NATURE OF SOIL

II-2 SOIL STRUCTURE AND ENVIRONMENTAL EFFECTS

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1. INTRODUCTION

1.1 Soil Structure

1) Definition

$$\text{Soil Structure} = \underset{\substack{\text{Types \& relative} \\ \text{magnitude}}}{\text{Interparticle Forces}} + \underset{\substack{\text{Orientation \& distribution} \\ \text{of particles}}}{\text{Fabric}}$$

2) Interparticle Forces: Want to describe how shear stresses (τ) and normal stresses are transmitted between soil particles. Start with normal stress.

- From **effective stress principle** (L & W Sect. 16.2)

  Effective normal stress ($\sigma' \equiv \bar{\sigma}$) = total normal stress (σ) minus pore water pressure ($u = u_w$)

- This effective stress is transmitted by forces acting between the soil particles (hence was previously termed "intergranular" stress)

- In general, for cohesive soils, this transmission occurs at two stress levels (or has two components à la Section 2.5)

  $\sigma' = $ net short range (contact) stress × contact area ratio

  $+$ net long range stress due to surface (double layer) forces

- We will see later that shear stresses (τ) are primarily carried by contact stresses

3) Fabric: We will distinguish between fabric at the macro-level (can observe visually) vs. that at the micro-level

4) In theory, soil structure completely defines soil behavior. But in reality, only can use in a qualitative fashion to help predict/explain certain aspects of soil behavior (e.g, what causes "quick clays").

1.2 Electrical Nature of Clay Particles

1) Electrical Charges

a) The two faces of all platy particles have a <u>negative charge</u>. It is caused by isomorphous substitution that is not neutralized by interlayer cation bonding (e.g. by K in illite)
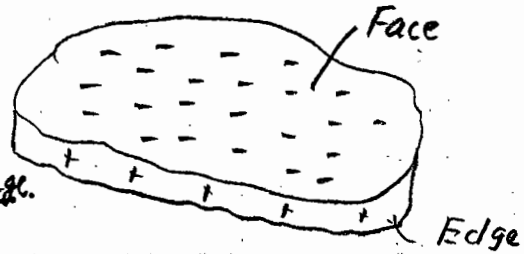
Face area > Edge area.

$$\text{Area ratio} \approx \frac{l}{2t} \quad \left\{ \begin{array}{l} \text{5 for kaol.} \\ \text{15 for illite} \\ \text{50 for Na mont.} \end{array} \right\}$$

b) The edges of clay particles usually have a <u>positive charge</u> at low to moderate pH[*]. But increasing pH may change this to a <u>negative charge</u>.

c) The NET charge of clay particles is always <u>negative</u>. Hence application of an electrical field to a suspension of clay particles will cause the particles to move to the anode. Called electrophoresis
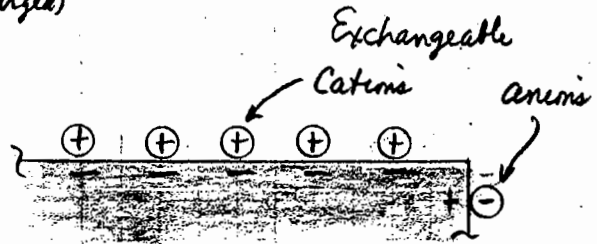
Anode   Cathode

Suspension of clay particles
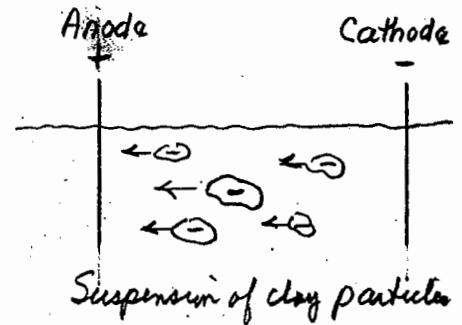
2) Exchangeable Ions.

Since the soil must be electrically neutral

• The negative faces attract <u>exchangeable cations</u> (Na^{+}, Ca^{+2}, Mg^{+2}, etc.)

• Positive edges attract exchangeable anions (or cations if negatively charged)

Edge view of clay particle + pure water after oven drying

Exchangeable Cations   anions

[*] $pH = -log_{10} (H^+ conc.)$ pH < 7 = acid;   pH > 7 = basic

Conc.=   (high H^+)   (low H^+, high OH^-)

3) Surface Charge Density (σ_0)

$$\sigma_0 = \frac{\text{No. of charges}}{\text{unit area}} = \frac{\text{Cation Exchange Capacity}}{\text{Specific Surface Area}} = \frac{CEC}{SSA}$$

$$CEC \text{ in } \frac{\text{milliequivalents}}{100g} = \frac{(10^{-3})(A_N)(e_c)}{100} = 0.965 \ C/g$$

($A_N = 6.02 \times 10^{23}$ molecules/mol ; $e_c =$ electronic charge $= 1.6 \times 10^{-19}$ coulomb)

From Shang, Lo & Quigley [1994, CGJ, 31(5)]

Clay Mineral	CEC (meq/100g)	SSA (m^2/g)	σ_0 (C/m^2)	Avg. Spacing ($\mathring{A}$) Between Charges
Kaolinite	5	15	0.32	7.1
Illite	25	84	0.29	7.5
Na. Mont.	100	800	0.12	11.5

Agrees with Part II-1 Sheet B

1.3 Overview of Coverage

1) Clay-water forces

 • Water vapor adsorption → nature of "adsorbed water" ($t < 10$-$15\mathring{A}$)

 • Interaction between clay particles

   Long range (double layer) forces ⎫ Physico-chemical effective
   Short range (contact) forces   ⎭ stress equation
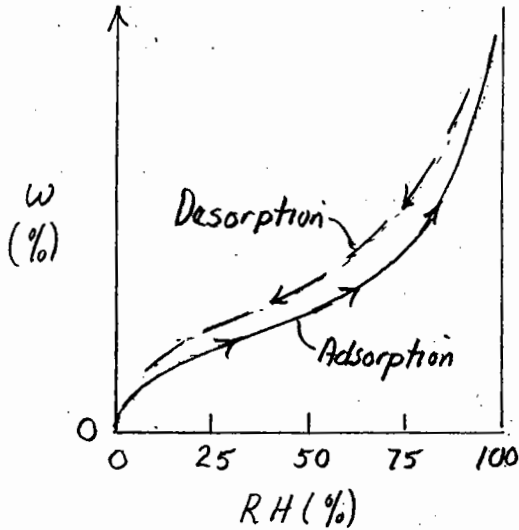
 • Strength generation in soils

2) Soil structure: effects of mineral composition and environmental factors

2. CLAY-WATER FORCES

2.1 Adsorbed Water

1) Water Vapor Sorption

a) Start with oven dried clay; increase Relative Humidity (RH) and measure water content (w)

$$RH(\%) = \frac{P_w}{P_s} \times 100$$

P_w = vapor pressure of water

P_s = saturation vapor pressure at same temperature

(Barshad 1955)

Mineral	RH = 50%	90%	95%
Na Kaol.	0.8	2.0	2.5
Na. Mont.	≈14	28	37

Water Content (%)

b) Adsorption vs. RH (from 1.322)

• At RH = 50%, $w(\%) \approx (0.05)(SSA \ m^2/g)$, i.e. ave. $t \approx 5\overset{\circ}{A}$

