8/19/96
9/1/97 = 9/98

II NATURE OF SOIL

II-1 SOIL COMPOSITION, INDEX PROPERTIES & SOIL CLASSIFICATION

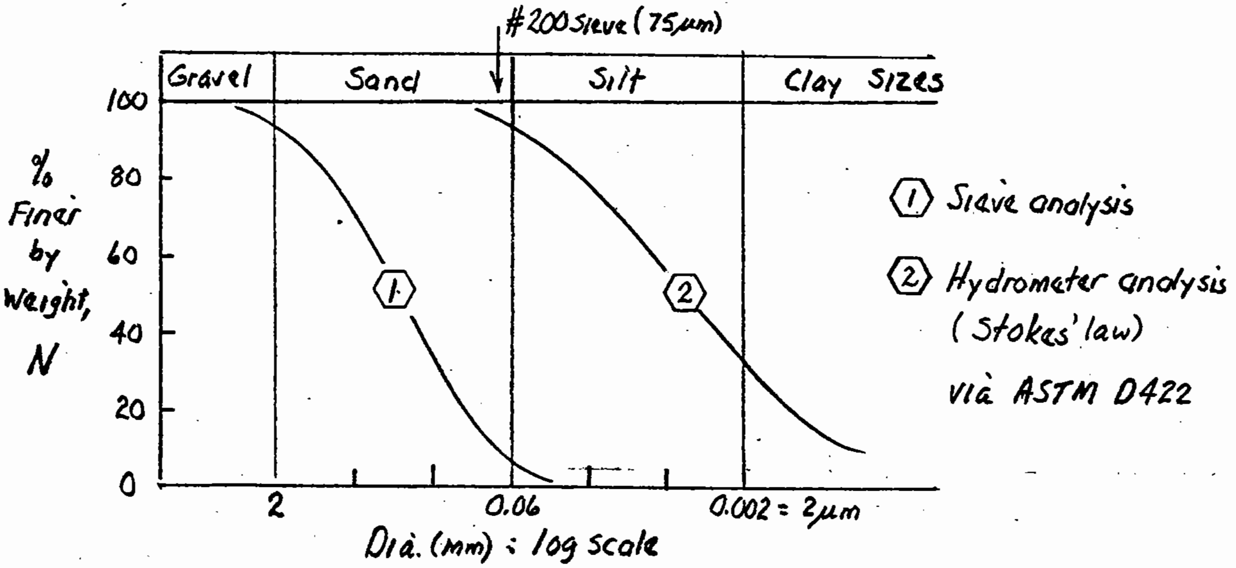
1 INTRODUCTION

1.1 Phase Relations & Definitions (L&W Chap.3) See Fig. II-1, p2a

- Know definitions of water content (w), void ratio (e), porosity (n), Specific gravity ($G = G_s$) & Unit weight = total (γ_t), dry (γ_d) & buoyant (γ_b)
- Remember that $G \cdot w = S \cdot e$ (for pore fluid = pure water), S = degr. of saturation
- If no prior soil mechanics, see Lambe (1951) Soil Testing for Engineers

1.2 Two Basic Soil Types

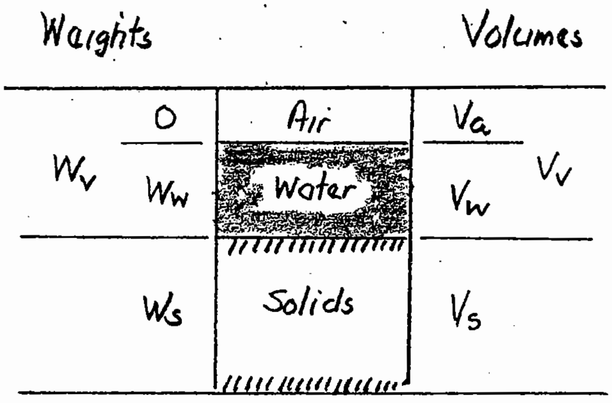
1) Particle Size Distribution (MIT Classification)



2) General Characteristics

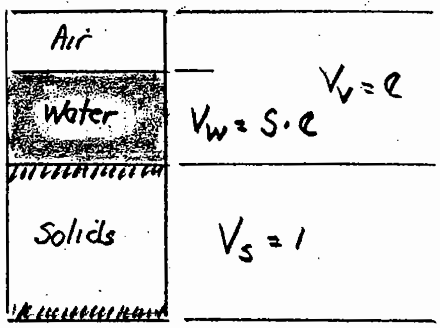
No.	Type	Particles & Features	k = Coef. of permeability } Hydraulic conductivity	Practical Implications
①	Granular (Cohesionless)	• Large equidimensional • Large voids • Very low SSA • Only mass forces	HIGH	• Max u_c very low • Engr. properties from in situ penetration tests • Drained loading
②	Cohesive (Clay minerals)	• Small platy shaped • Very small voids • High SSA > 10 m²/g • Also surface forces	VERY LOW	• Max u_c very high • Engr. properties from in situ + lab testing • Undrained loading

SSA = Specific Surface Area (m²/g); $u_c = u_a - u_w$ = capillary pressure (soil suction)



$W_T = W_w + W_s$ $V_T = V_v + V_s$

For $V_s = 1$



$W_s = G_s \cdot \gamma_w$

$W_w = S \cdot e \cdot \gamma_w$

$V_T = 1 + e$

$\therefore \gamma_t = \left(\frac{G_s + Se}{1+e}\right)\gamma_w$

$\gamma_d = \frac{G_s \cdot \gamma_w}{1+e}$

Definitions

Specific gravity, $G_s = \gamma_s / \gamma_w$

Void ratio, $e = V_v / V_s = G_s \cdot w / S$

Porosity, $n = V_v / V_T$

Specific volume, $v = V_T / V_s = 1 + e$

Water content, $w = W_w / W_s = S \cdot e / G_s$

Degree of saturation, $S = V_w / V_v = G_s \cdot w / e$

$$\boxed{G_s \cdot w = S \cdot e}$$

Unit Weights

Water, $\gamma_w = 9.81\ kN/m^3 = 62.4\ pcf = 1.00\ TCM$

Solids, $\gamma_s = G_s \cdot \gamma_w$

Total, $\gamma_t = W_T / V_T = \left(\frac{G_s + S \cdot e}{1+e}\right)\gamma_w$

Dry, $\gamma_d = W_s / V_T = \frac{G_s \cdot \gamma_w}{1+e}$

Buoyant, $\gamma_b = \gamma_t - \gamma_w$; for $S = 100\%$, $\gamma_b = \left(\frac{G_s - 1}{1+e}\right)\gamma_w$

Fig. II-1 Phase Relations (for water as pore liquid)

2. SOIL COMPOSITION

2.1 Overview (See Sheet A)

1) Differences in particle size & shape are mainly due to differences in the types & arrangement of elements in the crystalline structure = MINERALOGY (regular structural arrangement of atomic elements → X-ray diffraction pattern)

2) Five Main Groups
- Carbonates: Calcite & dolomite used to make cement
- Oxides
- Hydrous Oxides: Gibbsite & brucite minus OH's → sheets in clay minerals
- Phosphates: mining for fertilizer
- SILICATES: >90% of all Soil

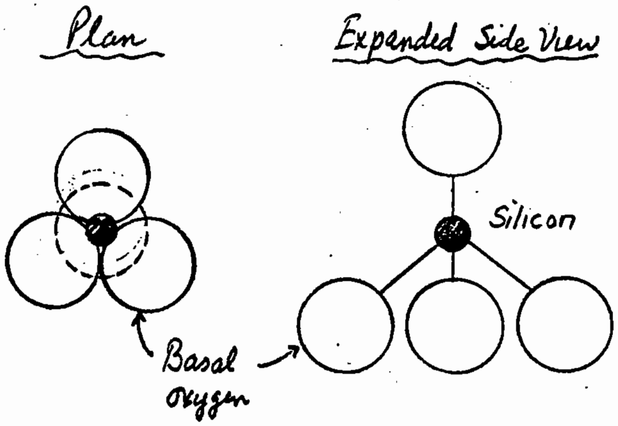
2.2 Silicates

1) Silica tetrahedron

v = valence

O = oxygen (v = -2)

Si = silicon (v = +4)



$Si^{+4}O_4^{-8} = -4$ net negative charge

∴ Can not exist alone

Primary valence bonding (covalent + ionic)

2) How these silica tetrahedra are arranged via the number of shared oxygens → different silicate minerals

---

	Element	O	Si	Al	Fe	Mg	Ca	Na	K
Glasstone (1946)	Valence	-2	+4	+3	+2	+2	+2	+1	+1
	Ionic Dia. (Å)	2.8	0.8	1.0	1.5	1.3	2.0	1.9	2.6^5

