Chapter 9*

SOIL MECHANICS

9.1 DEFINITIONS

9.1.1 *Solid-Air-Water Phase Relationship*

Water Content or Moisture Content

$$w = \frac{\text{Weight of water}}{\text{Weight of solids}} = \frac{W_w}{W_s}$$

Degree of Saturation

$$S_r = \frac{\text{Volume of water}}{\text{Total volume of void space}} = \frac{V_w}{V_v} = \frac{wG_s}{e}$$

Void Ratio

$$e = \frac{\text{Volume of voids}}{\text{Volume of solids}} = \frac{V_v}{V_s} = \frac{n}{1-n}$$

Porosity

$$n = \frac{\text{Volume of voids}}{\text{Total volume of soil}} = \frac{V_v}{V} = \frac{e}{1+e}$$

Air Content

$$A = \frac{\text{Volume of air}}{\text{Total volume of soil}} = \frac{V_a}{V} = \frac{e-wG_s}{1+e} = n(1-S_r)$$

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Bulk Density

$$\rho = \frac{\text{Total weight of soil}}{\text{Total volume of soil}} = \frac{W}{V} = \frac{G_s(1 + w)\ \rho_w}{1+e}$$

$$= \frac{G_s + S_r e}{1+e}\ \rho_w$$

$S_r = 1$, for fully saturated soil
$S_r = o$, for completely dry soil

Specific Gravity of Solid Particles

$$G_s = \frac{\text{Weight of solids}}{\text{Volume of solids x density of water}}$$

$$= \frac{Ws}{Vs \times \gamma_w}$$

γ_w = unit weight of water

Unit Weight of Soil

$$\gamma = \frac{\text{Total weight (force)}}{\text{Total volume}} = \frac{W}{V} = \frac{G_s(1 + w)}{1+e}\ \gamma_w$$

$$= \frac{G_s + S_r e}{1+e}\ \gamma_w$$

9.1.2 *Gradation of Soils*

Coarse-grained Soils

Soils in which the properties are mainly influenced by sand and gravel-sized particles (0.06 mm to 60 mm).

Fine-grained Soils

Soils in which the properties are mainly influenced by clay and silt-sized particles (0.001 mm to 0.06 mm).

Well-graded Soils

Coarse-grained soil which have no excess of particles in any size range and do not lack intermediate-sized particles. Represented by a smooth, concave grain size distribution curve (i.e., a semi-logarithmic plot of particle size versus percentage by weight of particles smaller than the given size).

Poorly-graded Soils

Uniformly-graded - has a high proportion of particles having sizes within narrow limits. Represented by an S type curve on the grain size distribution curve plotted on a semi-logarithmic graph.

Gap-graded - has both large and small sizes but with a relatively low proportion of particles of intermediate sizes. Represented by an almost flat curve at the middle of the grain size distribution curve.

9.1.3 *Plasticity of Fine-grained Soils*

Plasticity is the ability of a soil to undergo plastic (unrecoverable) deformation at constant volume without cracking or crumbling. Plasticity is due to the presence of clay minerals or organic material.

Liquid Limit, LL or w_L

The upper limits of the range of water content over which a soil exhibits little strength.

Plastic Limit, PL or w_P

The lower limit of the range of water content over which a soil exhibits plastic behaviour.

Plasticity Index, PI or I_p

The difference between liquid limit and plastic limit.

Liquidity Index

$$\text{LI or } I_L = \frac{\text{Water content of soil - plastic limit}}{\text{Plasticity Index}}$$

$$= \frac{w - w_p}{PI}$$

Shrinkage Limit

This is the water content stage at which the volume of a soil reaches its lowest value as it dries out.

9.1.4 *Soil Density*

Compaction is the process of increasing the density of a soil by packing the particles closer together with a reduction in the volume of air: there is no significant change in the volume of water in the soil. The degree of compaction is measured in terms of dry density, i.e., the mass of solids per unit volume of soil.

Bulk density of a soil, $$\rho = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v}$$

$$\rho = \frac{W_s + W_s \times w}{V_s + V_v} = \frac{W_s (1 + w)}{V_s + V_v}$$

$$= \frac{G_s \times V_s \times \rho_w (1+w)}{V_s + V_v} = \frac{G_s (1+w) \ \rho_w}{1 + e}.$$

Dry density of soil, $$\rho_d = \frac{G_s (1 + w) \ \rho_w}{1 + e} = \frac{G_s (1+0) \ \rho_w}{1 + e}$$

$$= \frac{G_s \ \rho_w}{1+e}.$$

$$\rho = \frac{G_s (1+w) \ \rho_w}{1+e} = \rho_d (1+w).$$

Therefore, $$\rho_d = \frac{\rho}{1 + w}.$$

Thus, the dry density of a soil can be found, if we know the bulk density and water content of the soil. Dry density, after compaction (at water content w) to an air content A, can be calculated by,

$$\rho_d = \frac{G_s (1 - A)}{1 + wG_s} .\rho_w$$

9.1.5 *Flow of Water*

Seepage

Soils under the water table may be under static water pressure, depending upon the depth below the water table, or under seepage pressure due to water flowing through the pores under a hydraulic gradient. Normally, the seepage velocities in soils are so small that the velocity head can be neglected. The total head, thus, is the sum of elevation head and pore pressure head caused by seeping water. The energy of water is used up in flowing through the soil.

Water Table or Phreatic Surface

The uppermost level of water at which the pressure is atmospheric.

Pore-Water Pressure

Water pressure at any point in the pores of a soil mass, due to static or seeping water, measured relative to atmospheric pressure. Thus the pore-water pressure at atmospheric pressure is zero.

Permeability of Soil

In accordance with Darcy's empirical law, it is the discharge velocity of water through a soil divided by the hydraulic gradient. The coefficient of permeability is a function of void ratio. If a soil deposit is stratified, the permeability for flow, parallel to the direction of stratification, is higher than that for flow perpendicular to the direction of stratification.

Degree of Saturation of Soil

The degree of saturation of soil below the water table is assumed to be a hundred per cent, i.e., fully saturated.

Perched Water Table

Local water table, caused by water contained by soil of low permeability, above the normal water table level.

Artesian Condition

A condition where an inclined sand layer of high permeability is confined locally by on overlying layer of low permeability. The pressure in the confined layer is governed not by the local water table level but by a higher water table at a distant location where the layer is unconfined.

Total Head

The total head at any point in a soil mass is the sum of elevation head from a datum and the head, caused by pore-water pressure in the soil, at the point in question. In other words, it is the elevation, from a given datum, of free water in a tube (manometer or piezometer) inserted in the soil at the point for which the total head is being determined. The head caused by pore-water pressure is the ratio of pore-water pressure at the point and the unit weight of water.