• At RH ≈ 99%, $H_2O \ t \approx 10\text{-}15 \overset{\circ}{A}$ (3-5 molecular thicknesses)

c) From thermodynamics, can compute equivalent pressure of attraction (tensile pressure required to remove adsorbed water). Is expressed in terms of capillary pressure (u_c) = soil suction (S)

$$Soil \ suction \ (S) = \frac{P_w R_g T}{M} \ln\left(\frac{100}{RH}\right)$$

P_w = density of H_2O (.998 kg/m³)

R_g = gas constant (8.314 J/mol·K)

T = absolute temp. (273 + temp. °C)

M = molecular mass of H_2O (18.0 g/mol)

$$S(bar) = 1350 \ \ln\left(\frac{100}{RH}\right) \ at \ 20°C$$

1 bar ≡ 100 kPa

RH (%)	S (bar)	S (atm)	
50	936	924	
90	142	140	} very strong attraction!
99	13.6	13.4	

2) Mechanisms of Water Vapor Adsorption (CCL 1.322; Chap.6 of Mitchell 1993)

a) H-bonding   ⎫ Probably most
b) Cation hydration ⎬ important

Cation	Hydrated Dia (Å)
K^{+1}	9 ± 2.5
Na^{+1}	13.5 ± 2
Ca^{+2}	19
Mg^{+2}	21.5

c) Orientation of H_2O dipoles
   in electric field (questionable)

d) van der Waals forces

(JKM, 1993, p 122)

3) Physical Properties of "Adsorbed Water" Layer
(Note: Discussion applies to first 10-15 Å of water adjacent to mineral
  surfaces for clays in contact with free water, i.e. with double layers)

· All agree that the structure of this water layer differs from that
  of ordinary water. However, two schools of thought:

1st - Is "ice-like" with a very high viscosity → generation of a
       cohesive strength that is responsible for creep effects

2nd - Is more like a 2-D liquid similar to ball bearings on a
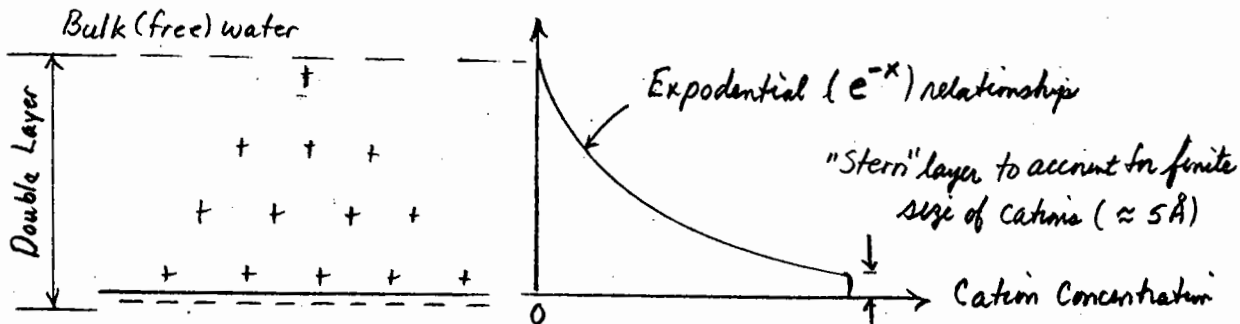   magnetic surface (R.T. Martin of MIT).
       Therefore does not contribute to strength
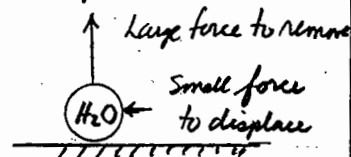
BOTH: Layer inhibits mineral to mineral contacts

↑ Large force to remove
H_2O ← Small force to displace

2.2 Diffuse Double Layer (DL)

1) Clay Particles in Pure Water   (+ = exchangeable cation)

Bulk (free) water

Double Layer

Expodential (e^{-x}) relationship

"Stern" layer to account for finite
size of Cations (≈ 5Å)

Cation Concentration

0

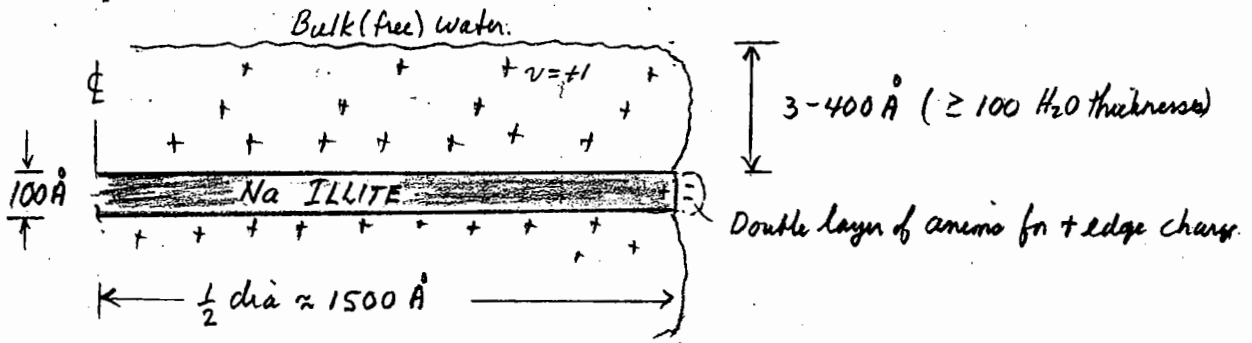· Balance between thermal energy of cations and the electrical attraction
  between the cations and the negative surface charge

Bulk (free) water.

¢ $+ \quad v = +1$

3-400 Å (≥ 100 H₂O thicknesses)

100Å

Na ILLITE

Double layer of anions for + edge charge.

$\frac{1}{2}$ dia ≈ 1500 Å

Development of the double layer is the most important mechanism of clay-water attraction at water thicknesses > 10-15 Å

2) Effect of Pore Fluid Chemistry on Double Layer Thickness

     a) Thickness <u>decreases</u> with:

- Increasing cation valence (v) : $\propto 1/v$

- Increasing salt conc. in bulk water (c_o): $\propto 1/\sqrt{c_o}$

- Decreasing dielectric constant (D): $\propto \sqrt{D}$

     b) Example calculations (see p7a for definition of Debye length)
        $T = 20°C$

Pore Fluid	Dielectric Constant (D)	Cation Valence & Bulk Conc. (c_o, M)		Debye Length (t_D, Å)	
Water	80	NaCl	10^{-4}	305	
		"	10^{-3}	96	$\times \frac{1}{10}$
		"	10^{-2}	30	$\times \frac{1}{2}$
		"	10^{-1}	10	
		CaSO₄	10^{-3}	48	
Alcohol	20	NaCl	10^{-4}	152	$\times \frac{1}{2}$ vs. H₂O
		"	10^{-2}	15	
CCl₄	2	NaCl	10^{-4}	48	
		"	10^{-2}	5	

3) Debye Length and Related Phenomena.

