CE 468 GEOTECHNICAL DESIGN

LECTURE 3: SITE CHARACTERIZATION

By : Prof. Dr. K. Önder Çetin

Middle East Technical University

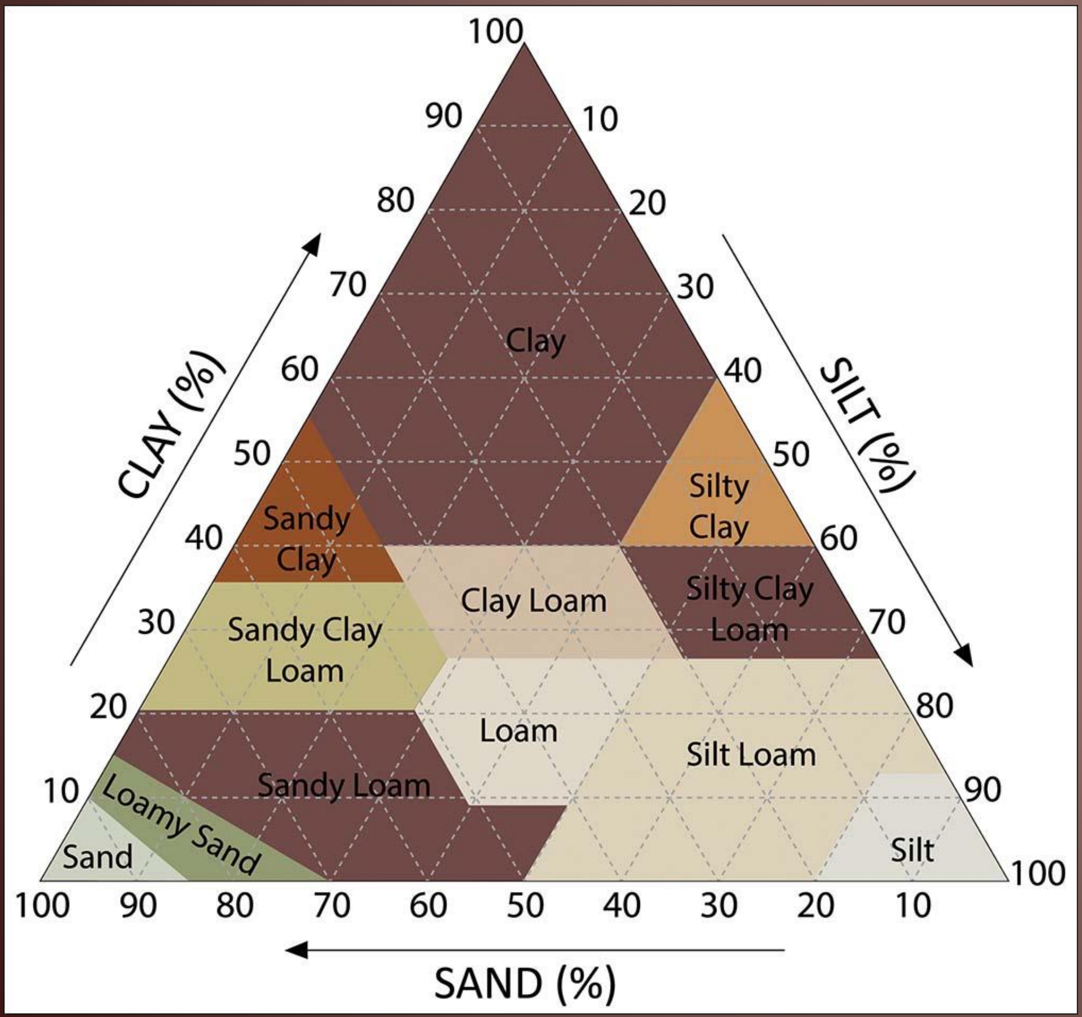
Civil Engineering Department

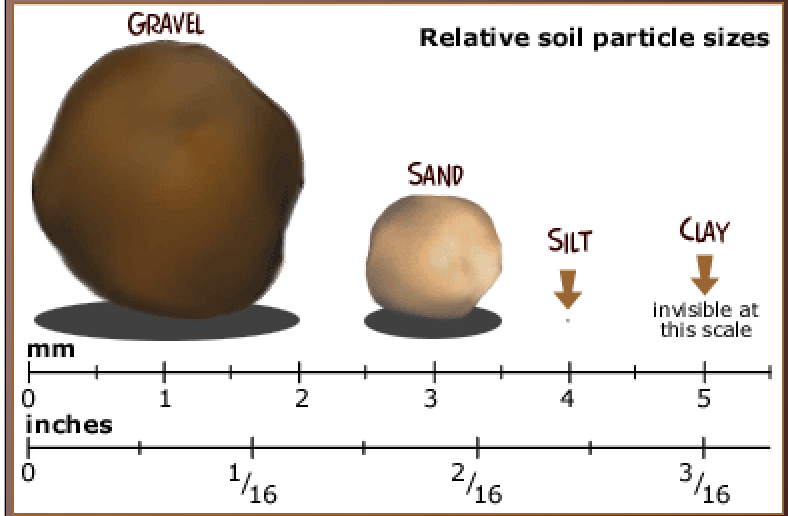
Site Characterization

- Soil classification and idealized soil profiles
- Estimation of soil design parameters:
  - State parameters
  - Undrained and drained shear strength parameters
  - Undrained and drained stiffness parameters
  - Permeability parameters