Flow Net

This is the family of flow lines and family of **equipotentials** drawn, by graphical representation of groundwater flow, to solve the problem of seepage in a soil. Flow lines or stream lines are just a few of the flow paths selected, from among an infinite number, of flow paths of water, flowing through all the interconnecting pore spaces in a soil. **Equipotential lines** or equipotentials are the lines joining points at which the total head is the same. These lines intersect the flow lines approximately at right angles in an isotropic soil. Figure 9.1 illustrates the flow net in two dimensions in a slope.

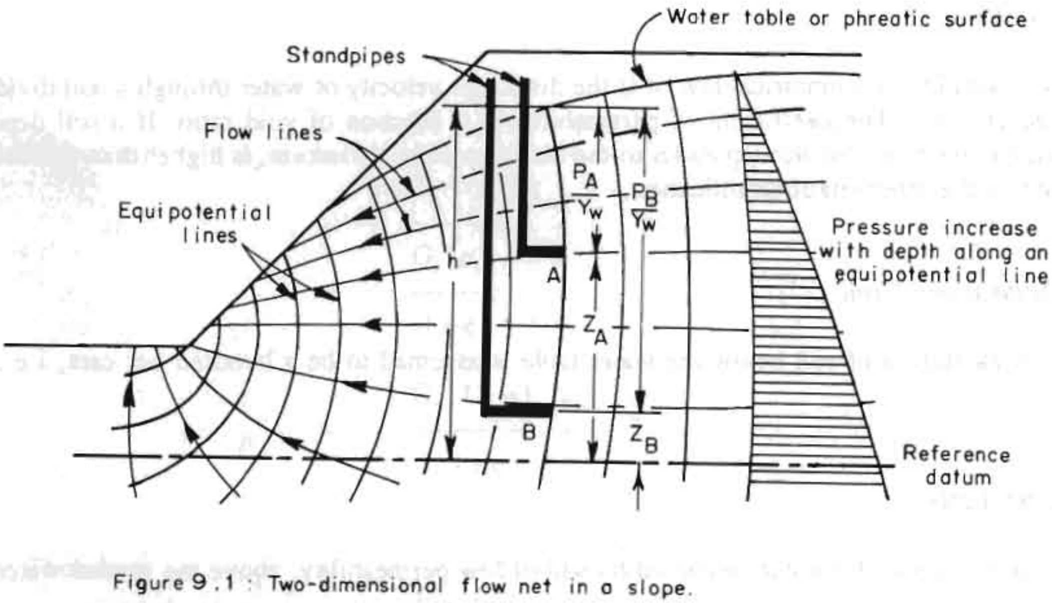


Figure 9.1 : Two-dimensional flow net in a slope.

Source: USDT 1981

Fig. 9.1 Two-dimensional flow net in a slope

9.1.6 *Stresses in a Soil Mass*

Effective Stress

The effective stress on a plane in a fully saturated soil mass, according to Terzaghi's Principle of Effective Stress, is the stress transmitted through the soil skeleton only. This can be expressed by the following relationship:

$$\sigma' = \sigma - u$$

where,

σ' = effective normal stress,
σ = total normal stress, i.e., the force per unit area normal to the plane, and
u = pore-water pressure, i.e., the pressure of the water filling the void space between solid particles.

Seepage Force

This is a force corresponding to the transfer of energy from water to solid particles, when water is seeping through the pores of a soil, dissipating the total head as **viscous friction** producing a **frictional drag**, acting in the direction of flow, on the solid particles.

Seepage Pressure (j) is defined as the seepage force per unit volume, i.e:

$j = i\ \gamma_w$ where, i = hydraulic gradient, and
γ_w = unit weight of water.

Resultant Body Force

Resultant body force in a soil mass is the combination of the forces in a soil mass due to gravity and seeping water.

Quick (Liquefaction) Condition

This is a condition caused when the contact forces between the soil particles are zero and the soil will have no strength. It occurs when there is an upward seepage in soil and the hydraulic gradient corresponds to zero resultant body force. The condition is said to be 'boiling' when the hydraulic gradient exceeds the gradient for zero resultant body force.

Piping

This is the process of internal erosion due to seeping water under a high hydraulic gradient.

9.1.7 *Shear Strength*

The strength (τ_f) of a soil at a point on a particular plane was originally expressed by Coloumb as a linear function of the normal stress (σ) on the plane at the same point:

$$\tau_f = c + \sigma \tan\phi$$

where,

c	=	cohesion, and
ϕ	=	angle of internal friction.

According to Terzaghi's fundamental concept, the **shear stress** in a soil can be resisted only by the skeleton of solid particles. **Shear strength** is expressed as a function of effective normal stress:

$$\tau_f = c' + \sigma' \tan\phi'$$

where,

c'	=	effective cohesion, and
ϕ'	=	effective angle of internal friction.

Mohr-Coloumb Failure Criterion

The relationship between effective principal stresses (ϕ_1'= major principal stress at failure and ϕ_3' = minor principal stress at failure) at failure and shear strength can be expressed by:

$$\sigma_1' = \sigma_3' \tan^2 (45° + \frac{\phi}{2}) + 2c' \tan (45° + \frac{\phi'}{2}) \ .$$

This relationship is referred to as the **Mohr-Coloumb Failure Criterion**.

9.1.8 *Consolidation*

Consolidation is the gradual reduction in volume of a fully saturated soil of low permeability due to drainage of some of the pore-water. The process continues until the excess pore-water pressure set up by an increase in total stress has been completely dissipated.

Degree of consolidation (U_z) at a particular instant of time, at depth z ($0 \le U_z \le 1$):

$$U_z = \frac{e_o - e}{e_o - e_1} = \frac{\sigma' - \sigma_o'}{\sigma_1' - \sigma_o'} = 1 - \frac{u}{u_i}$$

where,

e_o = void ratio before the start of consolidation,
e_1 = void ratio at the end of consolidation,
e = void ratio at the time in question during consolidation,
σ_o' = effective normal stress before the start of consolidation,
σ_1' = effective normal stress at the end of consolidation,
u = pore-water pressure in excess of u_o (pore-water pressure before the increase in total stress), and
u_i = increase in pore-water pressure above u_o (pore-water pressure before the increase in total stress) immediately after the increase in total stress.

9.1.9 *Bearing Capacity*

Ultimate Bearing Capacity (q_f or q_u)

This is the least soil pressure which would cause shear failure of the supporting soil immediately below and adjacent to a foundation.