[from J.K. Mitchell (1993 book) & Shang et al. (1994, CGJ 31(5)]

a) Equation for Debye length, t_D (measured from Stern layer)

$$t_D = \left(\frac{\varepsilon_0 \, D \, k \, T}{2 \, n_0 \, q_c^2 \, v^2} \right)^{0.5}$$

where

ε_0 = permittivity of vacuum (8.854×10^{-12} C²/J·m)

D = dielectric constant (see below)

k = Boltzmann constant (1.38×10^{-23} J/°K)

T = temperature (°K = 273 + °C)

n_0 = bulk cation conc. (number/m³)

q_c = electronic charge (1.60×10^{-19} C)

v = cation valence

$$\downarrow$$

$$t_D(\overset{\circ}{A}) = \frac{0.020}{v} \sqrt{\frac{D \cdot T}{C_0}}$$

where C_0 = cation concentration in bulk water in moles/liter (M = molar)

b) The Debye length is commonly used as a measure of the DL thickness and is the distance between a parallel plate condenser having the same surface charge density (σ_0) and electric potential (V = volts).
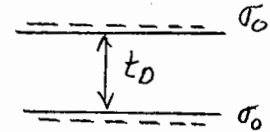
c) Dielectric constant, D

• Force (F) between two electric charges (Q, Q') separated by a distance d

$$F = \frac{Q \, Q'}{\varepsilon \, d^2}$$

where   ↙ for vacuum

ε = permittivity = $\varepsilon_0 \cdot D$

= ease with which molecules can be polarized and oriented in an electric field

• Polar molecules like H_2O (high D) → less force of attraction between DL cations & the negative surface charge → expanded DL
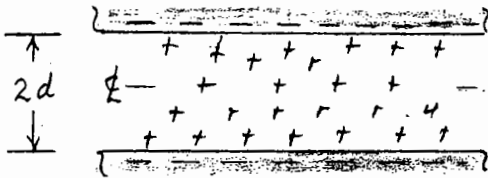
| Fluid	D (At Room Temp)
Water (H_2O)	80
Ethyl Alcohol (C_2H_6O)	24

2.3 Double Layer Repulsion (for infinite parallel particles)

1) Consider two parallel clay particles in pure water

Repulsion between 2 particles is caused by fact that H_2O molecules want to enter the double layer in order to reduce the concentration of cations.

2) Is exactly analogous to development of an Osmotic Pressure, (P_o)

Semi-permeable membrane
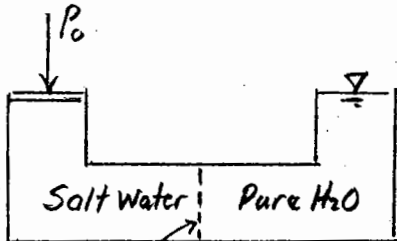
From ideal gas law $(PV = n R_g T)$

$$P_o = R_g T \left(\Delta \text{ ion concentration}; \begin{array}{c} \text{cations} \\ \text{+ anions} \end{array} \right)$$

$R_g = 8.314 \ J/mol\text{-}°K$

$\quad = 0.08205 \ liter\text{-}atm/mol\text{-}°K$

For $T = 293°K = 20°C$

$\therefore P_o (atm) = 24 \left(\Delta \text{ conc.}, M = mol./L; \begin{array}{c} \text{cations} \\ \text{+ anions} \end{array} \right)$

Salt Conc. (M)	10^{-3}	10^{-2}	10^{-1}	1
P_o (atm)	0.024	0.24	2.4	24

3) Values of DL repulsion (P_r) from Gouy-Chapman theory with Correction for Stern layer : See Fig II 2-1 for detailed plot
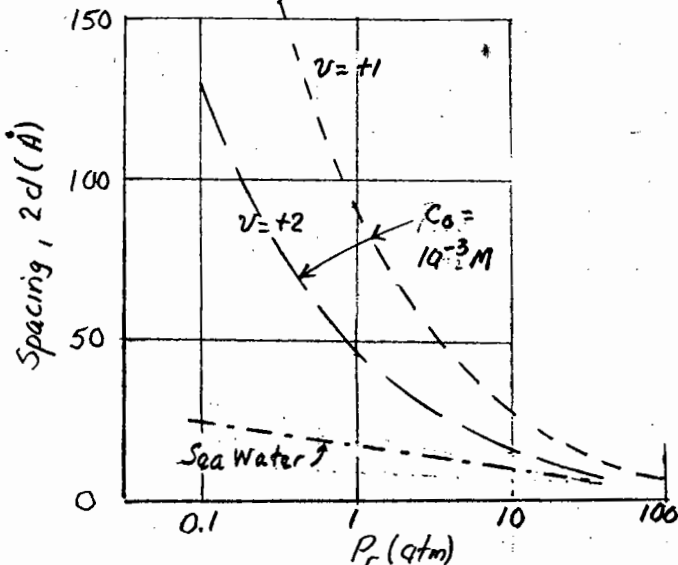
For $c_o = 10^{-3}$ Molar

P_r (atm)	$2d(\text{Å})$	Valence	
1	90	+1	←
4	45	"	} $\times \frac{1}{2}$ spacing
10	30	"	
1	45	+2	←

Very low P_r for sea water
$(35 \ g/l \ salt \approx 1.1 \ M; \ c_o \approx 0.6 \ M)$

Supplement on Double Layer Repulsion

<u>Single Double Layer:</u> Ion conc vs. distance   Na & Ca Montmorillonite

From Mitchell (1993)
Figs. 7.8 & 7.11

— NaCl
‑ ‑ Ca X

t_D = Debye thickness
= 333 Å Na
= 167 Å Ca

$n_c = n_a$ $C_0 = 0.83 \times 10^{-4} M$

$\times 6 \times 10^{23} \times \frac{1}{1000}$

"

