axis of normal stress σ_n and tangent to the mohr envelope at a point representing a given failure stress condition for the soil. A perfectly cohesionless soil or sand has strength only from friction where $c = 0$.

- Compressibility properties. These properties include both elastic and consolidation parameters. Elastic parameters define the ability of soil to resist elastic deformation and settlement from applied forces. Elastic deformation occurs almost immediately and accounts for nearly all or most of the settlement in cohesionless soil. Consolidation parameters define the ability of saturated soil to resist settlement or heave caused by applied forces. Changes in applied forces instantly cause corresponding changes in pore water pressure leading to the flow of water into or out of the soil. The resulting consolidation from changes in the water content occurs over time depending on the ability of the soil to conduct water (permeability properties). Consolidation in cohesive soil occurs over a relatively long time and often accounts for most of the settlement.

E, modulus of elasticity, kPa - This elastic modulus of deformation is the ratio of stress to strain for a soil under given loading conditions. E is often used to determine immediate settlement from static loads.

G, shear modulus, kPa - the shear moduus is the ratio of shear stress to shear strain under given loading conditions. G is often used to determine deformation or settlement from dynamic loads or vibrations. G is related to E by Poisson's ratio ν, $G = E/[2(1 + \nu)]$. Poisson's ratio is the ratio between linear strain changes perpendicular to and in the direction of a given uniaxial stress change.

C_c, compression index - The compression index is the slope of the linear portion of the pressure-void ratio curve on a semi-log plot. The linear portion occurs at pressures exceeding the maximum p[ast pressure σ_p that had been applied to the soil.

C_r, recompression index - The recompression index is the slope of the pressure-void ratio curve on a semi-log plot following removal of the maximum pressure σ_p that had been applied to the soil, but at pressures that exceed the vertical overburden pressure σ_v that was applied to the in situ soil.

Overconsolidation ratio OCR. The OCR is the ratio of preconsolidation pressure σ_p' to the effective overburden pressure σ_v'. $\sigma_v' = \sigma_v - u_w$, σ_v = total overburden pressure, u_w = pore water pressure, kPa. OCR of a normally consolidated soil is unity. OCR of overconsolidated soil exceeds unity. Wetland soils are often normally consolidated.

- Permeability Properties. Permeability is a property of a mass soil that controls the rate of flow of water Q through the soil. Permeability is influenced by the void ratio, continuity of voids, and fissures that may be caused by drying and wetting weather cycles.

k, coefficient of permeability, cm/sec - The permeability controls the flow of water Q through a cross-section area A of soil depending on the hydraulic gradient i, k = Q/(iA). The hydraulic gradient is Δh/L where Δh is the difference in height of the water columns in a standpipe inserted at the entrance end and at the exit end of a filter bed and L is the length of the filter bed between the standpipes.

c_v, coefficient of consolidation, cm^2/sec - c_v is used in the Terzaghi theory of consolidation containing the physical constants of a soil affecting its rate of volume change,

$$c_v = \frac{k\,(1 + e)}{\gamma_w a_v}$$

where e = void ratio, γ_w = unit weight of water, 1 g/cc, a_v = coefficient of compressibility, cm^2/g.

EVALUATION OF ENGINEERING PROPERTIES: Engineering properties may be approximated from classification data or evaluated from in situ and laboratory soil tests.

- Strength parameters. Angle of internal friction ϕ, deg. Angle between the normal stress axis and tangent to the Mohr envelope at a point representing a given failure stress of the soil. ϕ is required to evaluate the slope stability and bearing capacity of cohesionless soil or sands. ϕ is usually estimated from correlations of field soil tests such as cone penetration (CPT) or standard penetration (SPT) tests because undisturbed boring samples for laboratory tests are rarely obtainable for sands. Table 3-1 in EM 1110-1-1905 provides correlations of ϕ with relative density, CPT (ASTM D 3441), and SPT (ASTM D 1586). Figure 1 correlates the soil classification and the dry unit weight γ_d with ϕ when CPT or SPT data are not available.

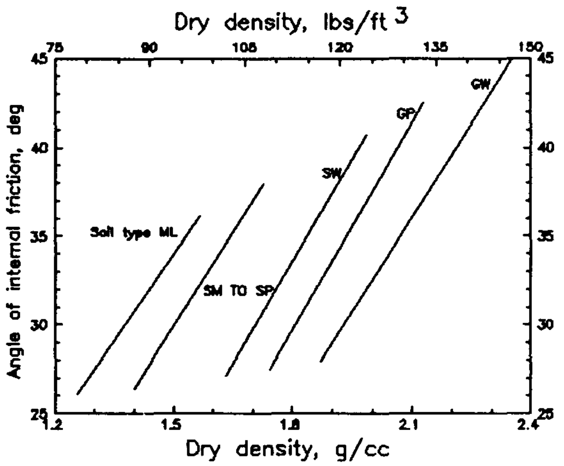

Figure 1. Strength characteristics for cohesionless soils

Unconfined compressive strength q_u, kPa. Strength at which an unconfined cylindrical specimen of soil will fail in a simple compression test. A simple portable field device for estimating q_u, the pocket penetrometer, is a small, hand-operated, spring-calibrated penetrometer for estimating the engineering consistency of cohesive, fine-grained soils, Table 1. This device is pushed into soil surfaces and it is calibrated to determine q_u in kilograms per square centimeter (1 kg/cm^2 = 100 kPa). The apparatus and procedure are described by Bradford (1986). Clays of medium or softer consistency are normally consolidated and may be in wetlands. Stiff and harder clays are overconsolidated.