Allowable Bearing Capacity (q_a)

This is the maximum soil pressure which may be applied to the soil such that 1) the factor of safety against shear failure of the supporting soil must be adequate, a value between 2.5 and 3 normally being specified, and 2) the settlement of the foundation should be tolerable and, in particular, differential settlement should not cause any unacceptable damage or interference with the function of the structure.

9.1.10 *Lateral Earth Pressure*

Earth Pressure at Rest (P_o)

This is the earth pressure associated with no lateral strain in soil:

$$P_o = K_o \gamma' z$$

where,

K_o = coefficient of earth pressure at rest, in terms of effective stress,

γ' = effective unit weight of soil, and

z = depth of soil.

Active Earth Pressure (P_a)

This is earth pressure, associated with lateral expansion of the soil and is a minimum value. It is applicable in the case of a retaining wall moving away from the backfill.

Passive Earth Pressure (P_p)

This is the earth pressure associated with lateral compression of the soil and is a maximum value. It is applicable in the case of a retaining wall moving into the backfill.

9.2 FIELD IDENTIFICATION OF SOILS

The soil classification system is so devised that it is possible, with experience, to classify most soils correctly on the basis of field identification methods alone. The easiest way to learn field identification is under the guidance of an experienced man. While learning the procedures, one should systematically compare the laboratory test results for typical soils in each group with the feel of these soils while performing the field identification tests.

The following tests were developed largely by Professor A. Casagrande, Graduate School of Engineering, Harvard University, and have been widely adopted for use in identification of soils. These tests can be performed without equipment and are simple in nature. Do not make a decision on the basis of a single test. Use all applicable tests, then identify the soil.

9.2.1 *Test Methods*

Grain Shape By Visual Examination

Observe and classify the sand and gravel particles according to degree of angularity or roundness (Fig. 9.2).

Grain Size and Gradation by Visual Examination

Sand and gravel sizes are readily identified by visual inspection. Individual grains below the smallest sand size cannot be seen by the naked eye and must be identified by other tests.

To estimate the gradation of **coarse-grained soils**, spread a representative sample out on a flat surface and observe the distribution or uniformity of grain sizes (Fig. 9.3a and b). Observe the proportion of fines and subject the **fine-grained fraction** to all tests described for fine-grained soils.

For gradation of **fine-grained soils**, shake the sample in a jar of water and allow it to settle out. Approximate gradation is indicated by the separation of the particles in the jar from top to bottom. Silt remains in suspension for at least one minute; clay, one hour or more. Table 9.1 can be used for soil classification based on these visual tests and other tests described below.

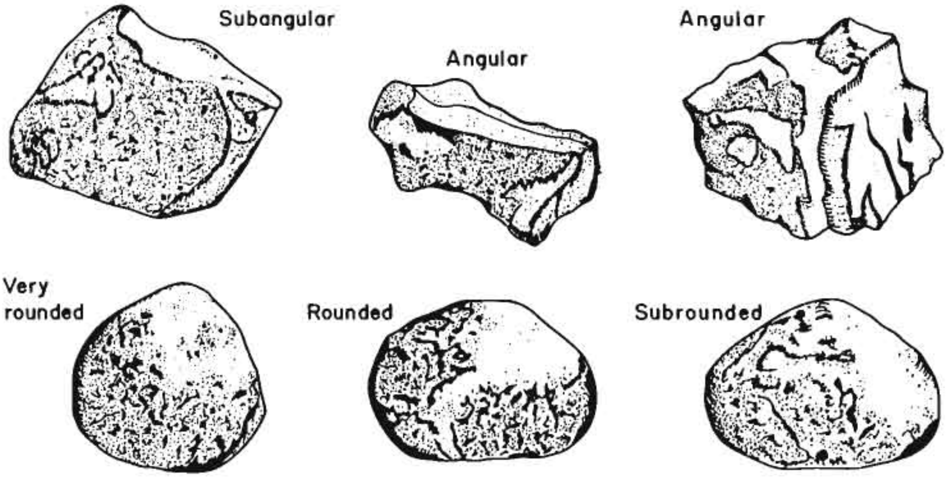
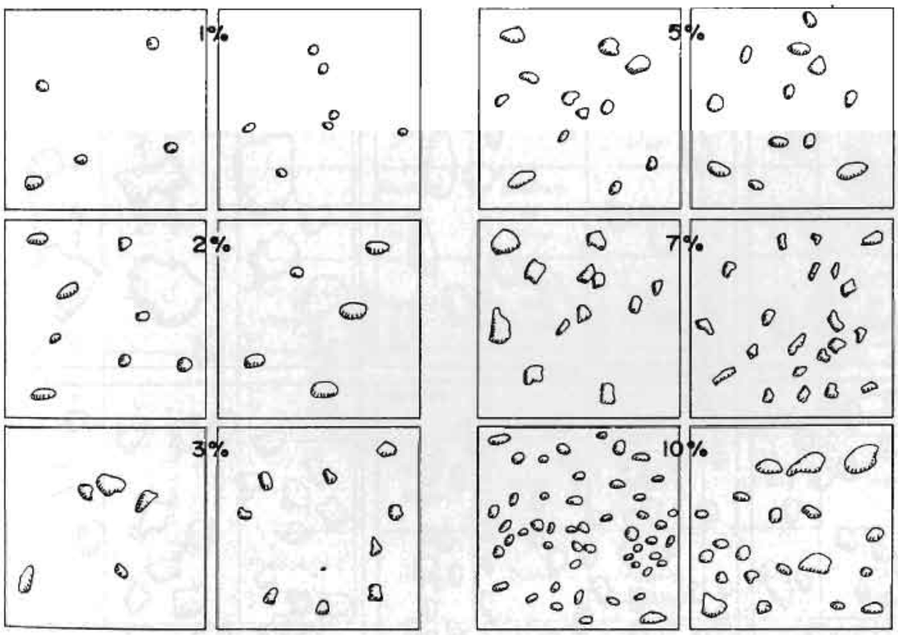


Fig. 9.2 Grain shape



Source: Krähenbuhl and Wagner 1983

Fig. 9.3a Visual estimation of percentage of material larger than 0.6 mm.