5×10^{16}

M = moles/l
"
6×10^{23} anions &
cations
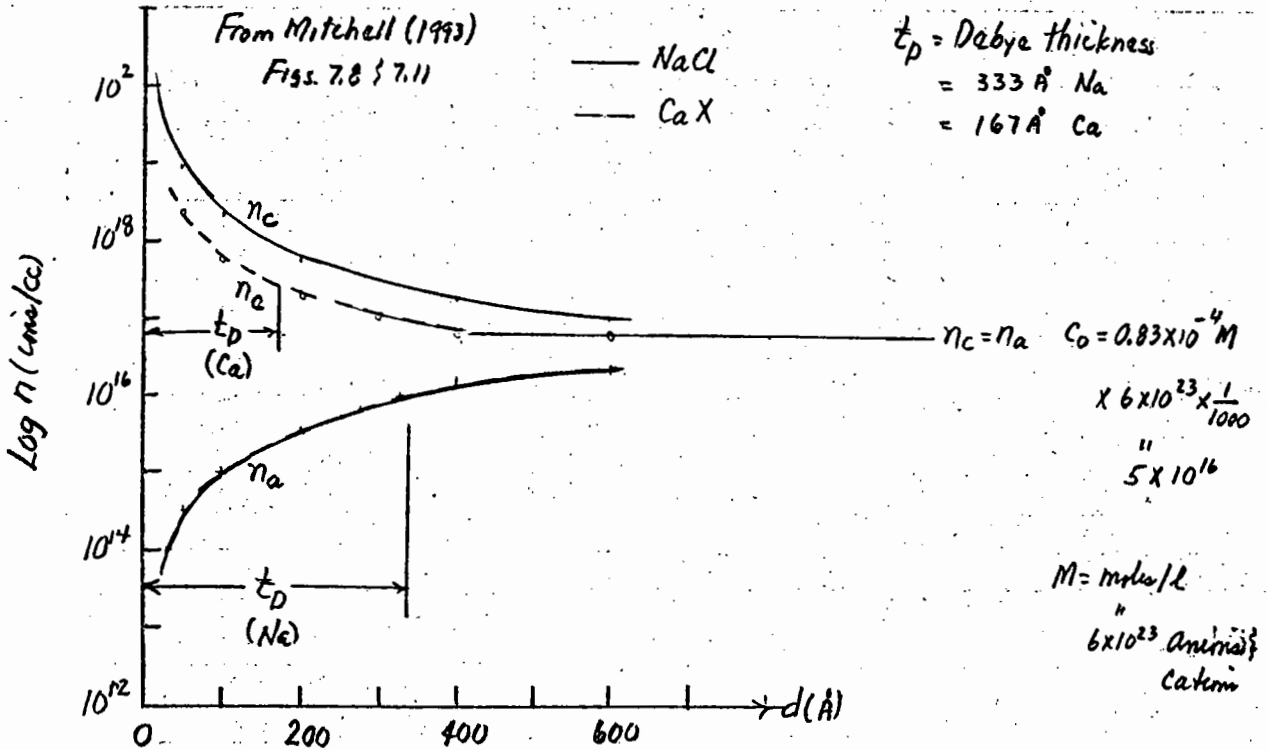
<u>Interacting Double Layer</u> (valence $v = v_c = v_a$; C_0 = bulk concentration, M = moles/l)
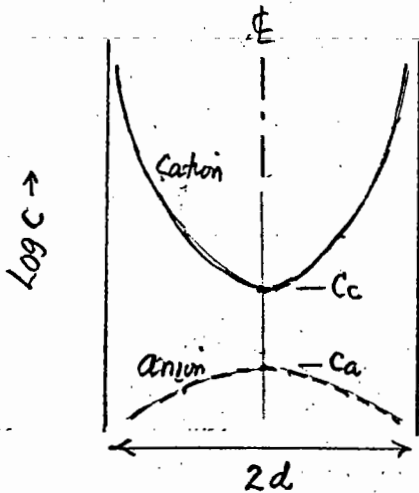
$P_r = R_g T \, (\underbrace{C_c + C_a}_{\text{mid-plane}} - \underbrace{2 C_0}_{\text{Bulk}})$

$T = 273 + °C$

$R_g = 8.314 \frac{J}{mol. °K}$

$C = M, moles/l$

$$\boxed{P_r(bar) = 24.37 \, (C_c + C_a - 2 C_0) \quad \text{at } 20°C, \, D = 80 \text{ for } H_2O}$$

Fig 2-1
1.361 Part II-2

C_0(M)	v	$2d$(Å)	P_r(bar≈atm)	
10^{-3}	1	200	0.2	$C_0 \to 0.06$ g/l NaCl
		100	0.8	
		50	3.3	
		25	12	
10^{-3}	2	100	0.2	≈ ½ spacing
		50	0.8	
		25	3.3	
0.1	1	50	0.6⁻	large conc. at larger spacings
		25	7	
	2	25	0.6	

2.4 Other Clay-Water Forces

1) Van der Waals Attraction (short to long range)

    a) For parallel particles $P_a = \dfrac{A''}{48\pi}\left[\dfrac{1}{d^3} + \dfrac{1}{(d+\delta)^3} - \dfrac{2}{(d+\delta/2)^3}\right]$

      A'' = Hamaker constant $\approx 2.5\times10^{-20}$ J (Novich & Ring 1984)

 δ = particle thickness   See Fig II 2-1 for plot for $\delta = 100\text{Å}$ (illite)

    b) Compared to double layer repulsion for clay-water systems

      • For very low salt concs., $P_r > P_a$ → particles repel each other during sedimentation

      • For sea water, $P_r < P_a$ → <u>flocculation</u>   sedimenting floc

2) Edge-to-Face Electrical Attraction (short to medium range)

    Sketch for 2 particles in water with pH ≤ 7

Electrostatic plus to menisi attraction

DL repulsion
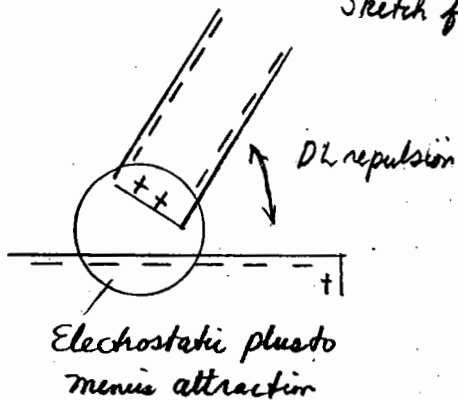
    • Can provide very substantial attraction between particles (esp. Kaolinite)

    • Add dispersant (large anion : TSPP) to clays to neutralize positive edge charge to prevent flocculation during hydrometer tests

    • Increasing pH → less positive edge charge (or even goes negative) → reduced attraction (or even repulsion)

3) For Mineral to Mineral Contact Between Particles

    a) Attraction due to primary valence bonding (covalent & ionic)

    b) Born repulsion which prevents interpenetration of matter

2.5 Physico-Chemical Effective Stress Equation (Ladd 1961)

1) Physical Model

- Look at how effective normal stress is transmitted between two particles per unit area

- Assume interparticle __contacts__ at spacing $2d \leq 20 \text{Å}$ (somewhat arbitrary)

- a_c = contact area ratio = Contact area per unit area
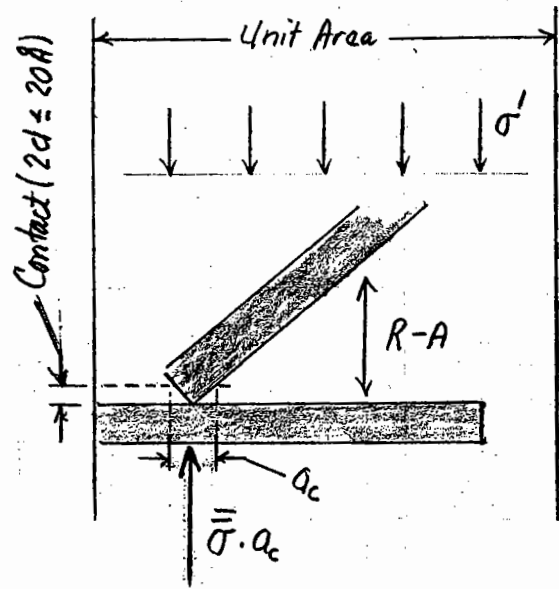
2) Equation for Components of Effective (normal) stress, $\sigma' = \sigma - u$

$$\sigma' = \text{Net Contact Stress} + \text{Net Long Range Stress}$$

$$= \bar{\bar{\sigma}} \cdot a_c + (R-A) = (\bar{\bar{\sigma}}_r - \bar{\bar{\sigma}}_a) a_c + (R-A)$$

- R = double layer (osmotic) repulsion = $f(P_r)$

- A = long range van der Waals attraction = $f(P_a)$

$\bar{\bar{\sigma}}$ = contact repulsive stresses $(\bar{\bar{\sigma}}_r)$ - contact attractive stresses $(\bar{\bar{\sigma}}_a)$