$1Å = 10^{-8}cm = 10^{-4}\mu m$

2.3 Silicate Frameworks & Composition of Granular Soils

Tetrahedra form 3-D array so that ALL oxygen are shared → one Si per two oxygen. Very resistant to weathering → large particles

① • Quartz $SiO_2 \times 4 = Si_4O_8$

② • K Feldspar $K\,Al\,Si_3O_8$

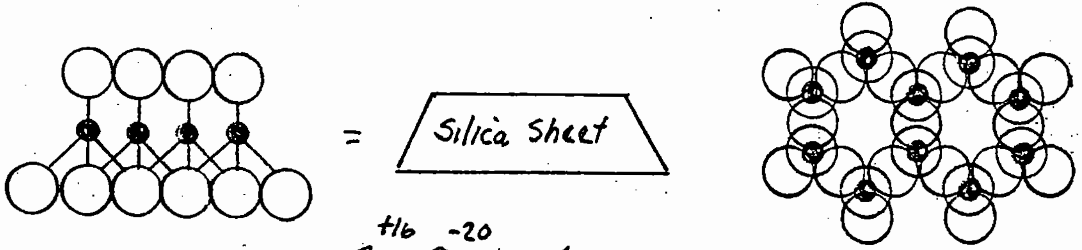
③ • Plagioclase

Relative abundance in sand & silt size particles. See Sheet A for other "granular" minerals, e.g. Calcite = ④, Dolomite = ⑤

Muscovite = ⑥

2.4 Building Blocks of Clay Minerals

1) All basal oxygen of silica tetrahedra are shared



$\overset{+16}{Si_4}\,\overset{-20}{O_{10}} = -4$ Still not neutral; therefore combines with octahedral sheets

2) Hydrous oxide octahedral sheets

$\boxed{\text{G = Gibbsite}}$ $\left.\begin{array}{l}6\,OH^{-1}\\ 4\,Al^{+3}\\ 6\,OH^{-1}\end{array}\right\}$ $Al_4(OH)_{12}$ minus some OH's

$\boxed{\text{B = Brucite}}$ $\left.\begin{array}{l}6\,OH\\ 6\,Mg^{+2}\\ 6\,OH\end{array}\right\}$ $Mg_6(OH)_{12}$ " " "

3) Which silica & hydrous oxide sheets are combined (via primary valence bonding) to form a LAYER and how these layers are "glued" together to form particles → different clay minerals

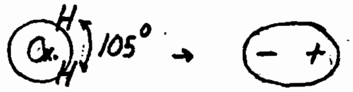
2.5 Types of Bonds

(1 mol = 6.023×10^{23} molecules = Avogadro's number)

1) Primary valence ($\underbrace{\text{covalent, ionic}}$ Silicates & metallic) = very strong (15-100 kcal/mol)

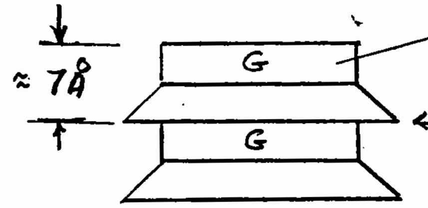
2) Hydrogen bonding = intermediate (≈ 4-5 kcal/mol for water)
H^{+1} fluctuates between two O^{-2}

3) van der Waals = universal attractive force (≤ 1/10th of H-bonds)

{ Water = H_2O ; Dia ≈ 3Å ; Dipole  }

2.6 Common Clay Minerals with Two Sheets per Layer (Sheets A & B)

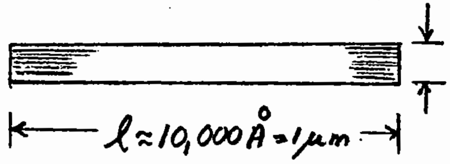
1) Kaolinite $(Al_4)[Si_4]O_{10}(OH)_8$



Gibbsite - 4 OH's → $Al_4(OH)_8$

Strong glue between layers (H-bonding + van der Waals) produces large hexagonal platy shaped particles

Edge View



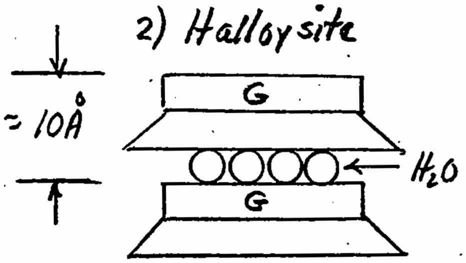
t ≈ 1000Å (140 layers)

∴ t/ℓ ≈ 1/10

} SSA ≈ 10 m^2/g

- Weathering conditions: High rainfall, good drainage, low pH, SiO_2 rich granitic rock
- Used for pottery & in Kaopectin ; favored for lab experiments

2) Halloysite



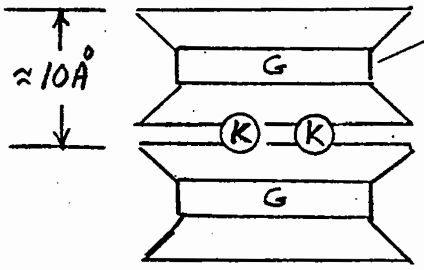
hollow tube

- Same basic composition as kaolinite, but 4 H_2O molecules trapped between layers during formation (hydrated form). Air drying removes this water → dehydrated form.
- Due to slight mismatch in crystal structures of G & S sheets, get pronounced warping → <u>hollow tube particles</u>
- Tubular particles + trapped H_2O → high w and low γ_d (even after compaction). But good fill material.
e.g., $w_{opt} \approx 50\%$, $\gamma_{d\,max} \approx 70$ pcf

2.7 Common Clay Minerals with Three Sheets per Layer (Sheets A & B)

1) Muscovite (Mica) $K_2(Al_4)[Al_2Si_6]O_{20}(OH)_4$

Gibbsite - 8 OH's → $Al_4(OH)_8$



- During mineral formation, 1 of 4 Si^{+4} replaced by Al^{+3} in silica sheets.

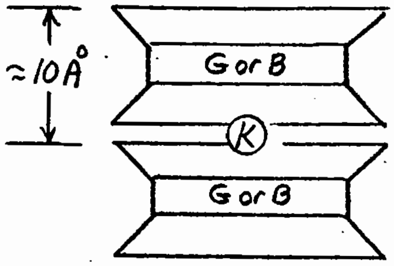
  Called Isomorphous Substitution (IS)

- Resultant negative charge in layer balanced by potassium cations (K^{+1})

- These K cations act as a very strong glue between layers → very large plate-like particles (can see mica flakes in some granular soils)

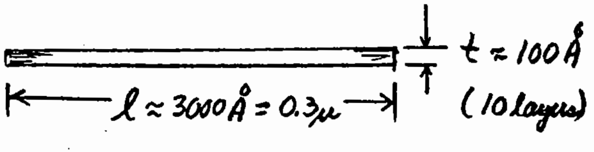
- Consider muscovite as reference mineral for "real" 3 sheet/layer clay minerals, e.g., illite, montmorillonite, chlorite, etc.

2) Illite (Hydrous Mica) $K(Al,Mg,Fe)_{4\text{ or }6}[Al,Si]_8O_{20}(OH)_4$



- Basic structure of mica altered due to
  - either G or B for octahedral sheet
  - less isomorphous substitution of Al for Si → less K glue → much smaller particles

Edge View

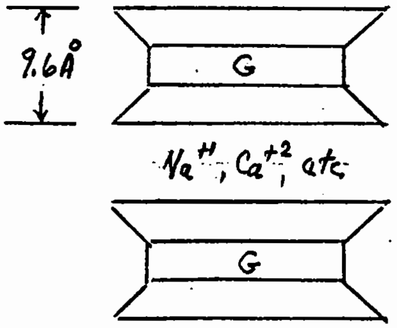


- Flaky (platy) shaped particles
- SSA ≈ 80 m^2/g

$\therefore t/l \approx 1/30$

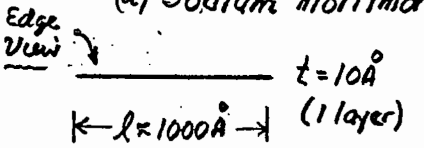
- Most common clay mineral. Especially dominant in cold climate, marine clays, such as Champlain clays in E. Canada and Boston Blue Clay

3) Montmorillonite (Part of Smectite group) $(Al_{3.3}Mg_{0.7})[Si_8]O_{20}(OH)_4$



- Relatively small amount of IS of Mg^{+2} for Al^{+3} in Gibbsite sheet + larger separation of minus/plus charges
- Relatively low negative charge in layer is balanced by exchangeable cations, i.e., Na^{+1} can be replaced by Ca^{+2} or Mg^{+2}, etc.
- Common mineral in arid regions from weathering of volcanic ash, alkaline igneous rocks, etc. (Gulf of Mexico, etc.)