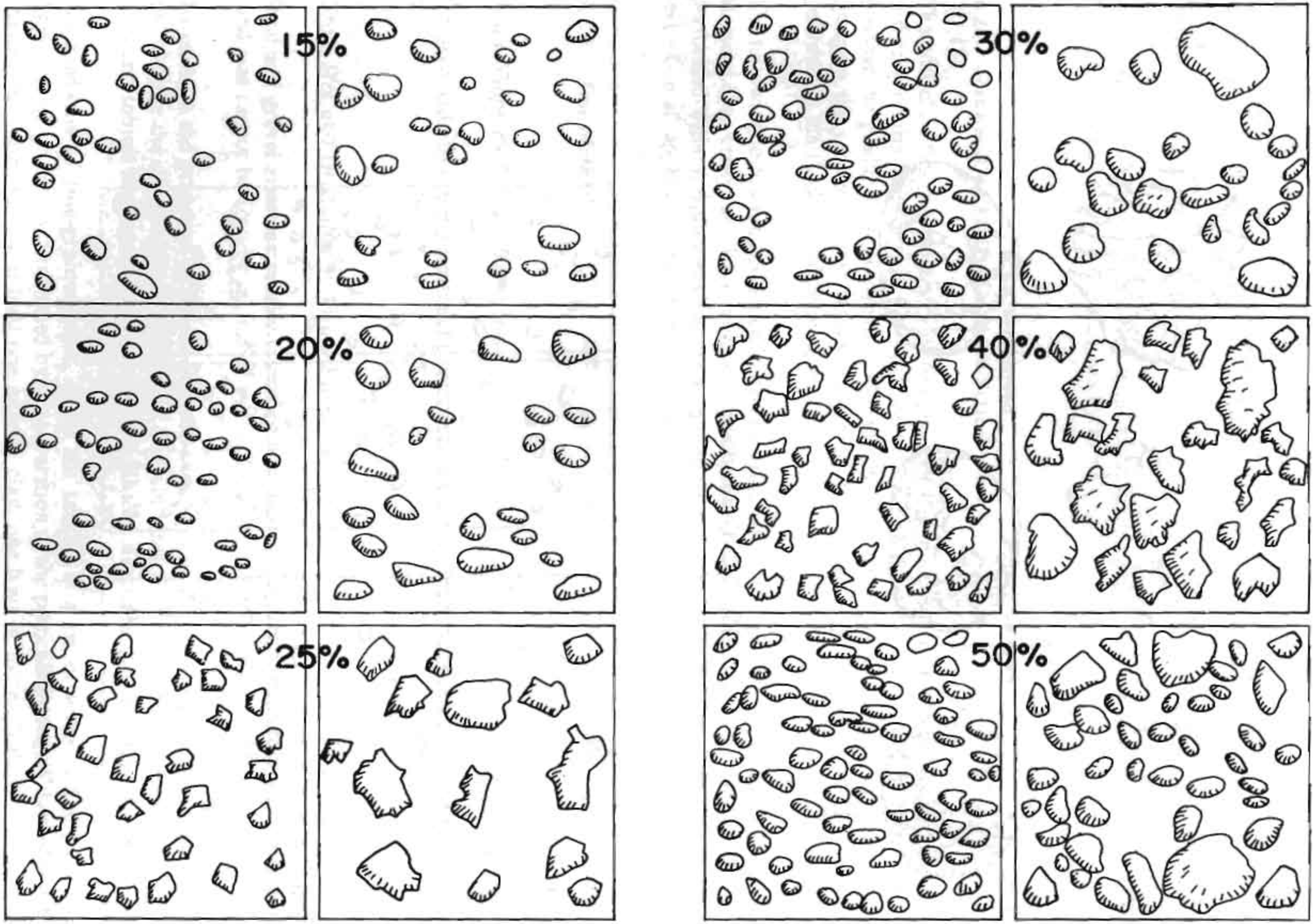


Fig 9.3b

Table 9.1 Field identification

Major division	Subdivision	Group	Description	
COARSE-GRAINED SOILS More than half of the material (by weight) is of individual grains visible to the naked eye	GRAVEL AND GRAVELLY SOILS More than half of coarse Fraction (by weight) is larger than 6 mm size	CLEAN GRAVELS Will not leave a dirt stain on a wet palm	Wide range in grain size and substantial amounts of all intermediate particle sizes	
			Predominantly one size or a range of sizes with some intermediate sizes missing	
		DIRTY GRAVELS Will leave a dirt stain on a wet palm	Nonplastic fines or fines with low plasticity (for identification of fines see characteristics of ML below)	
			Plastic fines (for identification of fines see characteristics of CL or CH below)	
	SAND AND SANDY SOILS More than half of coarse Fraction (by weight) is smaller than 6 mm size	CLEAN SANDS Will not leave a dirt stain on a wet palm	Wide range in grain size and substential amounts of all intermediate particle sizes	
			Predominantly one size or a range of sizes with some intermediate sizes missing	
		DIRTY SANDS Will leave a dirt stain on a wet palm	Nonplastic fines or fines with low plasticity (for identification of fines see characteristics of ML or CH below)	
			Plastic fines (for identification of fines see characteristics of CL or CH below)	

For visual classification the 6 mm size may be used as equivalent to the No. 4 sier size

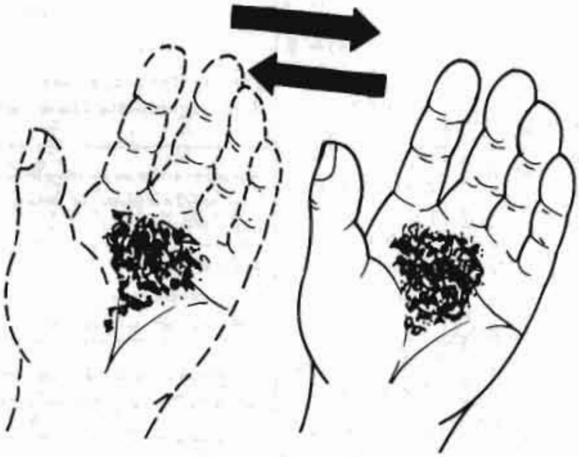
No. 200 sieve size is about the smallest particle visible to the naked eye

Major division	Subdivision	ODOUR	DRY STRENGTH	DILATANCY (SHAKE) REACTION	TOUGHNESS	RIBBON (NEAR THE PL)	SHINE (NEAR THE PL)	
FINE-GRAINED SOILS More than half of the material (by weight) is of individual grains not visible to the naked eye	SILTS AND CLAYS (Low liquid limit) See identification procedures		Slight	Rapid	Low to None	None	Dull	
			Medium to High	Medium to Slow	Medium	Weak	Slight to Shiny	
		Pronounced Organic	Medium	Slow to None	Low (Spongy)	None	Dull to Slight	
	SILTS AND CLAYS (High liquid limit)		Medium	Very slow to None	Medium to High	Weak to Strong	Slight	
			Very High	None	High	Strong	Shiny	
		Pronounced Organic	High	None	Low to Medium (Spongy)	Weak	Dull to Slight	

HIGHLY ORGANIC SOILS	Readily identified by color, odour, spongy feel and frequently by fibrous texture	

Shaking Test (Dilatancy)

The shaking test aids in the identification of fine-grained soils. After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about 10 cc. Add enough water, if necessary, to make the soil soft but not sticky.