Vane torque T_v, N·m. The turning moment required to shear a cylindrical column of cohesive soil. The torque may be determined by a four-bladed vane device according to standard test method ASTM D 2573.

Undrained shear strength C_u, kPa. The maximum resistance to shear forces when pore pressures are not drained. C_u is required to evaluate slope stability and bearing capacity of cohesive soils. C_u may be estimated from results of the pocket penetrometer test as 1/2 of q_u, the unconfined compressive strength. C_u may also be estimated from results of the field vane shear test by T_v/K_v where K_v is the vane constant. K_v depends on dimensions and shape of the vane (ASTM D 2573).

- Compressibility properties.

Compression index C_c. Slope of the linear portion of the pressure-void ratio curve on a semi-log plot. This parameter is required to evaluate settlement caused by consolidation of compressible soil. C_c may be estimated by -0.156 + 0.411e + 0.00058LL (Al-Khafaji and Andersland 1992) where the correlation coefficient is 0.957 and standard error is 0.077 based on 72 data points. Refer to EM 1110-1-1904 for other correlations.

Elastic Young's modulus E_s, kPa. Ratio of vertical stress σ_v to the vertical strain caused by σ_v. E_s is used to estimate elastic settlement of soils according to procedures given in EM 1110-1-1904. E_s may be estimated from a general classification given in Table 2.

Table 1. Correlation of Consistency With Shear Strength of Cohesive Soil

Relative Consistency	Unconfined Compressive Strength q_u, kPa
Fluid mud	< 2
Very soft	2-25
Soft	25-50
Medium	50-100
Stiff	100-200

Table 2. Typical Elastic Moduli

Soil	E_s, kPa
Clay	
Very soft	500 - 5,000
Soft	5,000 - 20,000
Medium	20,000 - 50,000
Stiff, silty	50,000 - 100,000
Sandy	25,000 - 200,000
Shale	100,000 - 200,000
Sand	
Loose	10,000 - 25,000
Dense	25,000 - 100,000
Dense w/gravel	100,000 - 200,000
Silty	25,000 - 200,000

- Permeability properties.

Coefficient of permeability k, cm/sec. Rate of discharge of water under laminar flow through a unit area of a porous medium for a unit hydraulic gradient at a standard temperature, usually 20°C. k is required to evaluate the quantity and rate of fluid flow through soils. k is given from classification data by Table 3. k may be estimated by Figure 2 for sands from gradation data and void ratio e. k may be estimated for clays from $0.1C_v\gamma_w m_v$ where C_v = coefficient of consolidation, cm²/sec, γ_w = unit mass of water, and m_v = coefficient of volume change,

kPa^{-1} ($1\ cm^2/g = 10\ kPa^{-1}$). C_v may be estimated from the liquid limit LL by Table 4. Undisturbed sediments not subject to wet/dry cycles should have C_v similar to those for virgin consolidation. Soil subject to wet/dry cycles should have C_v similar to soil subject to recompression. $m_v = 0.435C_c/[(1 + e)\sigma_{mv}]$ where C_c = compression index and σ_{mv} = mean vertical stress on the soil in the field, kPa.

Table 3. Coefficient of Permeability by Soil Classification

Soil Type	k, cm/sec
GW-SW	$> 10^{-2}$
GP-SP	$5\cdot10^{-4} - 10^{-2}$
MP-OL	$10^{-5} - 5\cdot10^{-4}$
GF-SF-MH	$5\cdot10^{-7} - 5\cdot10^{-4}$
GC-SC-CL	$5\cdot10^{-7} - 10^{-5}$
CL-CH-OH	$< 5\cdot10^{-7}$

Table 4. Correlation of Liquid Limit with the Coefficient of Consolidation. (After Lambe and Whitman 1969)

LL, Percent	C_v, cm^2/second	
	Recompression	Virgin
30	0.035	0.005
60	0.0035	0.001
100	0.0004	0.0001

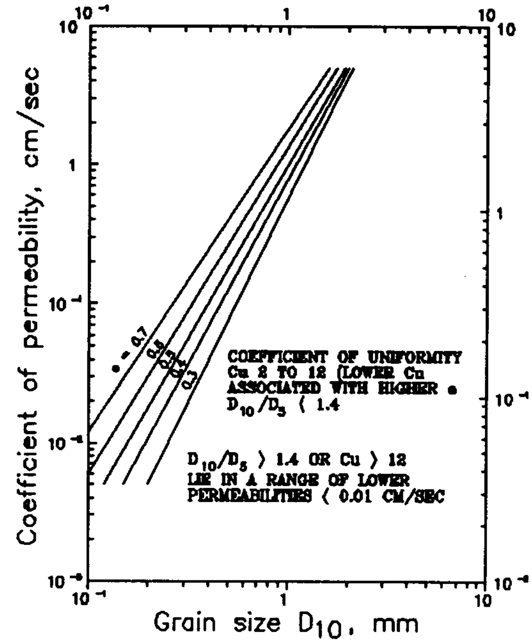

Figure 2. Permeability of sands and sand-gravel mixtures from void ratio and gradation data (After NAVFAC DM-7.1). e = void ratio; Cu = coefficient of uniformity, D_{60}/D_{10}

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POINT OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Roy Leach, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-GS-S, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, phone: (601) 634-2727, author.

Dr. Lawrence D. Johnson, U.S. Army Engineer Waterways Experiment Station, co-author.