(a) Sodium Montmorillonite (Bentonite)



- Na^{+1} cations do not glue layers together. Hence can get one layer = flaky shaped particle
- SSA ≈ 800 m²/g (6g ≈ area of football field)

- Was used as axle grease; now used for drilling mud, slurry walls, etc.
- Major problem soil since highly expansive & very low residual ϕ' (ϕ'_r)

(b) Montmorillonite with Other Exchangeable Cations

- Ca^{+2}, Mg^{+2}, $Fe^{+2,+3}$ act as moderate glue that can restrict interlayer spacing to ≈ 5-10Å and hence greatly reduce effective SSA. However, may still be expansive and have rather low ϕ'_r

4) Chlorite (Sheet B)

- Variation of I or M where positively charged Brucite sheet (i.e., minus OH's) provides very strong glue between layers → very small SSA. Fairly common in marine illitic clays

5) Varmiculite (Sheet B)

- Variation of mica where K replaced by Ca or Mg cations, which greatly reduces bonding between layers so that can have one layer = particle. Hence very high SSA. However, not very common clay mineral

2.8 Relationship Between Soil Composition & Engineering Properties

1) Mineralogy does strongly affect the size and shape of particles in soil. For cohesive soils, knowledge of the composition is helpful in predicting and/or explaining unusual or adverse behavior, e.g.

- Halloysite → very low γ_d
- Montmorillonite → highly expansive
- Illite → quick clays (Part II-2)

2) However, composition per se cannot predict the engineering properties of most cohesive soils because of the following complicating factors.

(a) Variation in particle size of same mineral

- Quartz: from stone size to all silt size (Rock Flour)

(b) Cementing agents (e.g., $CaCO_3$, Al/Fe oxides, organic matter) cause aggregation of particles → much lower effective SSA

(c) Usually have several minerals in most soils

- Take 50-50 mixture of sand and clay } clay → very low k
  Sand → very high ϕ'

(d) Effect of pore fluid composition, i.e. type & concentration of cations, pH, etc. (covered in Part II-2)

3. INDEX PROPERTIES TO GROUP SOILS WITH SIMILAR ENGINEERING PROPERTIES

3.1 Objective

1) Want relatively simple tests in order to determine:

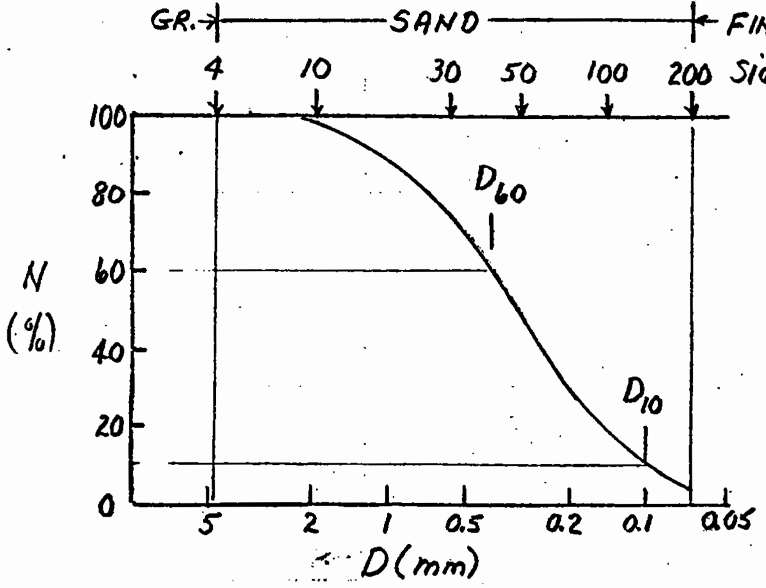
1st The SOIL TYPE
2nd It's RELATIVE STATE } Then can expect similar engineering properties, e.g. Coef. of permeability
Compressibility
Strength

2) Will present a simplified approach and distinguish between GRANULAR versus COHESIVE soils

3.2 Granular Soils

1) Soil Type: Use particle size distribution ASTM D422*

GR. | SAND | FINES à la ASTM (See Section 4.2)



a) Smallest Size (Related to k)

D_{10} or % Fines (% -No. 200 sieve = 75 μm)

b) Gradation (Related to Δe range)

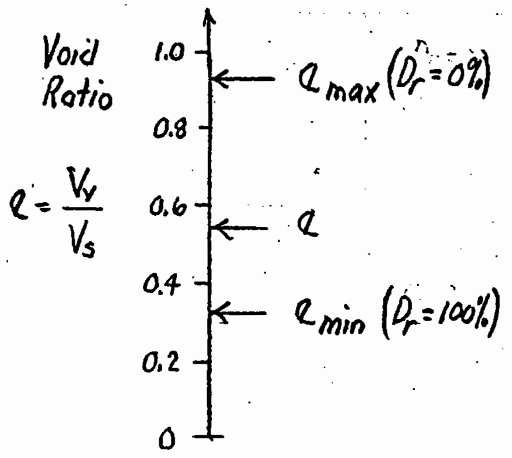
Coef. of Uniformity, C_u

$$C_u = D_{60} / D_{10}$$

$> 5 \pm 1$ = well graded

< 2 = uniform

2) Relative State: Use Relative Density, D_r (L&W Tables 3.2 & 3.3)



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

- e_{min} (max. density) via ASTM D4253 (vibration in mold with surcharge load)
- e_{max} (min. density) via ASTM D4254 (pour through funnel into mold)
- $D_r \geq 70\%$ is "dense"; $D_r \leq 30\%$ is "loose" (worry about liquefaction during earthquake)

3) Empirical correlations for granular soils

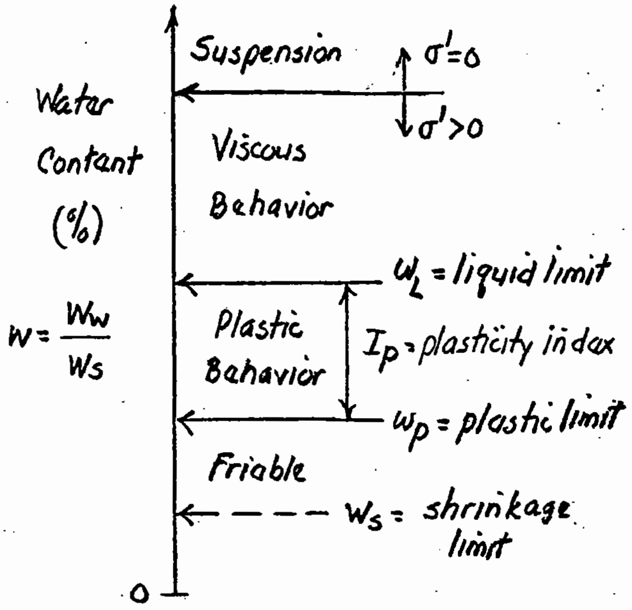
- $k\,(\text{cm/sec}) \approx [D_{10}\,(\text{mm})]^2$ Very good for loose, fairly uniform sands
- See Sheet C for estimation of in situ density & drained friction angle (φ')

---

* Sieve No.	4	8	10	16	20	30	40	50	60	100	140	200
Dia. (mm)	4.75	2.36	2.00	1.18	0.85	0.60	0.425	0.30	0.25	0.15	0.106	0.075

3.3 Cohesive Soils

1) Soil Type: Use Atterberg Limits via ASTM D4318



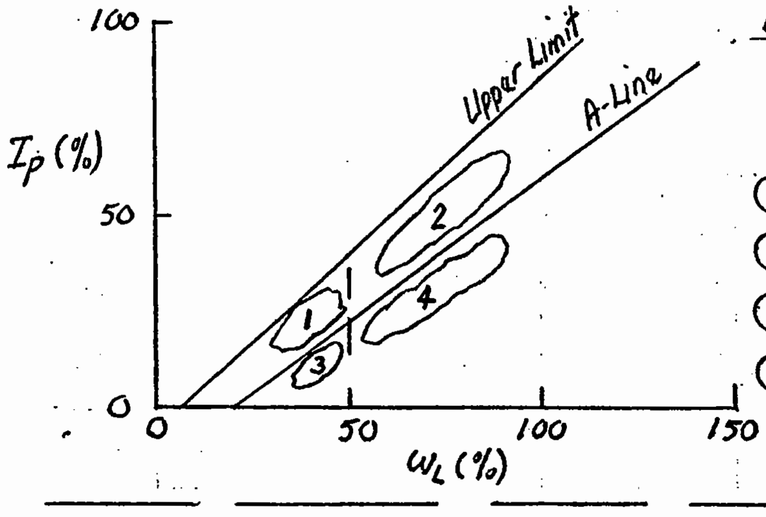
- Tests run on remolded soil passing #40 sieve. NOTE: Best to start with soil at w_N because air/oven drying can reduce w_L & I_p of soils containing organic matter, smectite, Al & Fe oxides, etc.
- w_L corresponds to low undrained shear strength $s_u \approx 20\,g/cm^2 \approx 40\,psf \approx 2\,kPa$ * (like butter at room temperature)
- w_p when soil loses ability to deform plastically (crumbling of 3.2 mm = 1/8 in. dia. thread of soil)
- w_s = computed w for $S = 100\%$ after oven drying cube of saturated soil