Method of Shaking

Fig. 9.4 Shaking test

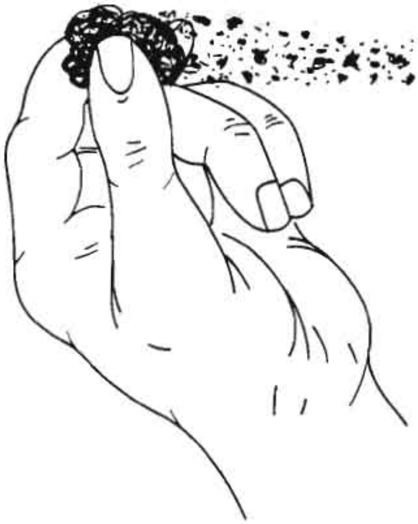
Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times (Fig. 9.4). A positive reaction consists of the appearance of water on the surface of the pat which becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. Shake the broken pieces until they flow together again. Distinguish between slow, medium, and rapid reactions to the shaking test.

A **rapid reaction** indicates a lack of plasticity, such as is the case with a typical inorganic silt, a rock flour, or a very fine sand. A **slow reaction** indicates a slightly plastic silt or silty clay. **No reaction** indicates a clay or a peaty (organic) material. Use these results with Table 9.1.

Breaking Test (Dry Strength)

The breaking test may be used to determine the dry strength of a soil, and this is a measure of its cohesiveness.

After removing particles larger than No.40 sieve size, mould a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun, or air drying, and then test its strength by breaking and crumbling between the fingers (Fig. 9.5). This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.



Method of crumbling soil between fingers

Figure 9.5 Breaking Test

Low dry strength indicates an inorganic silt, a rock flour, or a silty sand. However, the sand feels gritty when the sample is powdered. The dried soil pat can be powdered with slight finger pressure.

Medium dry strength indicates a low to medium plastic inorganic clay. Considerable finger pressure is required to powder the sample.

High dry strength indicates a highly plastic, inorganic clay. The dried sample may be broken but cannot be powdered by finger pressure.

Cohesion or high dry strength may be furnished by some cementing materials such as calcium carbonate or iron oxide. For example, non-plastic lime rock or coral may develop high dry strength.

Odour Test

Freshly sampled organic soils usually have a distinctive odour which aids in their identification. The odour can be made more apparent by heating a wet sample.

Acid Test

Drop a little hydrochloric acid on a piece of soil. A fizzing reaction indicates calcium carbonate.

Shine Test

Rub a dry or slightly moist sample with the fingernail or a knife blade. A shiny surface indicates a highly plastic clay; a dull surface indicates a silt or clay of low plasticity (Fig. 9.6).

A. Method of rolling thread
B. Thread of soil above plastic limit
C. Crumbling thread as plactic limit is reached

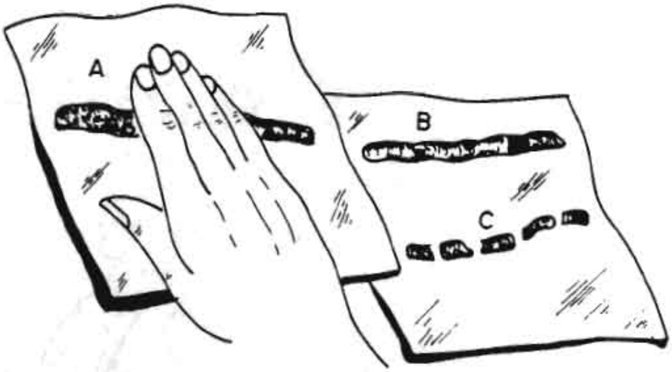


Fig. 9.6 Plasticity Test

Colour

The colour of a soil in both moist and dry conditions should be described as accurately as possible by use of standard colour designations. Acceptable soil colour descriptions are: white, gray, black, brownish-black, reddish-gray, brownish-gray, orange, red-brown, yellowish-brown, olive-brown, yellow, olive, blue, green, etc. These terms should be further modified by the adjectives light, medium, dark, or vivid. Use of the Munsell soil colour charts and plates is recommended when more precise soil colour descriptions are desired.

Mottles or streaks should be indicated and their description should follow the main colour designation of the soil; for example - stiff clay, plastic when moist, friable when dry; medium blue, mottled with brown when moist; light green, mottled with brown when dry.

Texture

The term texture refers to the distinctive appearance and feel of the soil, which are direct indications of the fineness and uniformity of the soil. Texture should be described by a standard adjective as listed below.

Sharp - typical of gravelly or sandy soils
Gritty - typical of coarse silts or sandy silts and clay
Floury - typical of fine silts
Smooth - typical of clays or fine silty clays

Consistency

The term consistency refers to the degree of adhesion between soil particles or the resistance to deformation or rupture under applied pressure. Consistency of the moist soil in both the undisturbed and remoulded states should be described by standard adjectives in Table 9.1 as listed below:

(1) Cohesionless Soils (Sands and Silts)

Loose - poorly-graded, lacks binder or cementing agent, not well compacted.
Dense - well-graded, well compacted, may contain binder or cementing agent.

(2) Cohesive Soils (Clays)

Very Soft	-	easily penetrated several centimetres by fist.
Soft	-	easily penetrated several centimetres by thumb.
Medium	-	can be penetrated by thumb with moderate effort.
Stiff	-	readily indented by thumb; penetrated only with great effort.
Very Stiff	-	readily indented by thumbnail.
Hard	-	indented with difficulty by thumbnail.

Additional adjectives used in connection with the terms listed above in describing the consistency of cohesive soils are: sticky, plastic, friable, brittle, jointed, stratified, and varved.

Moisture Content

The apparent moisture content of the soil should be described by such terms as dry, moist, wet, saturated, etc.

9.3 UNIFIED CLASSIFICATION SYSTEM

9.3.1 *Soil Properties Used in Classification*

This system identifies soils according to their textural and plasticity qualities and on their groupings with respect to behaviour. The system is based on those characteristics of a soil that indicate how it will behave as an engineering construction material.

The soil properties that have been found most useful for this purpose and form the basis of soil identification are:

a. percentage of gravel, sand, and fines (fraction passing No. 200 sieve),
b. shape of grain size distribution curve, and
c. plasticity and compressibility characteristics.