- $\bar{\bar{\sigma}}_r$ = resistance due to displacement of "adsorbed water"

  + Born repulsion (if mineral to mineral contact)

- $\bar{\bar{\sigma}}_a$ = short range van der Waals attraction = $f(P_a)$

  + edge-to-face electrostatic attraction

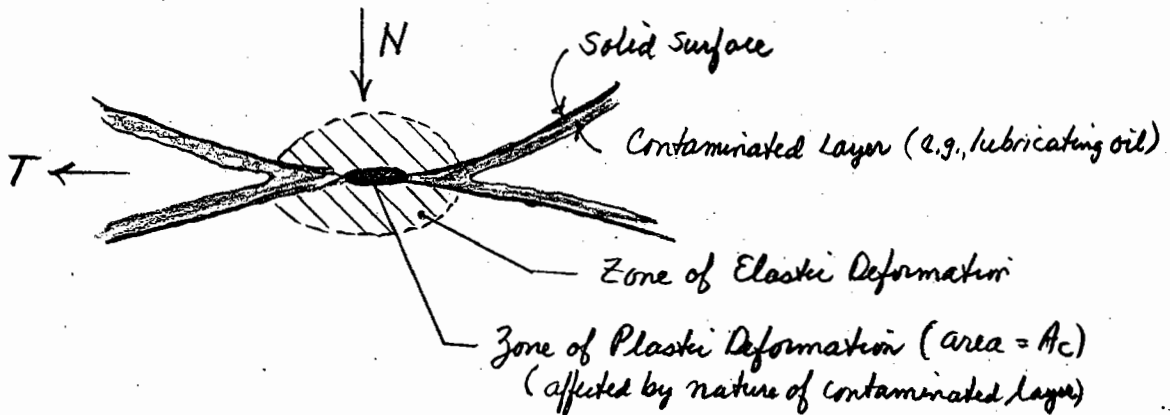 + primary valence bonding (if mineral to mineral contact)

2.6 Strength Generation in Soils

2.6.1 Frictional Resistance

1) Terzaghi-Bowden-Tabor <u>Adhesion</u> theory (developed for metals)
   (1940s)

All surfaces are rough at microscopic scale. Therefore
get contacts at asperities

Normal force = $N = A_c \cdot \bar{\bar{\sigma}}_y$, where $\bar{\bar{\sigma}}_y$ = yield stress

Shear force = $T = A_c \cdot \bar{\bar{\tau}}$, where $\bar{\bar{\tau}}$ = shear strength due to primary valence bonding

Increasing $N \rightarrow$ increasing $A_c \rightarrow$ increasing T $\left.\begin{array}{c} \\ \\ \end{array}\right\}$ Constant coef. of friction $= T/N$

Decreasing $N \rightarrow$ decreasing A_c due to elastic rebound $\rightarrow$ decreasing T $\qquad = \bar{\bar{\tau}} / \bar{\bar{\sigma}}_y = \tan\phi'_\mu$

• Tests on Quartz by Bromwell (1966)

Ultra smooth surfaces, $\phi'_\mu = 10 - 35°$ is function of surface contamination

Regular, rough surfaces, $\phi'_\mu = 25 \pm 5°$ independent of contamination

2) Granular Soils

$$\sigma' = \bar{\bar{\sigma}} \cdot a_c \text{, where } \bar{\bar{\sigma}} \approx 10,000 \text{ atm at typical stress levels}$$

(For $\sigma' = 1$ atm, $a_c = 0.01\%$)

3) Cohesive Soils

   a) Are there mineral to mineral contacts in clays at typical
      σ' levels (say $\sigma' \geq 1$ atm)?

     , Ladd (1961) back calculated likely values of contact shear
       stresses $\to \bar{\bar{\tau}} \approx 100's$ of atm. $\therefore$ must have primary valence bonding
                              at min.- min contacts

     • Mitchell (1993 book), but based on research in 1960's using
       rate process theory $\to$ activation energy of bonding

Material	Activation Energy ($kcal/mol$)	
Water	4-5	Calorie $\times 4.2 = J = N \cdot m$
Ice	10-15	
Metals & Concrete	≥ 50	
Soil	30 ± 5	Sands & clays, both wet & dry !

   b) Conclusion: clays develop a frictional resistance (ϕ') due to
     primary valence bonding at contacts. However, get wide variation
     in ϕ' due to wide variation in $\bar{\sigma} \cdot a_c / \sigma'$ ratio (Section 3.2)

2.6.2 Cohesive Resistance (True Cohesion)

   1) Very controversial since difficult to measure or even define

   2) However one can list potential sources of true cohesion

     a) Cementation due to carbonates, Fe/Al oxides, amorphous silica
      • Difficult to quantify, but certainly occurs $\to$ brittle behavior
        Calcareous sands, calcareous clay shales, Champlain clay,

     b) When physico-chemical $\bar{\bar{\sigma}}_a > \bar{\bar{\sigma}}_r$, so that added energy
      required to break contacts during shearing (Energy diagrams)

     c) Adsorbed water ?? Some still promote "ice-like" behavior

     NOTE: Unconfined shear strength of ovendried remolded clay can be
      high. Can't be due to adsorbed water ; must be caused
      by $\bar{\bar{\sigma}}_a > \bar{\bar{\sigma}}_r$

3. SOIL STRUCTURE: EFFECTS OF MINERALOGY AND ENVIRONMENTAL FACTORS

3.1 Clay Fabric

Refers to orientation and distribution of particles; distinguish between fabric at macro-level & micro-level.

1) Macro-Level (Illustrated via radiographs in class)

Radiography measures changes in soil density and is ideally suited for detecting features such as:

- Varved deposits = alternating layers of "silt" (summer deposition) and "clay" (winter deposition) in fresh water, glacial lake deposits

- Distribution of silty/sandy layers/lens in sedimentary deposits
                                                    (Arctic silt)
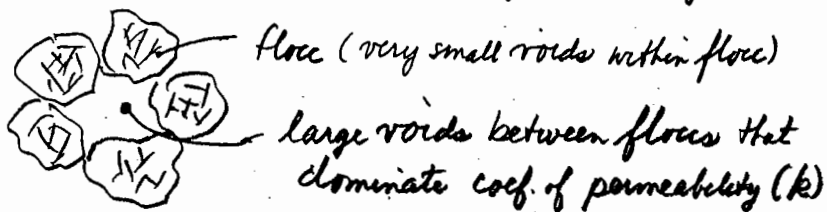- Pattern of fissuring

○ Presence of shells, stones, etc.