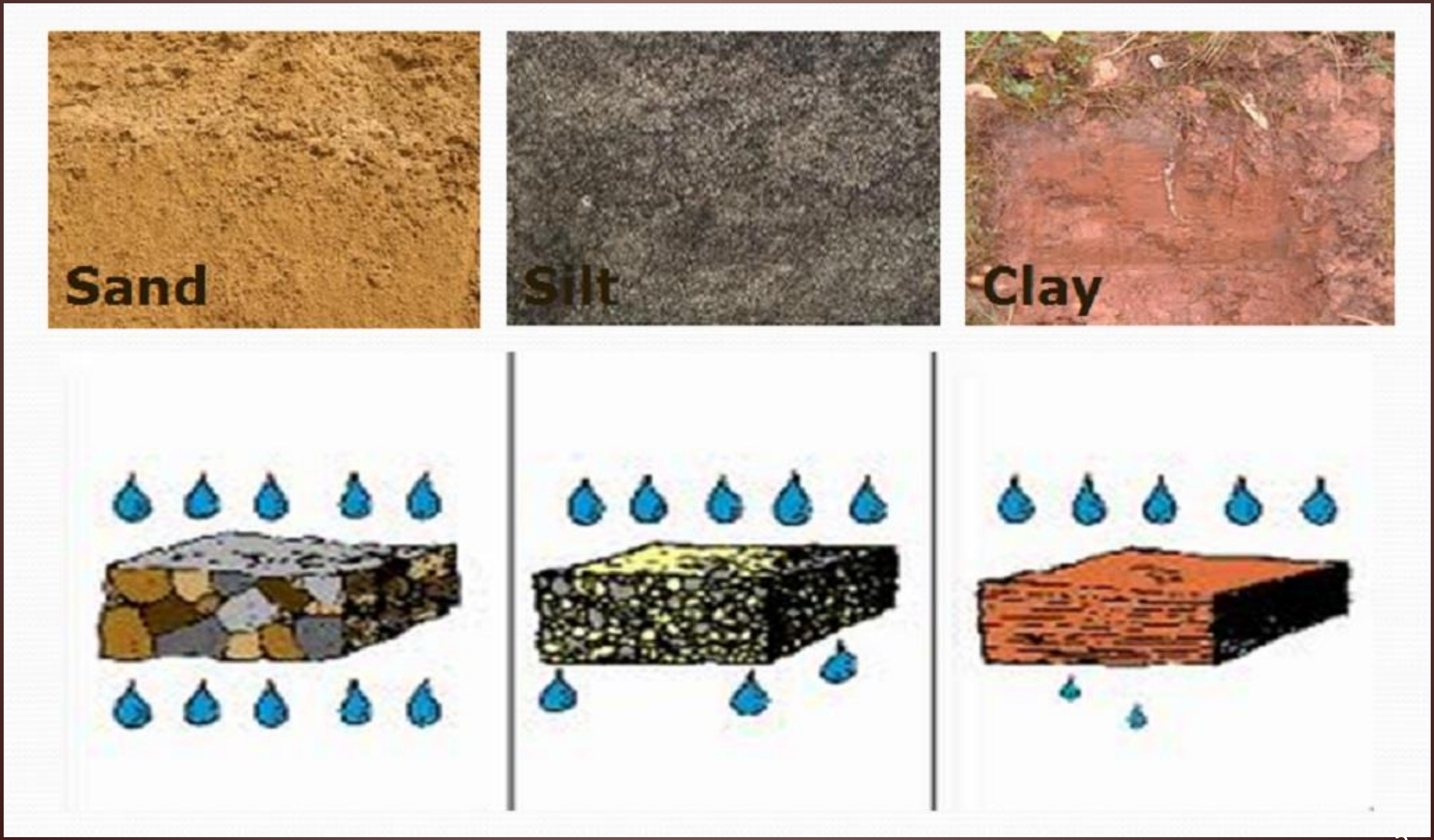
SOIL CLASSIFICATION

SOIL CLASSIFICATION





SOIL CLASSIFICATION



SOIL CLASSIFICATION

UNIFIED SOIL CLASSIFICATION SYSTEM

Name			Group Symbols	LABORATORY CRITERIA: Fines (%)	Grading	Plasticity	Notes
Coarse grained (more than 50% larger than 63 µm BS or No.200 US sieve size)	Gravels (more than 50% of coarse fraction of gravel size)	Well graded gravels, sandy gravels, with little or no fines	GW	0-5	C_u>4 1<C_c<3		Dual symbols if 5-12% fines. Dual symbols if above A-line and 4<PI<7
		Poorly graded gravels, sandy gravels, with little or no fines	GP	0-5	Not satisfying GW requirements		
		Silty gravels, silty sandy gravels	GM	>12		Below A-line *or* PI<4	
		Clayey gravels, clayey sandy gravels	GC	>12		Above A-line *and* PI>7	*Reminder*
	Sands (more than 50% of coarse fraction of sand size)	Well graded sands, gravelly sands, with little or no fines	SW	0-5	C_u>6 1<C_c<3		$C_u=\frac{D_{60}}{D_{10}}$
		Poorly graded sands, gravelly sands, with little or no fines	SP	0-5	Not satisfying SW requirements		$C_c=\frac{D_{30}{}^2}{D_{10}*D_{60}}$ *PI=LL-PL*