- $I_p = PI = w_L - w_p$ is Δw range over which soil exhibits plastic behavior

- Activity = $\frac{I_p\,(\%)}{\% - 2\mu m \text{ (clay fraction)}}$

- $I_L = LI$ = liquidity index
$= (w_N - w_p)/(w_L - w_p = I_p)$ $\left\{ I_L \geq 1.5 \rightarrow \text{high sensitivity}, S_t = \frac{s_u(U)}{s_u(R)} \approx 100 \pm 50 \right\}$

Casagrande's Plasticity Chart



Above A-Line = Inorganic Clays
- High oven dried strength
- Very low k
- Tough at w_p

Below A-Line = Silts & Organic Soils
- Very friable as $w \rightarrow w_p$
- Lower oven dried strength

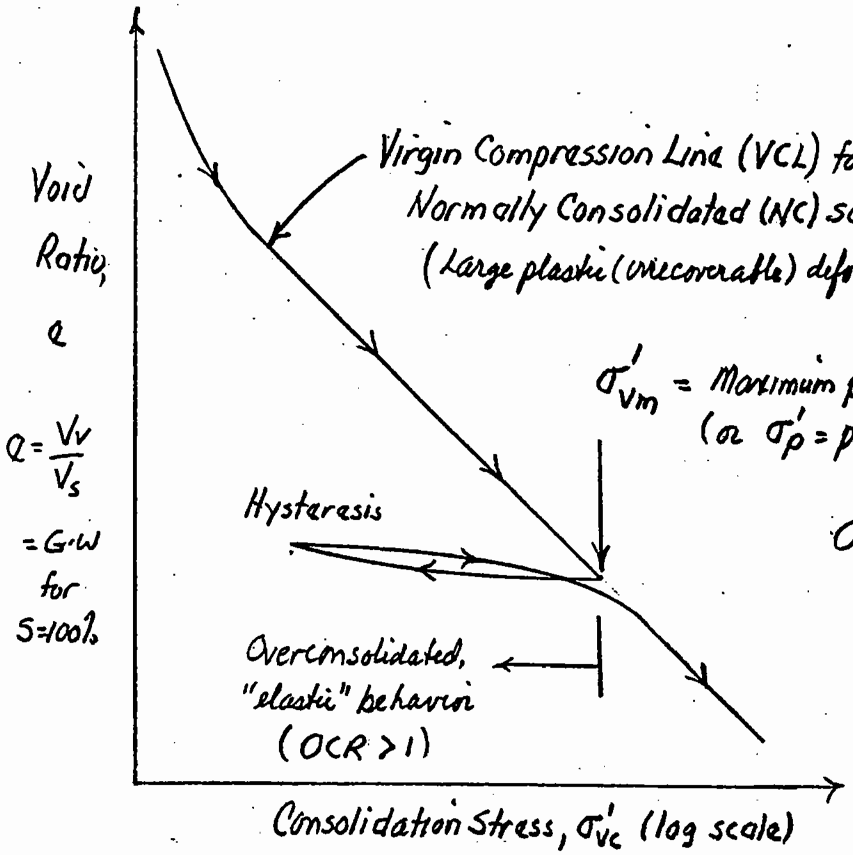
① Marine illitic clays (BBC)
② Deltaic smectitic clays (Gulf Mexico)
③ Arctic silts (Alaska)
④ mudflat deposits (N.E. Coastline)

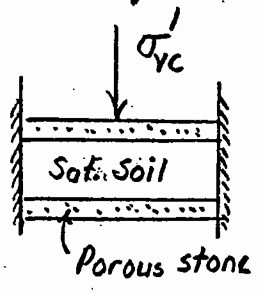
---

* $1\,atm \approx 1\,Kgf/cm^2 \approx 2000\,psf = 1\,TSF \approx 10\,TSM \approx 100\,kPa = 1\,bar$
$100\,kN/m^2$

2) Relative State: Use Stress History (current σ'_{vc} plus σ'_p or OCR)

- Illustrate via 1-D consolidation test starting with soil slurry





σ'_{vm} = Maximum past vertical stress
(or σ'_p = preconsolidation pressure)

Overconsolidation Ratio =
$OCR = \sigma'_{vm} / \sigma'_{vc}$

NOTE: $\sigma' \equiv \bar{\sigma} = \sigma - u$ = effective stress

3) Empirical correlations for cohesive soils

a) Coefficient of consolidation, c_v : See Sheet D1 (excellent correlation)

b) Virgin compression index, $C_c = -de/d\log\sigma'_{vc}$ = slope of VCL

$C_c \approx 0.009\,(w_L - 10\%)$ (Terzaghi & Peck 1967)

c) Remolded undrained shear strength [at w_L, $s_u = 1.6\,kPa \approx 33\,psf$]

$s_u(kPa) = 1/(I_L - 0.21)^2$ [Leroueil et al. 1983, CGJ 20(4)]

d) SHANSEP equation for design s_u of homogeneous sedimentary cohesive soils

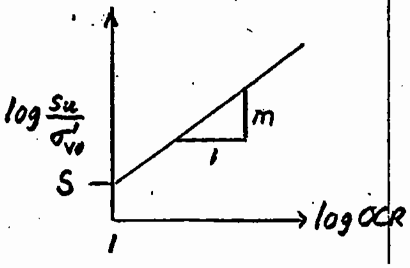
$s_u/\sigma'_{vo} = S\,(OCR)^m$

(Also see Sheet D1)

CL & CH clays $S = 0.22 \pm 0.03$ SD
Soils below A-Line $S = 0.25 \pm 0.05$ SD
$m = 0.8 \pm 0.1$
(Ladd 1991)

e) Drained shear strength (values of c' & φ')

See Sheet D2



4. UNIFIED SOIL CLASSIFICATION SYSTEM (USCS)

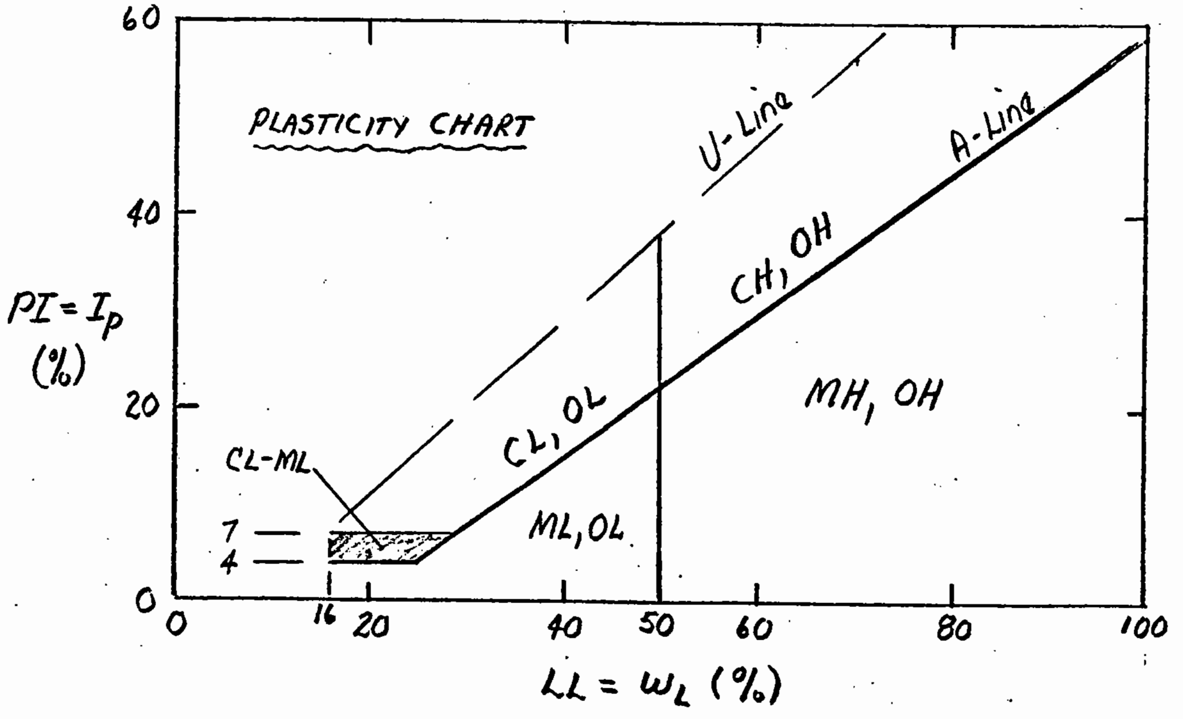
4.1 Overview of USCS (ASTM D 2487)