NOTE: Also excellent for detecting evidence of sample disturbance.
MIT x-rays all tube samples prior to testing → best quality
                                              → most representative

2) Micro-Level

a) Methods of measurement   (1) Scanning electron microscope (SEM)
                                → "picture" (down to ≈10Å, but must dry)
   (2) x-ray diffraction → orientation of platy particle
   (3) pore size distribution from Hg intrusion (also must dry)

b) Most sedimentary cohesive soils are composed of floccs =
   group of particles that stuck together during sedimentation

   — flocc (very small voids within flocc)

   — large voids between floccs that dominate coef. of permeability (k)

c) Effects of sediment environment on fabric of flocs (illitic clays)

- Sedimentation in fresh water ($R > A$) →

    "Dispersed" fabric - small flocs with semi-parallel particles

- Sedimentation in sea water ($R < A$) →

    "Flocculated" fabric - large flocs with edge to face orientation

d) Effects of application of stresses

- 1-D compression → preferred orientation of plates ⊥ to σ'_{vc} direction

- Shearing → <u>breaking of contacts</u> and preferred orientation
    of plates parallel to τ_{ff}

Data on kaolinite from x-ray diffraction (Martin & Ladd 1975)

Effect of initial preparation
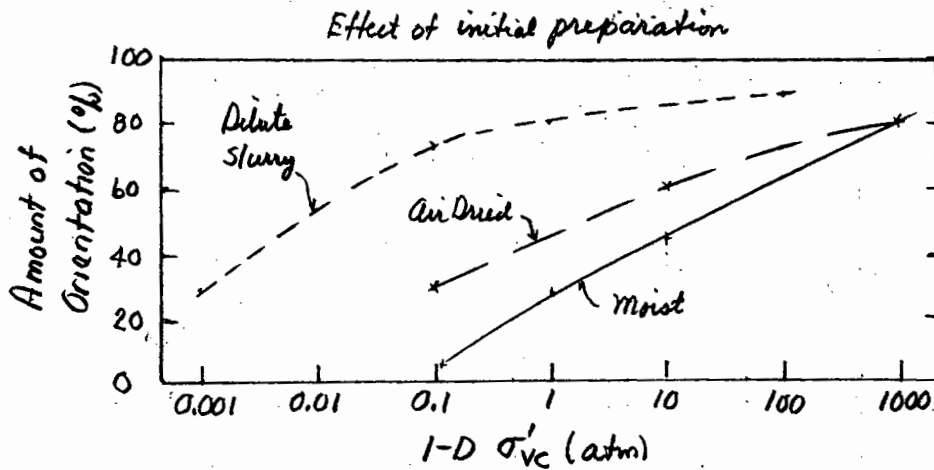
∴ Initial fabric has a large effect on the <u>rate</u> of
particle reorientation during 1-D compression

3.2 Structure of Different Clay Minerals and Influence of Environmental Factors

3.2.1 Montmorillonite

1) Na in pure water

300Å

$t = 10 \text{Å}$

$\longleftarrow 1000 \text{Å} \longrightarrow$
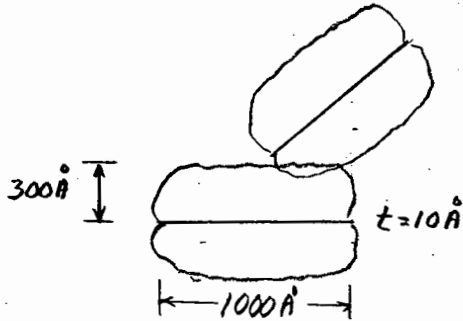
- Overlapping DL inhibits contacts and lead to parallel plate orientation

- After 1-D compression to 50 atm,
  $$\sigma'_{vc} = R - A \approx P_r \quad (\text{à la Fig. II.2-1})$$

- Hence very low shear strength ($\phi' < 5°$) due to very low $\bar{\bar{\sigma}} \cdot a_c / \sigma'$ ratio

2) Effect of pore fluid chemistry

- Ca^{+2} exchangeable cations → $\begin{cases} \text{reduced } R-A \\ \text{domains}^* \end{cases}$

  $$\sigma' = \bar{\bar{\sigma}} \cdot a_c + (R-A) \; ; \; \text{increased } \bar{\bar{\sigma}} \cdot a_c \rightarrow \text{higher } \phi' \; (\approx 10\text{-}15°)$$

- Increasing $\underset{\wedge}{\text{NaCl}}$ salt concentration has a similar effect
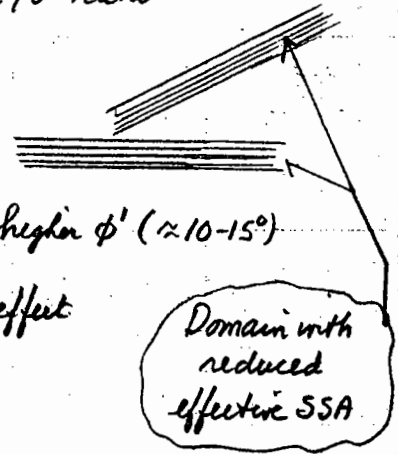
3) Smectites in general

- Major mineral in expansive clays

- Swelling potential & ϕ' greatly affected by factors that influence the DL repulsion (R), ie. - cation valence and interlayer swelling   salt concentration   dielectric constant

Domain with reduced effective SSA

$*$ Domain = particle composed of several parallel layers ($t = 10\text{Å}$) separated by $2d \leq 9\text{Å}$; this occurs because Ca^{+2} acts as a weak glue that prevents further expansion between layers.

3.2.2 Kaolinite

1) Particles in pure H_2O ($pH \leq 7$)

10,000Å

1000Å

$DL \approx 400$Å

Negligible interaction between double layers
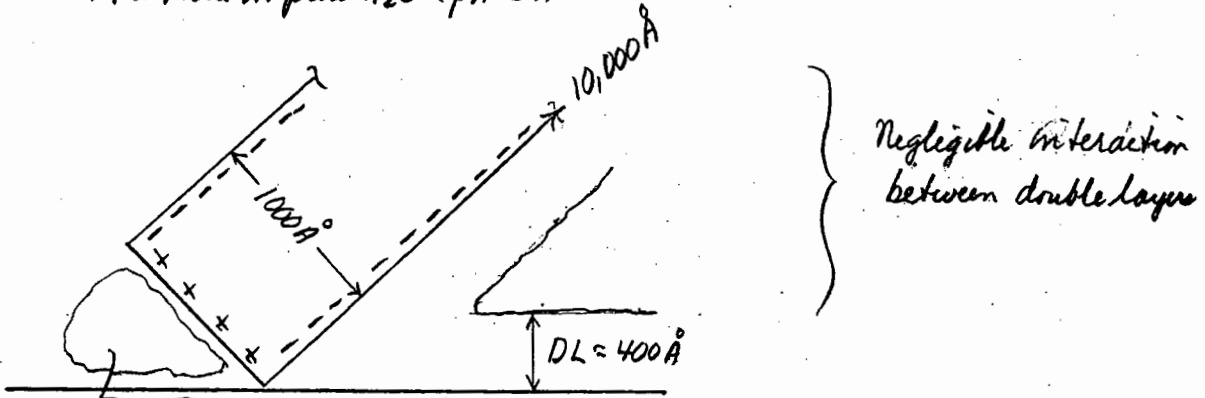
Get very strong edge-to-face electrostatic attraction
(as exchangeable cations & anions migrate away)

2) All of σ' carried by contacts → $\sigma' = (\bar{\bar{\sigma}}_r - \bar{\bar{\sigma}}_a) a_c$