		Silty sands	SM	>12		Below A-line *or* PI<4	
		Clayey sands	SC	>12		Above A-line *and* PI>7	

Name			Group Symbols	LABORATORY CRITERIA
Fine grained (more than 50% smaller than 63 µm BS or No.200 US sieve size)	Silts and Clays (liquid limit less than 50)	Inorganic silts, silty or clayey fine sands, with slight plasticity	ML	Use plasticity chart
		Inorganic clays, silty clays, sandy clays of low plasticity	CL	Use plasticity chart
		Organic silts and organic silty clays of low plasticity	OL	Use plasticity chart
	Silts and Clays (liquid limit greater than 50)	Inorganic silts of high plasticity	MH	Use plasticity chart
		Inorganic clays of high plasticity	CH	Use plasticity chart
		Organic clays of high plasticity	OH	Use plasticity chart
Highly organic soils		Peat and other highly organic soils	Pt	Use plasticity chart

Table 1.6

Primary letter		Secondary letter	
G:	Gravel	W:	Well graded
S:	Sand	P:	Poorly graded
M:	Silt	M:	With non-plastic fines
C:	Clay	C:	With plastic fines
O:	Organic soil	L:	Of low plasticity (LL < 50)
Pt:	Peat	H:	Of high plasticity (LL > 50)