= Sieve size
% fines = % passing #200 (75μm)

	Six Main Soil Types	< 5% Fines GRADATION	Between DUAL	>12% Fines PLASTICITY
		Modifiers		
< 50% passing #200	G = Gravel — #4 S = Sand	W = Well graded P = Poorly graded	Use Both, eg., SW-SM	M = Silty C = Clayey

>50% passing #200	M = Silt	Below A-Line	Plasticity Chart L = Low (LL < 50) H = High (LL >50)
	C = Clay	On/Above A-Line	
	O = Organic	$\frac{LL\ dried}{LL\ not\ dried} < 0.75$	
	Pt = Peat	Mostly organic matter	

A-Line: $PI = 0.73(LL-20)$ U-Line: $PI = 0.9(LL-8)$

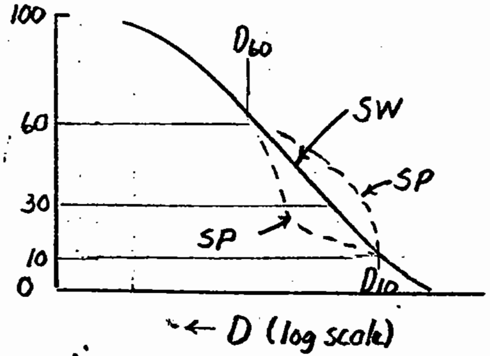


4.2 Details of USCS

See Sheet E

4.3 Remarks & Examples

1) Coarse Grained (granular)



- Well vs. Poorly graded

$C_u = D_{60}/D_{10} > 4$ or 6 requires a wide range in particle sizes

$1 \le C_c = \frac{(D_{30})^2}{D_{60} \cdot D_{10}} \le 3$ prevents gap grading

C_c = Coef. of curvature

- < 5% Fines, e.g., GW, GP = Well, Poorly graded Gravel
- > 12% Fines, e.g., SM, SC = Silty, Clayey Sand
- 5 ≤ % Fines ≤ 12% → Dual classification for both Gradation & Plasticity

e.g.,
GW-GM = Well graded Gravel with silt
SP-SC = Poorly graded Sand with clay

2) Fine Grained (Cohesive)

- On or above A-Line
  CL, CH = lean, fat Clay
  OL, OH = organic Clay (CCL → lean, fat organic Clay)

- Below A-Line
  ML, MH = silt, elastic Silt (CCL → lean, plastic Silt)
  OL, OH = organic Silt (CCL → lean, plastic organic Silt)

- For Both
  If > 30% + #200; add "sandy" or "gravelly" before the name
  If 15-29% + #200; add "with sand" or "with gravel" after the name

e.g. Sandy, lean Clay

e.g., lean Silt with gravel

1.361-1.366 Part II-1

Composition of Soil

1.322 Soil Technology
Dept. of Civil Engr. - M.I.T.

CCL & RTM 9/65
CCL 9/95

- **SOIL**
  - **ORGANIC**
  - **INORGANIC**
    - **AMORPHOUS**
      - Opal
      - Hydrous oxides of Si, Fe, Al
    - **CRYSTALLINE**
      - **CARBONATES**
        - ④ Calcite - $CaCO_3$
        - ⑤ Dolomite - $CaMg(CO_3)_2$
      - **OXIDES**
        - ⑭ Rutile - TiO_2
        - ⑮ Magnetite - Fe_3O_4
      - **HYDROUS OXIDES**
        - Goethite
        - Gibbsite - $Al_4(OH)_{12}$
        - Brucite - $Mg_6(OH)_{12}$
      - **PHOSPHATES**
        - ⑳ Apatite - $Ca_5(F,Cl,OH)(PO_4)_3$
      - **SILICATES**
        - **INDEPENDENT TETRAHEDRONS**
          - ⑪ Olivine - $(Mg,Fe)_2SiO_4$
          - ⑫ Sillimanite - Al_2SiO_5
          - ⑬ Zircon - $ZrSiO_4$
          - ⑰ Staurolite
          - ⑱ Garnet
          - ⑲ Sphene - $CaTiSiO_5$
        - **DOUBLE TETRAHEDRONS**
          - Lawsonite
        - **RINGS**
          - ⑯ Tourmoline
        - **CHAINS**
          - Pyroxene (single)
            - ⑩ Augite
          - Amphibole (double)
            - ⑨ Hornblende
            - Palygorskite (Attapulgite)
        - **SHEETS**
          - Two Sheet
            - Serpentine - $Mg_6Si_4O_{10}(OH)_8$
            - Kaolinite - $Al_4Si_4O_{10}(OH)_8$
            - Halloysite -
          - Three Sheet
            - Talc - $Mg_6Si_8O_{20}(OH)_4$
            - Pyrophyllite - $Al_4Si_8O_{20}(OH)_4$
            - ⑥ Muscovite - $K_2Al_4[Al_2Si_6]O_{20}(OH)_4$
            - ⑦ Biotite
            - Vermiculite
            - Illite - $K(Al,Mg,Fe)_{4\,or\,6}[Si,Al]_8O_{20}(OH)_4$
            - Montmorillonite - $(Al_{3.3}Mg_{0.7})[Si]_8O_{20}(OH)_4$
            - ⑧ Chlorite
        - **FRAMEWORKS**
          - ① Quartz - Si_4O_8
          - ② K Feldspar - $KAlSi_3O_8$
          - ③ Plagioclase - $NaAlSi_3O_8 \rightarrow CaAl_2Si_2O_8$

Smectite ⟷ Montmorillonite

③ Numbers refer to order of abundance in sands and silts
(Clays & Clay Technology, Bulletin 169, 1955)

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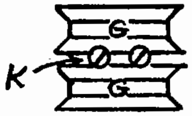
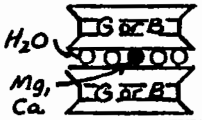
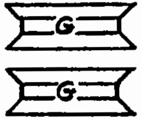
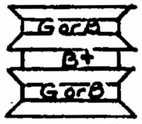
Data on Common Clay Minerals

CCL & RTM
9/65
9/95

1.322 Soil Technology

Dept. of Civil Engineering
M.I.T.

Mineral	Unit Cell Formula	Structural Symbol	Isomorphous Substitution	Charge Density (meq/100g) (1)	Interlayer Bonding	Typical Particle		CEC (2) $\left(\frac{meq}{100g}\right)$	SSA (3) $\left(\frac{m^2}{g}\right)$	σ (4) $\left(\frac{charge}{100Å^2}\right)$	Var. d(001)
						Shape	Size				
Kaolinite	$(Al)_4[Si]_4O_{10}(OH)_8$		Al for Si Mg for Al (~1 in 400)	~2	Secondary valence + H-bonding Strong	Hexagonal sheets	d=3-10μ $t=\frac{1}{3}-\frac{1}{10}d$	~3	10-15	1.2	No
Hydrated Halloysite Dehydrated	$(Al)_4[Si]_4O_{10}(OH)_8\cdot nH_2O$ n=4 n=0		As above	~8	As above except weak if larger spacing	Hollow tubes	OD=.07μ ID=.04μ ℓ~.5μ	~12	30-50	1.8	Yes No
Muscovite (Mica)	$K_2(Al)_4[Al_2Si_6]O_{20}(OH)_4$		Al for Si (~1 in 4) Maybe Mg, Fe for Al	250	K-bonding + sec. val. Very strong	Platy	Very large	3-10	1-10	~2.2	No
Vermiculite	$(Mg,Al,Fe)_{6\ or\ 4}-[Si,Al]_8O_{20}(OH)_4\cdot nH_2O$		Mainly Al for Si (~1 in 8) Also Mg, Fe for Al Al, Fe for Mg	150±20	Weak primary val. (Ca, Mg) + sec. val. Weak	Sheets	Variable	150 ±20	500-700 when expanded.	2.2	Yes
Illite (Hydrous mica)	$K(Al,Mg,Fe)_{4\ or\ 6}-[Si,Al]_8O_{20}(OH)_4$		Mainly Al for Si (1 in 6-8) Also Mg, Fe for Al Al, Fe for Mg	~150	K-bonding + sec. val. Fairly strong	Flakes	d=.1-2μ $t\leq\frac{1}{10}d$	25 ±5	80-100	1.5	No
Sodium Montmorillonite	$(Al_{3.3}Mg_{0.7})[Si]_8O_{20}(OH)_4$		Mainly Mg for Al (~1 in 6)	100	Weak secondary valence	Sheets	d=.1-1μ $t\leq\frac{1}{100}d$	95 ±10	700-800	0.75	Yes
Chlorite	$(Mg,Al,Fe)_{4\ or\ 6}[Si,Al]_8-O_{20}(OH)_4\cdot(Mg,Al,Fe)_6(OH)_{12}$		Al for Si Fe, Mg for Al Fe, Al for Mg in B^+	200-250	Primary valence via B^+ sheet Very strong	Platy	Variable	2-40	5-30	—	No