3) Pore fluid chemistry that alters $\bar{\bar{\sigma}}_a$ electrostatic attraction very important
   - Incr. pH → less + edge charge → smaller $\bar{\bar{\sigma}}_a$ (less cohesion)
   - Large anions (TSPP) can neutralize + charge → zero attraction
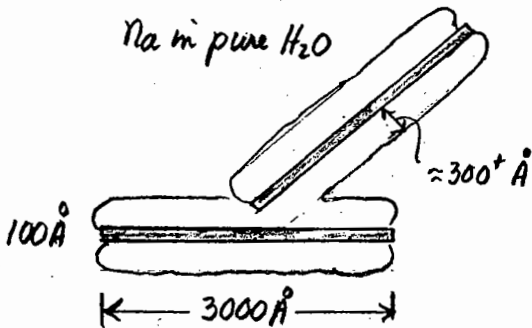   - Increasing salt conc. reduces electric field → smaller $\bar{\bar{\sigma}}_a$

4) Engineering properties
   - $\phi' \approx 25-30°$
   - 1-D compression $pH = 7 → e = 1.35$ at $\sigma'_{vc} = 1$ atm
     (Olsen 1961)   add TSPP → $e = 0.8$ " " ^

3.2.3 Illite

1) general

Na in pure H_2O

$\approx 300^+$ Å

100Å

3000Å

- Intermediate between Mont. & Kaol.
  $$\sigma' = (\bar{\bar{\sigma}}_r - \bar{\bar{\sigma}}_a) \cdot a_c + (R - A)$$
  Both components important

- Friction angle, ~3μm, $I_p = 50\%$ (Olson 1974)

  Na $\phi' \approx 16° → 20°$ w/ incr. salt concentration
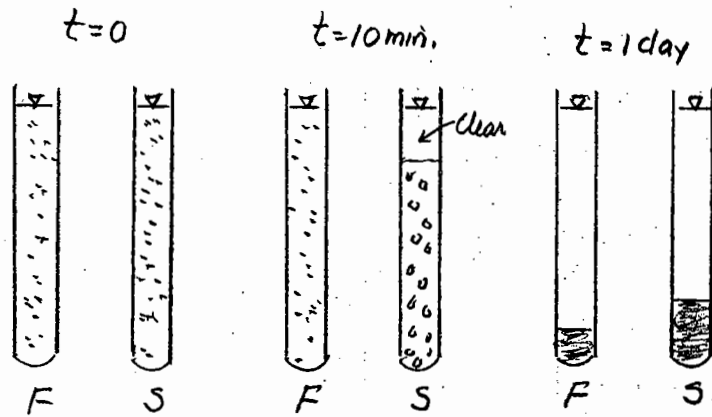
  Ca $\phi' \approx 25°$ indep. of salt conc.

2) Deposition of Na illitic clay in fresh vs. sea water and
effect of leaching

• Sedimentation behavior in test tubes

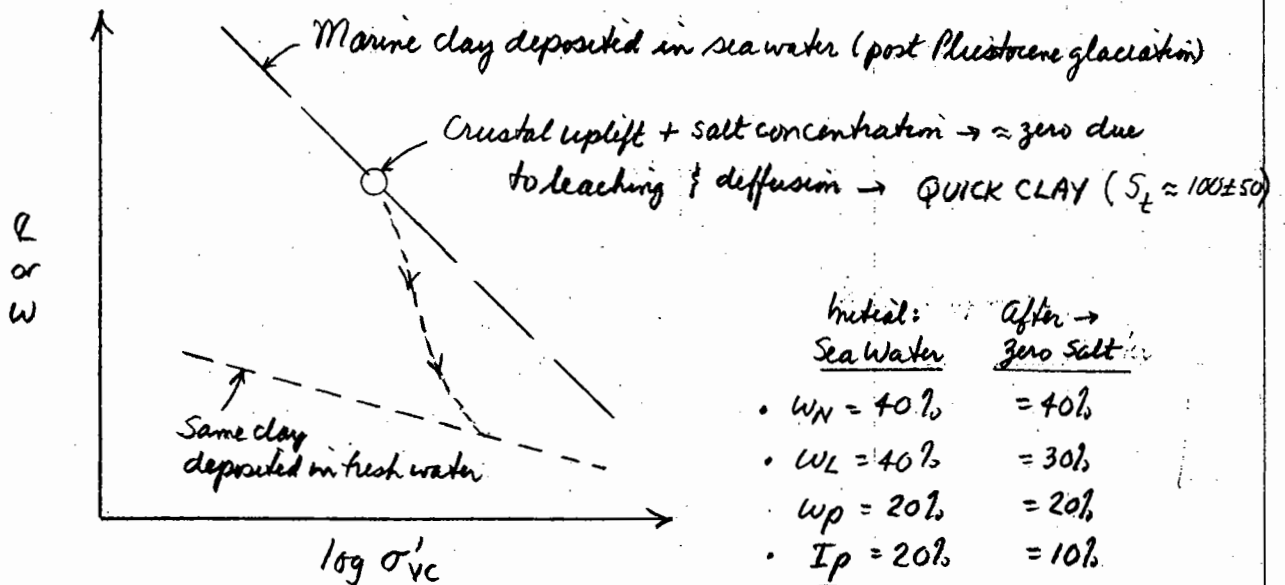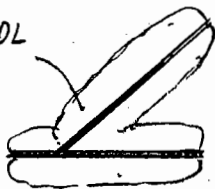F = fresh water ($R > A$)
S = sea water ($R < A$)
($35 g/\ell \approx 1.1 M$; $C_0 \approx 0.6$)

$t = 0$ $t = 10$ min. $t = 1$ day

← Clear

F   S   F   S   F   S

Fresh → "Dispersed"

Sea → "Flocculated"

Large floc dia →
faster sedimentation

Marine clay deposited in sea water (post Pleistocene glaciation)

Crustal uplift + salt concentration → ≈ zero due
to leaching & diffusion → QUICK CLAY ($S_t \approx 100 \pm 50$)

R
or
W

Same clay
deposited in fresh water

$\log \sigma'_{vc}$

	Initial: Sea Water	After → Zero Salt
• $w_N =$	40%	= 40%
• $w_L =$	40%	= 30%
$w_p =$	20%	= 20%
• $I_p =$	20%	= 10%
• $I_L =$	1.0	= 2.0 → extremely low $s_u (R)$

Metastable Structure

Expanded DL
after
leaching

$\sigma' = \overline{\sigma} \cdot q_c + (R - A)$

$1 = 1 + 0$ Porefluid = sea water

$1 = <1 + >0$ " = fresh water

• 1-D compression → large increase in compressibility
• Undrained shear → breaking of contacts → very low remolded s_u
→ flow slides (Eastern Canada, Norway; photos on 3rd Fl. Bldg 1)

3.3 Summary

1) Physico-chemical effective stress equation

$$\sigma' = (\bar{\bar{\sigma}}_r - \bar{\bar{\sigma}}_a) \cdot a_c \quad + \quad (R - A)$$

Contacts generate
shear resistance

magnitude affects amount of $\sigma' \rightarrow$
contacts & ability to remake contacts
during shear. Also affects initial fabric

2) See p19

3) Changes in pore fluid chemistry affect DL repulsion (R),
$\bar{\bar{\sigma}}_a$ electrostatic attraction, and effective SSA

• Very important influence on soil structure (esp. fabric) during
sedimentation, e.g., fresh vs sea water illitic deposits
Na vs Ca on effective SSA of montmorillonite

• Change in pore fluid after deposition also can be very important
  - reduced salt conc. → more expansive smectite
  - increased pH reduces cohesion of kaolinite
  - leaching of marine illitic clay → quick clay