These properties are determined by mechanical analysis, liquid limit, and plastic limit tests.

9.3.2 *Definition of Soil Components* (Fig. 9.7)

Component	Size Range
Boulders	Larger than 300 mm in diameter
Cobbles	Between 80 mm and 300 mm in diameter
Gravel	Between No.4 mesh (4.76 mm) and 80 mm in diameter
Sand	Between No. 200 mesh (.074 mm) and No. 4 mesh
Fines*	Smaller than No. 200 mesh

A comparison of the size of the soil components as defined in the UNIFIED, the American Association of State Highway and Transportation Officials (AASHTO), and the United States Department of Agriculture (USDA) textural classification systems is shown in Figure 9.8.

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* Fines include silt and clay. A material is called a silt if it is non-plastic or very slightly plastic and exhibits little or no strength when air-dried. Silt fines fall below A-line, Figure 9.7. A material is called a clay if the fines exhibit plasticity within a range of water contents and if it has considerable strength when air-dried. Clay fines fall above the A-line (Fig. 9.6).

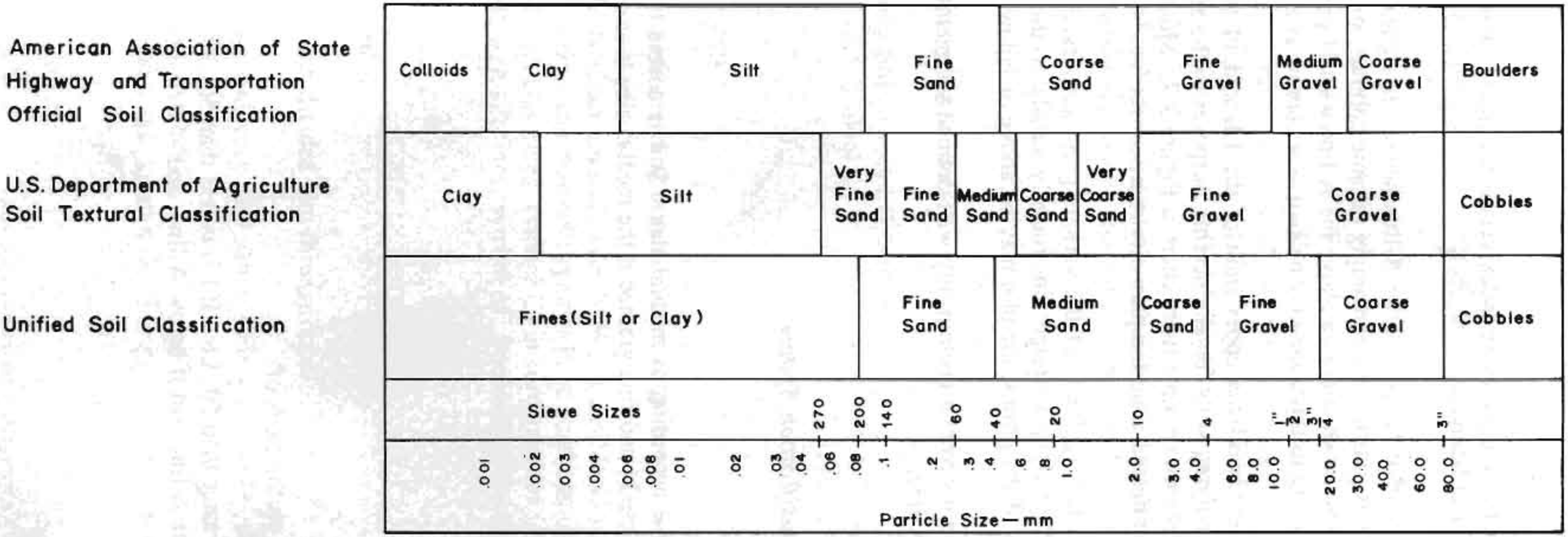
LABORATORY CRITERIA FOR UNIFIED SOIL CLASSIFICATION SYSTEM

LABORATORY CLASSIFICATION CRITERIA[1]							GROUP SYMBOLS	TYPICAL NAMES[2]
Coarse Grained Soils Less than 50% passing No.200 sieve	Sands and Gravels	GRAVELS Less than half of the coarse fraction passes the No.4 sieve size	Less than 5% passing the No. 200 sieve size		$C_u = D_{60}/D_{10}$ Greater than 4; $C_c = (D_{30})^2/D_{10} \times D_{60}$ Between 1 and 3		GW	Well graded gravels, gravel-sand mixtures, little or no fines
					Not meeting both C_u and C_c requirements above		GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
			More than 12% passing the No. 200 sieve size	Borderline cases requiring the use of dual symbols (i.e. SW-SC)	Above "A" line with PI between 4 and 7 requires the use of dual symbols (GC-GM)	Atterberg limits below "A" line, or PI<4	GM	Silty gravels, gravel-sand-silt mixtures
						Atterberg limits above "A" line, and PI>7	GC	Clayey gravels, gravel-sand-clay mixtures
		SANDS More than half of the coarse fraction passes the No.4 sieve size	Less than 5% passing the No. 200 sieve size		$C_u = D_{60}/D_{10}$ Greater than 4; $C_c = (D_{30})^2/D_{10} \times D_{60}$ Between 1 and 3		SW	Well-graded sands, gravelly sands, little or no fines
					Not meeting both C_u and C_c requirements above		SP	Poorly graded sands, gravelly sands, little or no fines
			More than 12% passing the No. 200 sieve size	5% to 12% passing the No. 200 sieve size	Above "A" line with PI between 4 and 7 requires the use of dual symbols (SC-SM)	Atterberg limits below "A" line, or PI<4	SM	Silty sands, sand-silt mixtures
						Atterberg limits above "A" line, and PI>7	SC	Clayey sands, sand-clay mixtures
Fine Grained Soils More than 50% passing No. 200 sieve	Silts and Clays	GO TO PLASTICITY CHART					ML	Inorganic silts and very fine sands, rock flour silty or clayey fine sands with slight plasticity
							CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
							MH	Inorganic silts, micaceous or diatomaceous, fine sandy or silty soils, elastic silts
							CH	Inorganic clays of high plasticity, fat clays
							OL	Organic silts and organic silt-clays of low plasticity LL<50
			Below "A" line and		$\frac{\text{LL (oven dry soil)}}{\text{LL (air dry soil)}} < 0.75$		OH	Organic clays of medium to high plasticity LL>50
			Visual identification only				PI	Peat or other highly organic soils

[1] Work from left to right across chart
[2] Typical names not necessarily appropriate for individual soil description

Source: Krahenbuhl and Wagner 1983

Fig. 9.7 Laboratory criteria for unified soil classification system



Source: Modified from the PCA Soil Primer

Fig. 9.8 A comparison of grain size limits in the 3 classification systems

9.3.3 *The Plasticity Chart* (Fig. 9.7)

The plasticity chart is based on a plot of the plasticity index versus the liquid limit. The A-line on the plasticity chart is an important empirical boundary.