(1) Charge density = $\frac{\text{charge/formula} \times 10^5}{\text{formula weight}}$

Mineral	Formula Wgt.
Kaolinite	517
Talc	750
Pyrophyllite	710

(2) CEC = cation exchange capacity

(3) SSA = specific surface area

(4) σ = surface charge density

- Octahedral & Tetrahedral Sheets
- Unit Layer = 2 or 3 sheets
- Particle = Σ Layers

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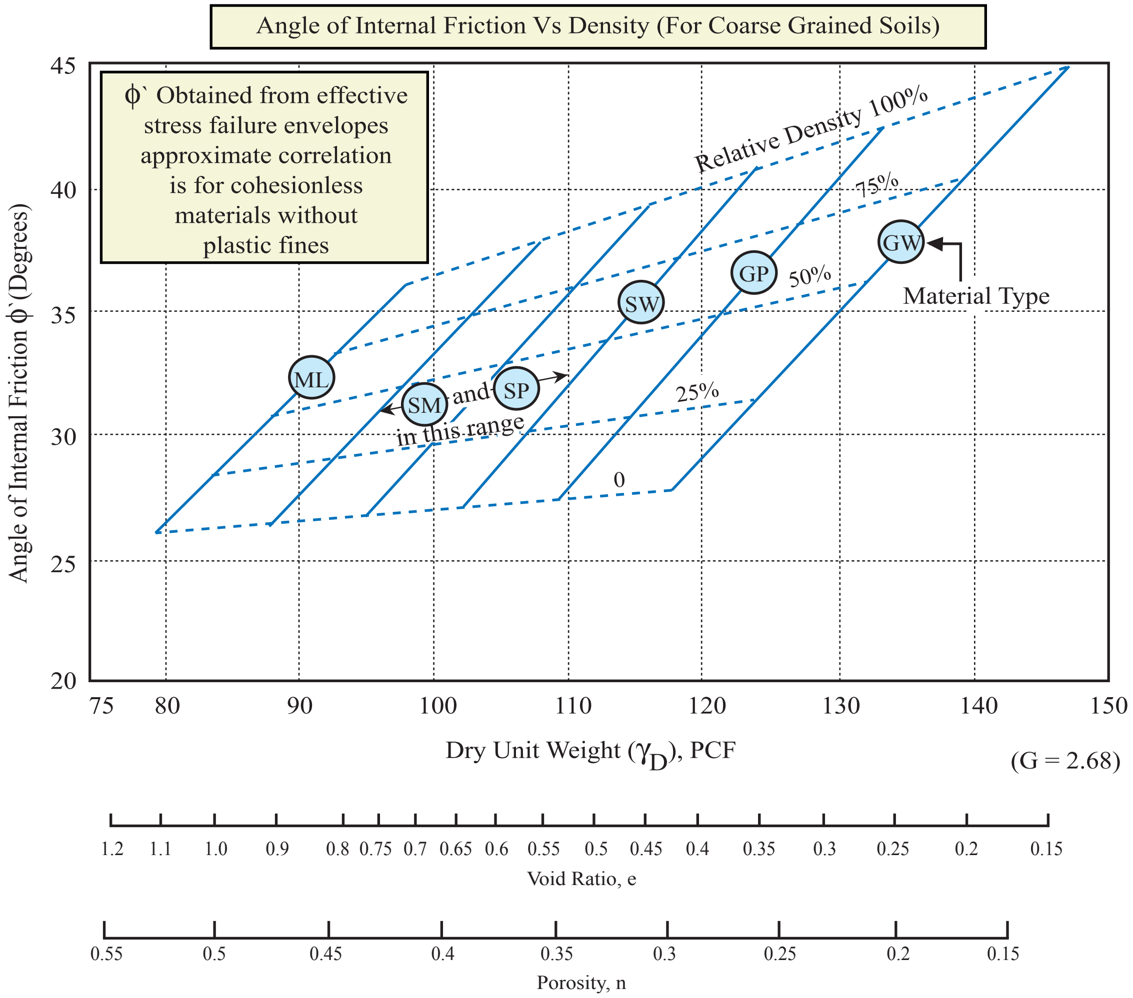
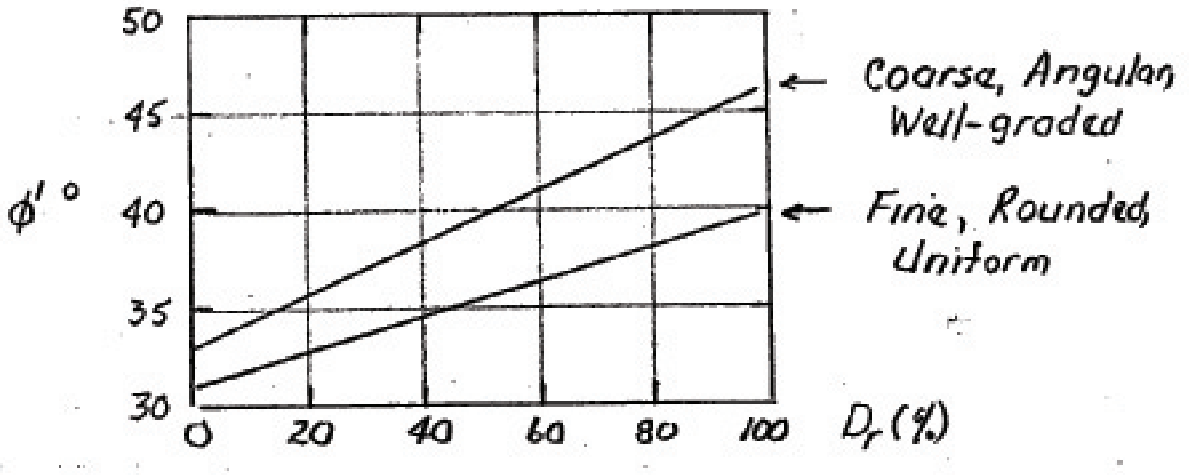


Correlations Of Strength Characteristics For Granular Soils

Adapted from NAVFAC DM-7.1 (5/82) p 7.1 - 149

Friction Angle (Schmertmann 1975)