• Significant difference in $\bar{\bar{\sigma}} \cdot a_c / \sigma'$ ratio of M vs K vs I and hence
  - values of ϕ'
  - effects of change in pore fluid chemistry

• If Δ pore fluid chemistry → Δ Atterberg limits (esp w_L), then
probably change in engr. properties

• Extreme example of change in engr. properties (Fernandez & Quigley 1985, CGJ)
but data plotted by CCL
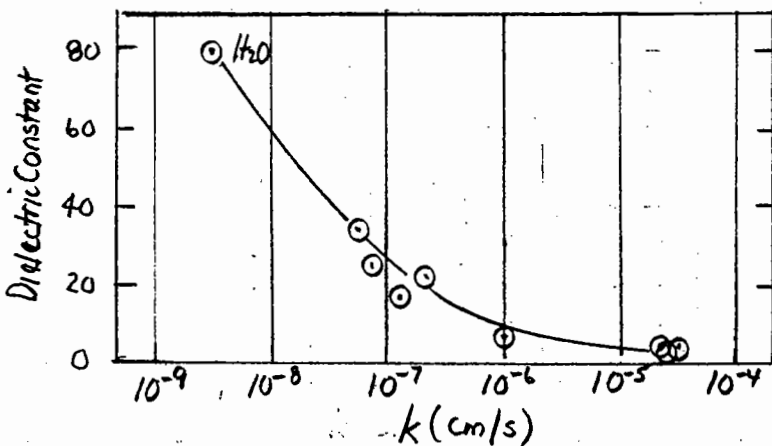
Brown Sarnia Clay (I, C & S)
$w_L = 38$, $I_p = 20.5$
CEC = 33 meq/100g, SSA = 120 m²/g

Samples molded with
pore fluid at $a \approx 0.8$

Results correlate very
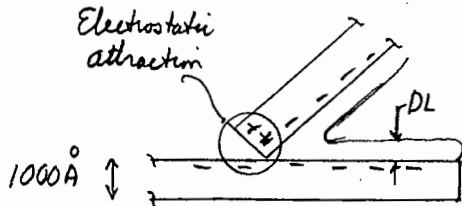well w/ Debye length of DL

Dielectric Constant vs k (cm/s)

3.3 Continued

2) Effect of mineralogy on compressibility and strength of Cohesive soils : look at two extremes

a) Kaolinite (low SSA) in water with $pH \leq 7$

Electrostatic attraction

$1000\overset{\circ}{A}$

$w_L = 65 , I_p = 30$

- $\sigma' \approx \left(\bar{\bar{\sigma}}_r - \bar{\bar{\sigma}}_a \right) a_c$

- Low Compressibility

- High friction angle ($\phi' \approx 25-30°$)

- Evaluate effect of pore fluid on $\bar{\bar{\sigma}}_a$

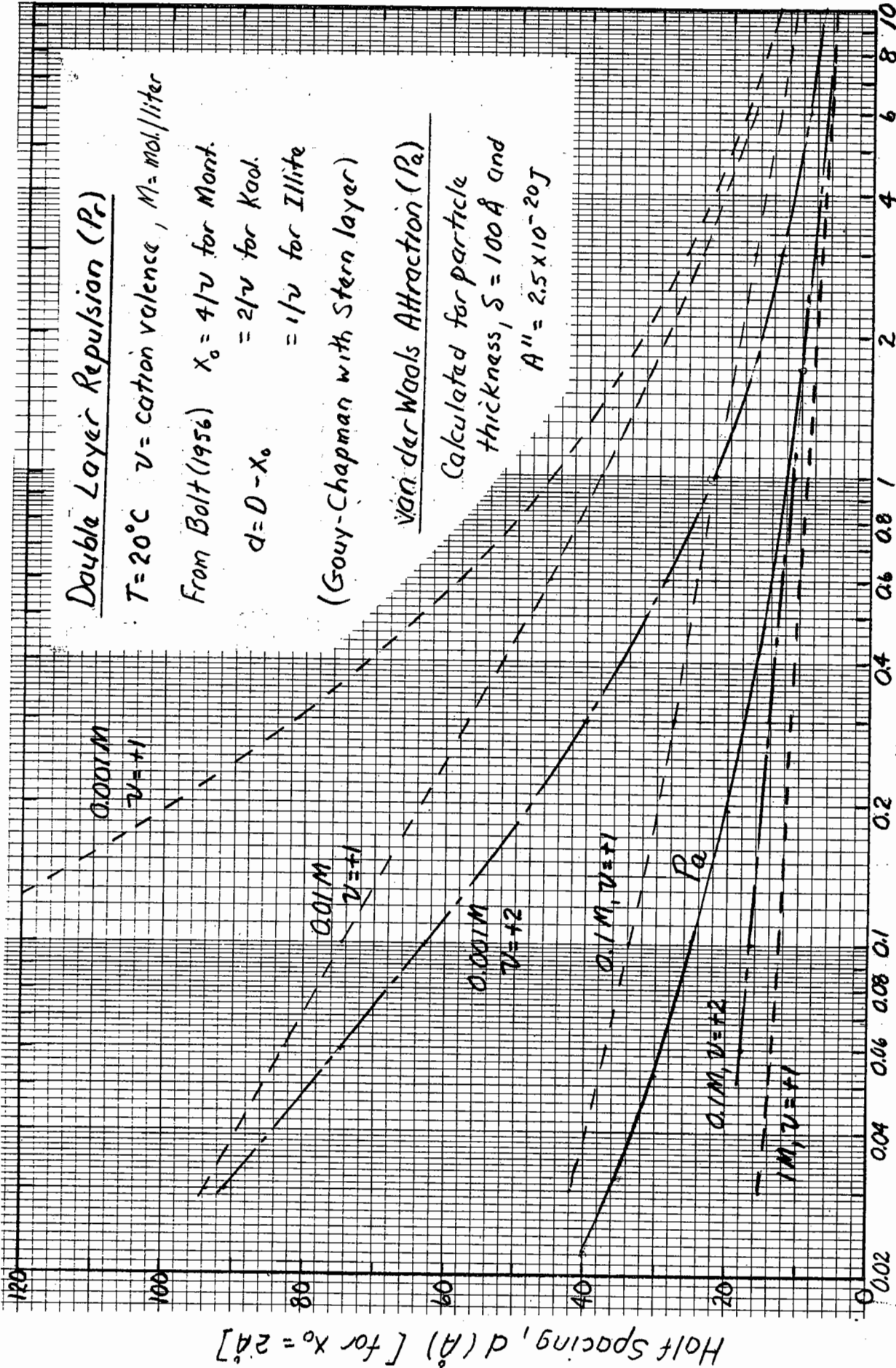b) Na Montmorilonite (v. high SSA) in water

$w_L = 1500$

$I_p = 1450$

- $\sigma' = \bar{\bar{\sigma}} \cdot a_c + (R-A)$

- Very high compressibility

- Very low friction angle ($\phi' \approx 5°$)

- Evaluate effects of pore fluid on R and effective SSA

Fig.II2-1 Double Layer (Osmotic) Repulsion and van der Waals Attraction vs. Half Spacing for Parallel Infinite Plates (after Ladd, 1961 Sc.D Thesis)