In general, soils with Atterberg limits that fall above the A-line behave as typical non-organic clays. Soils falling below the A-line behave as plastic soils containing organic colloids, or as typical inorganic silts. An exception to the above rule is the shaded area above the A-line with PI greater than 4 and less than 7. Soils with Atterberg limits falling in this zone may behave as a clay or as a silt.

The U-line on the plasticity chart represents the upper limit of the LL and PI plots for soils. The plasticity chart is very useful in classifying soils for engineering purposes. The soil groupings of the unified soil classification system are shown on a plasticity chart in Figure 9.7. Much useful information about the behaviour of a soil can be inferred from the plasticity chart.

If a mineral is ground up and the Atterberg limits of the various grain size fractions determined, the points representing such test results plot along a straight line roughly parallel to the A-line. Depending upon the mineralogical compositions of the grains, the plot may be above or below the A-line.

The points representing the limits of soils from a geologically well-defined sedimentary deposit will plot along a line roughly parallel to the A-line.

9.3.4. *Summary of the Unified Classification System*

a. Designates soils as fine or coarse according to median size. Soil is coarse if the median size is larger than 0.074 mm (No. 200 mesh) and fine-grained if the median size is smaller than 0.074 mm (No. 200 mesh).

b. Coarse-grained soils are classified on the basis of:

   - grain size and distribution,
   - quantity of fines, and
   - character of fines

c. Fine-grained soils are classified on the basis of:

   - liquid limit - high if LL is greater than 50, Low if LL is less than 50,
   - plasticity index - clay if above A-line, silt if below A-line, and
   - grading is of minor importance.

d. Soil groups and group symbols of the Unified Classification System.

Basic Symbols		Modifying Symbols	
G -	gravel	W -	Well-graded
S -	sand	P -	poorly-graded
C -	clay	C -	with clay fines
M -	silt	M -	with silt fines
O -	organic	L -	low liquid limit
Pt -	peat	H -	high liquid limit

Each soil is classified and identified with a verbal description and a group symbol consisting of two of the above letters. The letters may be considered to be initials of the name of the most typical soil in the group.

Sub-division of Coarse-grained Soils

- gravel and gravelly soils; symbol G, and
- sands and sandy soils; symbol S.

Sand and Gravel Groups

The gravels and the sands are each divided into four groups.

a. Well-graded, fairly clean material; symbol W, in combinations GW and SW.
b. Poorly-graded, fairly clean material; symbol P, in combinations GP and SP.
c. Coarse material with clay fines, symbol C, in combinations GC and SC.
d. Coarse materials with silt fines, symbol M, in combinations GM and SM.

Fine-grained Soil Groups

Fine-grained soils are sub-divided into three groups.

1. The inorganic silty and very fine sandy soils; symbol M, used for fine-grained, non-plastic, or slightly plastic soils.
2. The inorganic clays; symbol C.
3. The organic silts and clays; symbol O.

Each of these types of fine-grained soils is grouped according to its liquid limit as:

- fine-grained soils having liquid limits less than 50; symbol L, in combinations ML, CL, and OL, and
- fine-grained soils having liquid limits greater than 50: symbol H, in combinations MH, CH, and OH.

Highly organic soils, usually fibrous, such as peat and swamp soils having high compressibility, are not sub-divided and are placed in one group; symbol Pt. The sequence of the group symbols need not be memorized but meanings of the symbols and sequence of the major divisions, i.e., G-S-L-H, should be learned. When a material does not clearly fall into one group, boundary classifications such as GW-SW or CL-ML should be used.

9.4 ENGINEERING PROPERTIES

Assessment of soil slope instability hazards during the feasibility stage requires at least an approximate estimation of soil strength parameters such as unit weight, friction angle, cohesion, moisture conditions, and water table depths. These parameters may be estimated in the field by visual identifications and index tests. The estimated values of these parameters should account for the worst conditions during the life of the proposed road or structures.

Tables 9.1 to 9.6 and Figure 9.9 are presented to facilitate the right classification of transported soils and soil strength parameters from rapid field tests. Residual soils (eluvial soils) are likely to have higher strength parameters than those for transported soils.

An alternative method to determine shear strength of slope material is to back-analyse existing slope failure in order to determine the shear strength parameters that must have been mobilized at the time of failure. It may be noted that back-analysis cannot determine both c and ϕ. It is, therefore, necessary to determine cohesion from laboratory tests on fine material or run back analyses for several slope failures in the same material. In case of boulder deposits, back-analysis is very fruitful because cohesion may be negligible.

Table 9.2 Compressibility

Term	Compression Index	Liquid Limit
Slight or low compressibility	0 - 0.19	0-30
Moderate or intermediate	0.20 - 0.39	31-50
High compressibility	0.40 and over	51 and over

Example for :-

GP – Poorly-graded gravel

Dr – Dense (from table)