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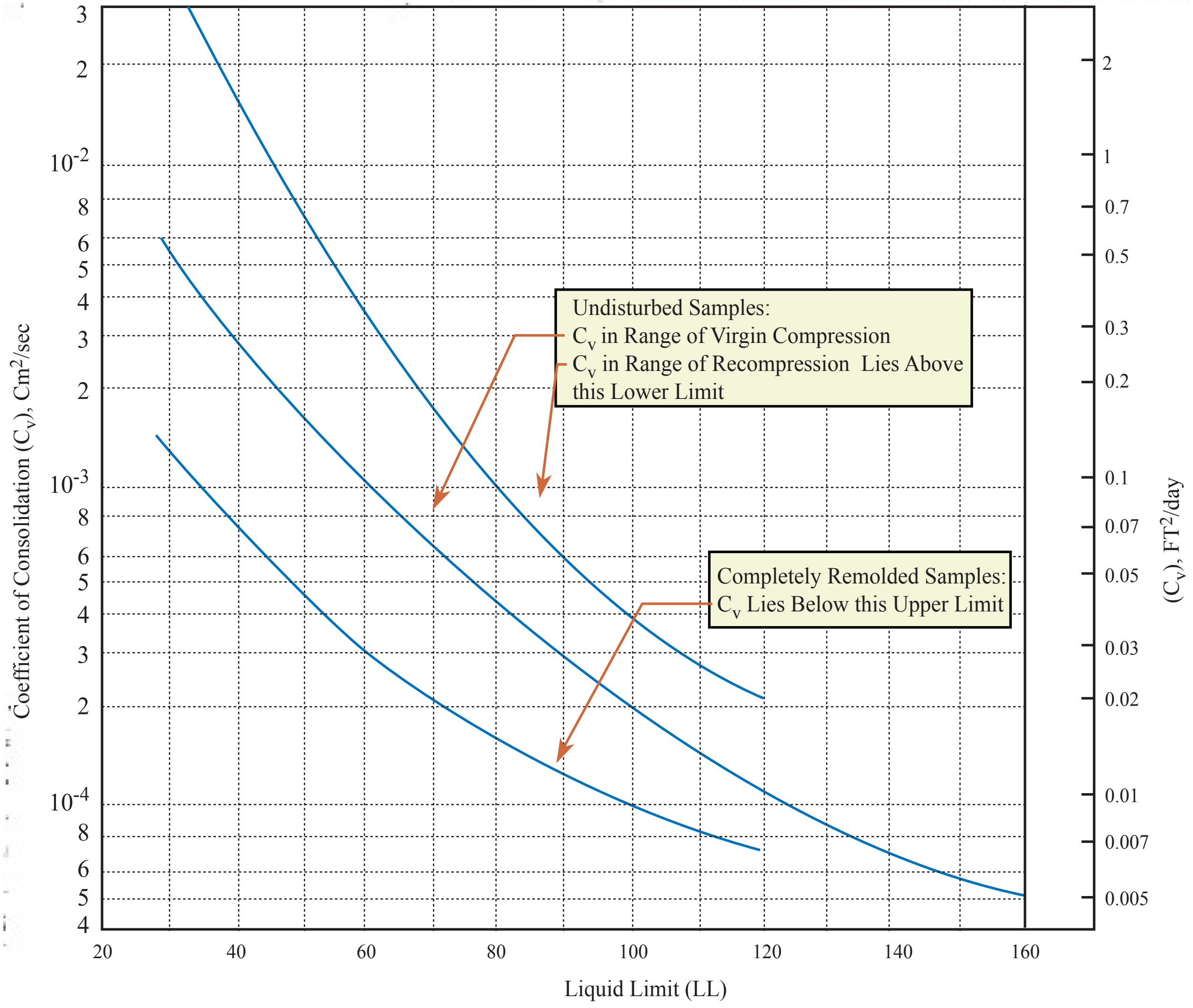
1,361-1,366 Part II-1

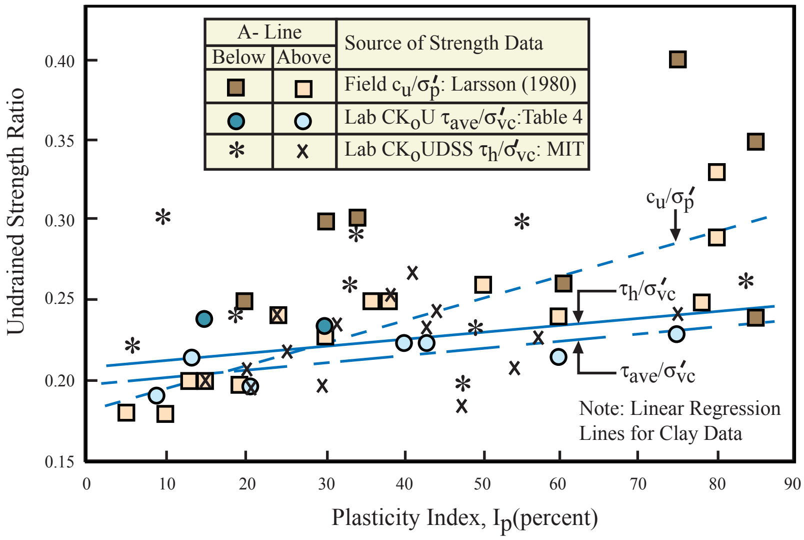


Undisturbed Samples:
C_v in Range of Virgin Compression
C_v in Range of Recompression Lies Above this Lower Limit

Completely Remolded Samples:
C_v Lies Below this Upper Limit

Coefficient of Consolidation Vs Liquid Limit

Adapted from NAVFAC DM-7.1 (1982)



Note: Linear Regression Lines for Clay Data

Note: $C_u = S_u$
Undrained shear strength for design (stability analyses)

Comparison of field and laboratory undrained strength ratios for nonvarved sedimentary soils (OCR = 1 for laboratory *CK_oU* testing)

Adapted from Ladd (1991), JGE, ASCE, 117(4)

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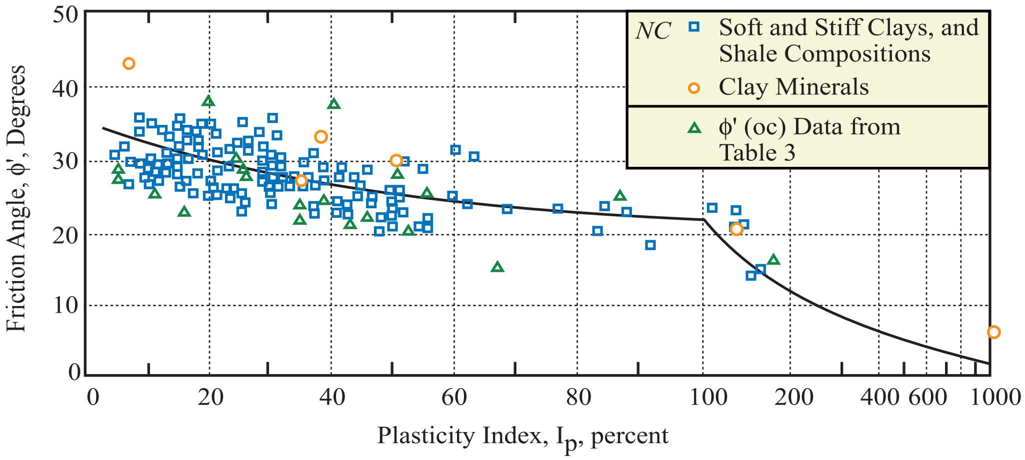
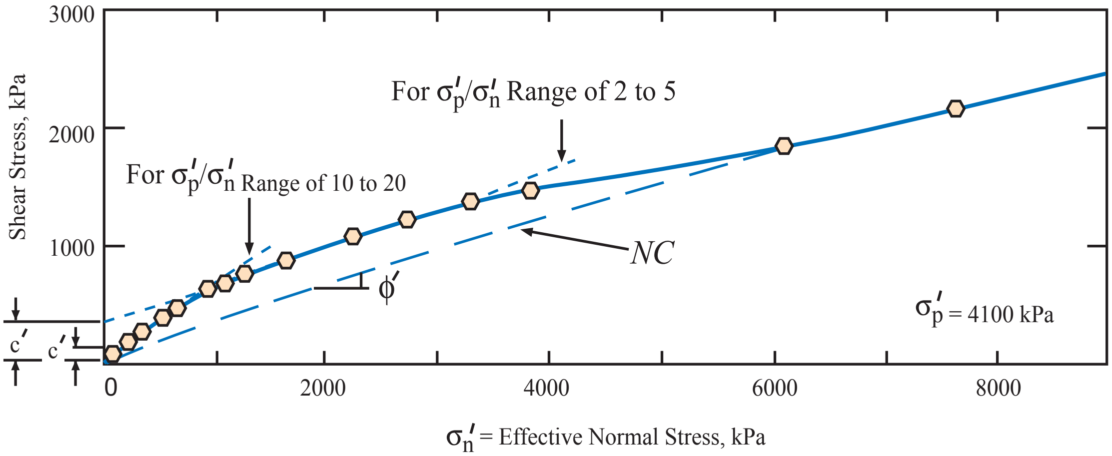
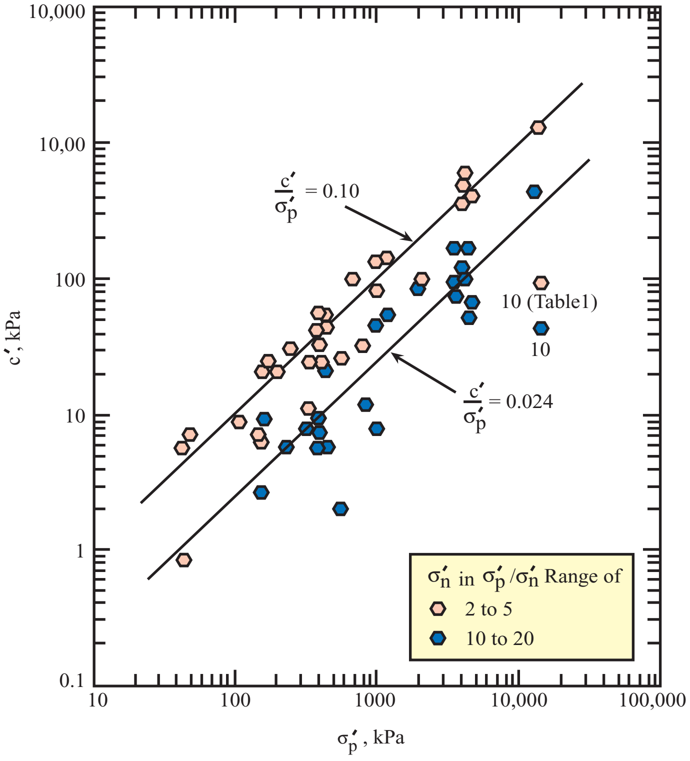




Peak Strength against Effective Normal Stress Relationship of London Clay Sample from 35 m Depth (Data from Bishop et al. 1965)



Relationship between Cohesion Intercept and Preconsolidation Pressure

D2

Adapted from Mesri & Adel - Ghaffar (1993), JGE, ASCE, 119(8)

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TABLE 1 Soil Classification Chart

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification	
				Group Symbol	Group Name[B]
COARSE-GRAINED SOILS More than 50 % retained on No. 200 sieve	Gravels More than 50 % of coarse fraction retained on No. 4 sieve	Clean Gravels Less than 5 % fines[C]	Cu ≥ 4 and 1 ≤ Cc ≤ 3[E]	GW	Well-graded gravel[F]
			Cu < 4 and/or 1 > Cc > 3[E]	GP	Poorly graded gravel[F]
		Gravels with Fines More than 12 % fines[C]	Fines classify as ML or MH	GM	Silty gravel[F,G,H]
			Fines classify as CL or CH	GC	Clayey gravel[F,G,H]
	Sands 50 % or more of coarse fraction passes No. 4 sieve	Clean Sands Less than 5 % fines[D]	Cu ≥ 6 and 1 ≤ Cc ≤ 3[E]	SW	Well-graded sand[I]
			Cu < 6 and/or 1 > Cc > 3[E]	SP	Poorly graded sand[I]
		Sands with Fines More than 12 % fines[D]	Fines classify as ML or MH	SM	Silty sand[G,H,I]
			Fines classify as CL or CH	SC	Clayey sand[G,H,I]
FINE-GRAINED SOILS 50 % or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	inorganic	PI > 7 and plots on or above "A" line[J]	CL	Lean clay[K,L,M]
			PI < 4 or plots below "A" line[J]	ML	Silt[K,L,M]
		organic	$\frac{\text{Liquid limit – oven dried}}{\text{Liquid limit – not dried}} < 0.75$	OL	Organic clay[K,L,M,N] Organic silt[K,L,M,O]
	Silts and Clays Liquid limit 50 or more	inorganic	PI plots on or above "A" line	CH	Fat clay[K,L,M]
			PI plots below "A" line	MH	Elastic silt[K,L,M]
		organic	$\frac{\text{Liquid limit – oven dried}}{\text{Liquid limit – not dried}} < 0.75$	OH	Organic clay[K,L,M,P] Organic silt[K,L,M,Q]
HIGHLY ORGANIC SOILS		Primarily organic matter, dark in color, and organic odor		PT	Peat

[A] Based on the material passing the 3-in. (75-mm) sieve.

[B] If field sample contained cobbles or boulders, or both, add "with cobbles or boulders, or both" to group name.

[C] Gravels with 5 to 12 % fines require dual symbols:
GW-GM well-graded gravel with silt
GW-GC well-graded gravel with clay
GP-GM poorly graded gravel with silt
GP-GC poorly graded gravel with clay

[D] Sands with 5 to 12 % fines require dual symbols:
SW-SM well-graded sand with silt
SW-SC well-graded sand with clay
SP-SM poorly graded sand with silt
SP-SC poorly graded sand with clay

[E] $Cu = D_{60}/D_{10}$ $Cc = \frac{(D_{30})^2}{D_{10} \times D_{60}}$

[F] If soil contains ≥ 15 % sand, add "with sand" to group name.

[G] If fines classify as CL-ML, use dual symbol GC-GM, or SC-SM.

[H] If fines are organic, add "with organic fines" to group name.

[I] If soil contains ≥ 15 % gravel, add "with gravel" to group name.

[J] If Atterberg limits plot in hatched area, soil is a CL-ML, silty clay.

[K] If soil contains 15 to 29 % plus No. 200, add "with sand" or "with gravel," whichever is predominant.

[L] If soil contains ≥ 30 % plus No. 200, predominantly sand, add "sandy" to group name.

[M] If soil contains ≥ 30 % plus No. 200, predominantly gravel, add "gravelly" to group name.

[N] PI ≥ 4 and plots on or above "A" line.

[O] PI < 4 or plots below "A" line.

[P] PI plots on or above "A" line.

[Q] PI plots below "A" line.

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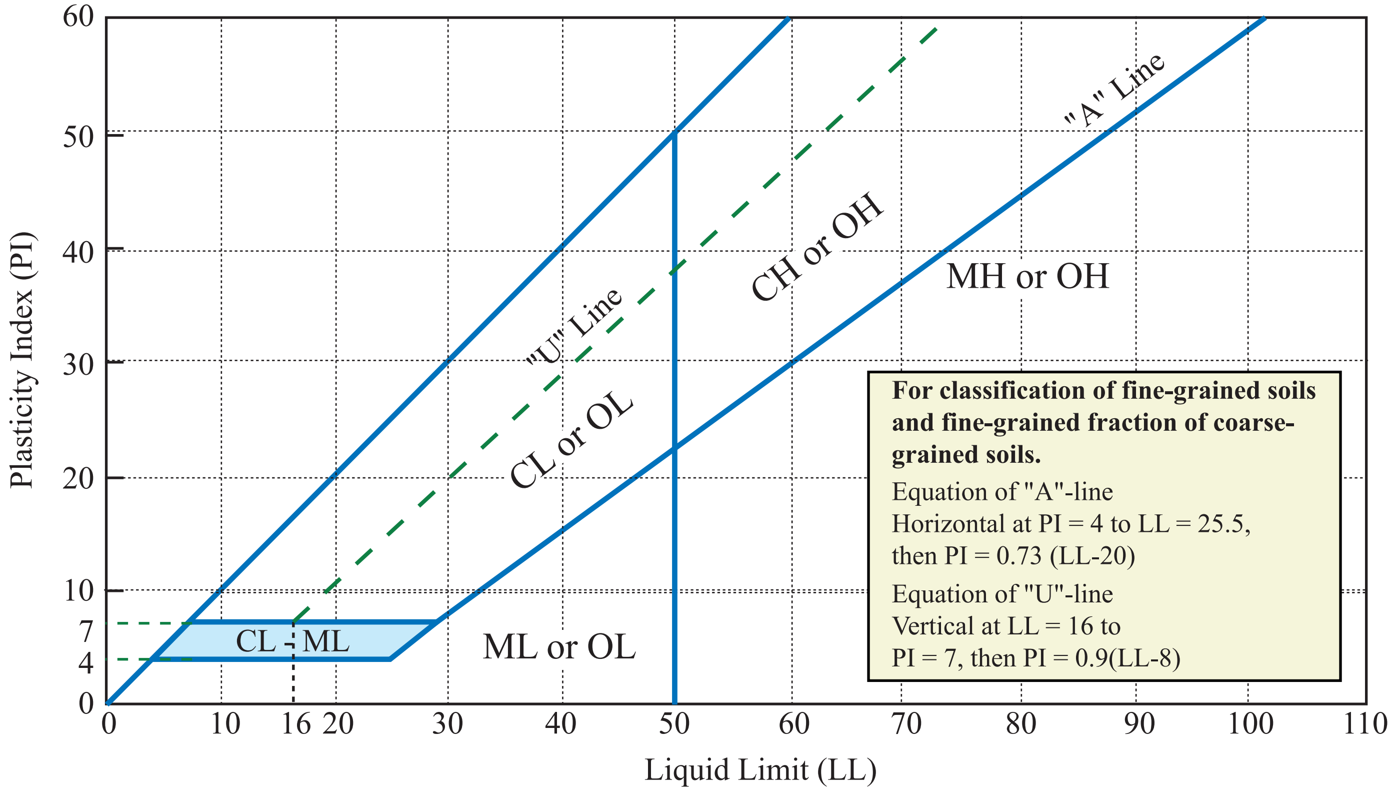

Plasticity Chart

E