Moisture content = 6 %

Find

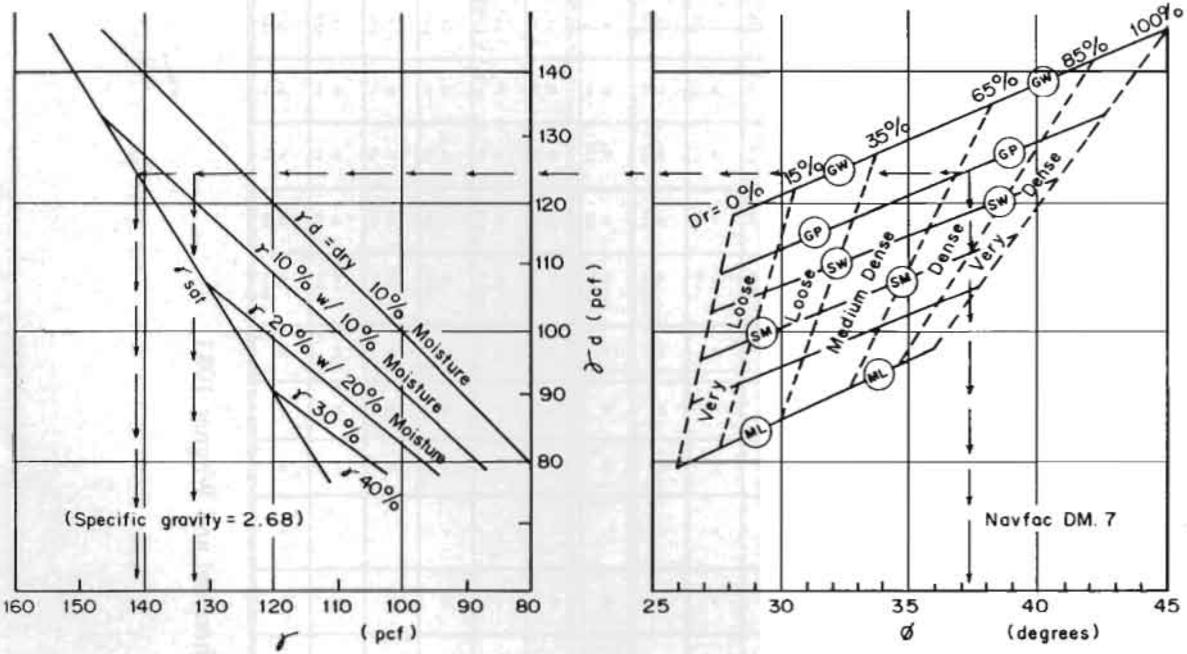
$\phi' = 37.4°$

γd = 125 pcf

γ = 133 pcf (6% Moisture)

γsat = 141.5 pcf

γsub = 141.5 − 62.4 ≃ 79 pcf



Field test with No. 4 rebar	Dr %
	100
Can be driven only a few inches with 5 lb. hammer	
	90
Can be driven only one foot with a 5 lb. hammer	
	70
Easily driven with 5 lb. hammer	
	50
Easily pushed by hand	

Fig. 9.9 Cohesionless soil - D_γ v.s. γ and $\bar{\phi}$

Table 9.3 Soil Classification and Properties

[illegible]	[illegible]	[illegible]				[illegible]			[illegible]			[illegible]			[illegible]	[illegible]	[illegible]	
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	γ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clean gravel, well graded	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clean gravel, poorly graded	[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silty gravel, poorly graded	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clayey gravel, little fines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silty gravel, many fines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silty to clayey gravel	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clayey gravel, many fines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clayey gravel, fines with high plasticity	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clean sand, well graded	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clean sand, poorly graded	[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silty sand, little fines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clayey sand, little fines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silty sand, many fines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silty to clayey sand	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clayey sand, many fines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clayey sand, fines with high plasticity	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silt	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Silt to clayey silt	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clayey silt	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Clay	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Organic clayey silt	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Organic clay	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Inorganic silt of high compressibility, elastic silts	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Source: Adapted from Krähenbuhl and Wagner 1983

Table 9.4 Typical strength characteristics of soil

Group Symbol	Cohesion of soil t/m²		ϕ' (Effective stress envelope) degrees	$Tan\phi'$
GW	0	0	>38	>0.79
GP	0	0	>37	>0.74
GM	-	-	>34	>0.67
GC	-	-	>31	>0.60
SW	0	0	38	0.79
SP	0	0	37	0.74
SM	0.5	0.2	34	0.67
SM-SC	0.5	0.15	33	0.66
SC	0.75	0.1	31	0.60
ML	0.7	0.1	32	0.62
ML-CL	0.65	0.2	32	0.67
CL	0.9	0.15	28	0.54
OL	-	-	-	-
MH	0.75	0.21	25	0.47
CH	1.0	0.1	19	0.35

Source: Driscoll 1979

Table 9.5 Engineering use chart for soils classified by Unified Soil Classification System (USCS)

DESCRIPTION					
Typical Names of Soil Groups	**Group Symbol**	**Permeability when compacted**	**Shearing strength when compacted and saturated**	**Compressibility when compacted and saturated**	**Workability as a construction material**
Well-graded gravel, gravel-sand mixtures little or no fines.	GW	Pervious	Excellent	Negligible	Excellent
Poorly-graded gravel, gravel-sand mixtures, little or no fines.	GP	Very pervious	Good	Negligible	Good
Silty gravel, poorly-graded gravel-sand-silt mixtures.	GM	Semi-pervious to impervious	Good	Negligible	Good
Clayey gravel, poorly-graded gravel-sand mixtures.	GC	Impervious	Good to fair	Very low	Good
Well-graded sands, gravelly sands, little or no fines.	SW	Pervious	Excellent	Negligible	Excellent
Poorly-graded sands, gravelly sands, little or no fines.	SP	Pervious	Good	Very low	Fair
Silty sands, poorly-graded sand-silt mixtures.	SM	Semi-pervious to impervious	Good	Low	Fair
Clayey sands, poorly-graded sand-clay mixtures.	SC	Impervious	Good to fair	Low	Good
Inorganic silt, poorly-graded sand, rock flour, silty or clayey fine sands with slight plasticity.	CL	Semi-pervious to impervious	Fair	Medium	Fair
Inorganic clays of low to medium plasticity: gravelly sandy and lean clays.	CL	Impervious	Fair	Medium	Good to fair
Organic silts and organic silt clays of low plasticity.	OL	Semi-pervious or impervious	Poor	Medium	Fair
Inorganic silts, micaceous or diatomaceous fine sandy or silt soils, elastic silts.	MH	Semi-pervious to impervious	Fair to Medium	High	Poor
Inorganic clays of high plasticity, fat clays.	CH	Impervious	Poor	High	Poor
Organic clays of medium to high plasticity.	OH	Impervious	Poor	High	Poor
Peat and other highly organic soils.	Pt				

Source: Adapted from Krähenbuhl and Wagner 1983

Table 9.6 Relative desirability for various uses

	Canal Sections		Foundations		Roadways		
	Erosion resistance	Compacted earth lining	Seepage important	Seepage not important	Fills		Surfacing
					Frost Important	Heave Possible	
GW	1	-	-	1	1	1	3
GP	2	-	-	3	3	3	-
GM	4	4	1	4	4	9	5
GC	3	1	2	6	5	5	1
SW	6	-	-	2	2	2	4
SP	7	-	-	5	6	4	-
SM	8	5	3	7	8	10	6
SC	5	2	4	8	7	6	2
ML	-	6	6	9	10	11	-
CL	9	3	5	10	9	7	7
OL	-	7	7	11	11	12	-
MH	-	-	8	12	12	-	-
CH	10	8	9	13	13	8	-
OH	-	-	10	14	14	14	-

Source: Adapted from Krähenbuhl and Wagner 1983

Note: 1 is most desirable and 14 is least desirable.