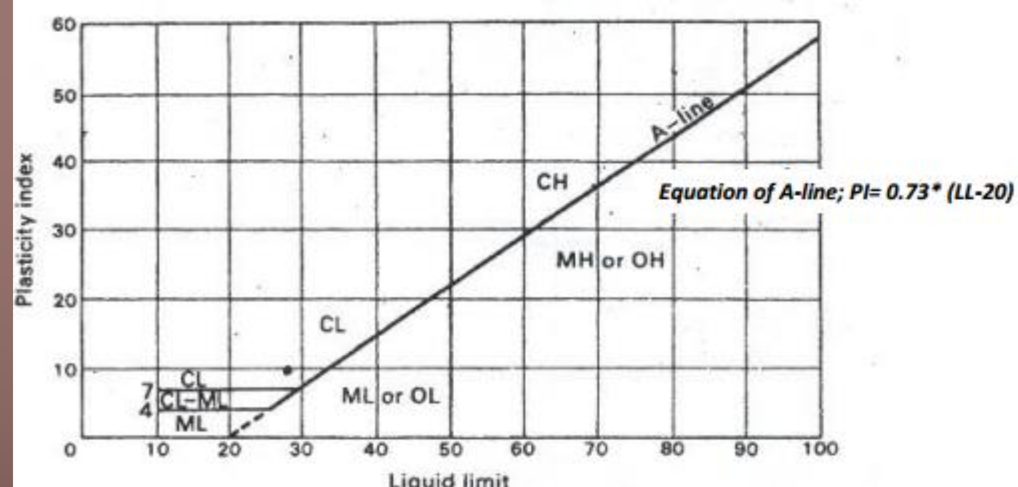


Fig. 1.7 Plasticity chart: Unified system. (Reproduced from Wagner, A. A. (1957) *Proceedings of the Fourth International Conference on Soil Mechanics and Foundation Engineering*, by permission of Butterworth & Co.)

SIEVE ANALYSIS

ATTERBERG TEST

Middle East Technical University

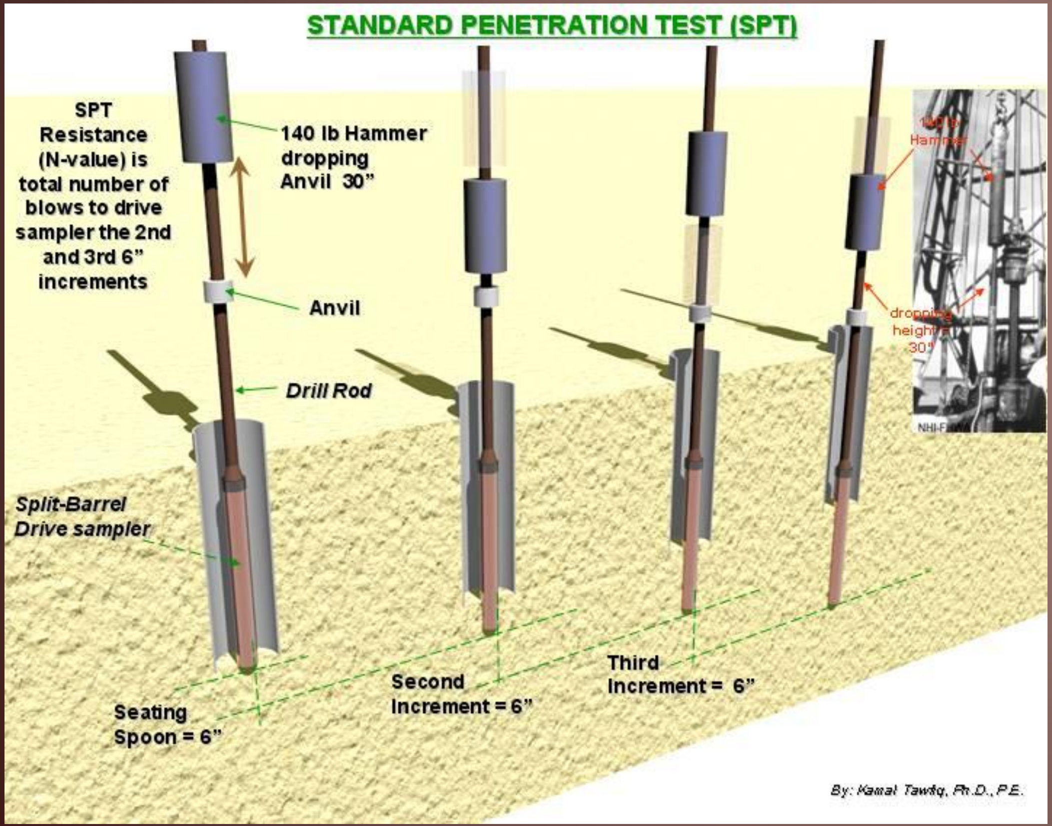
Department of Civil Engineering

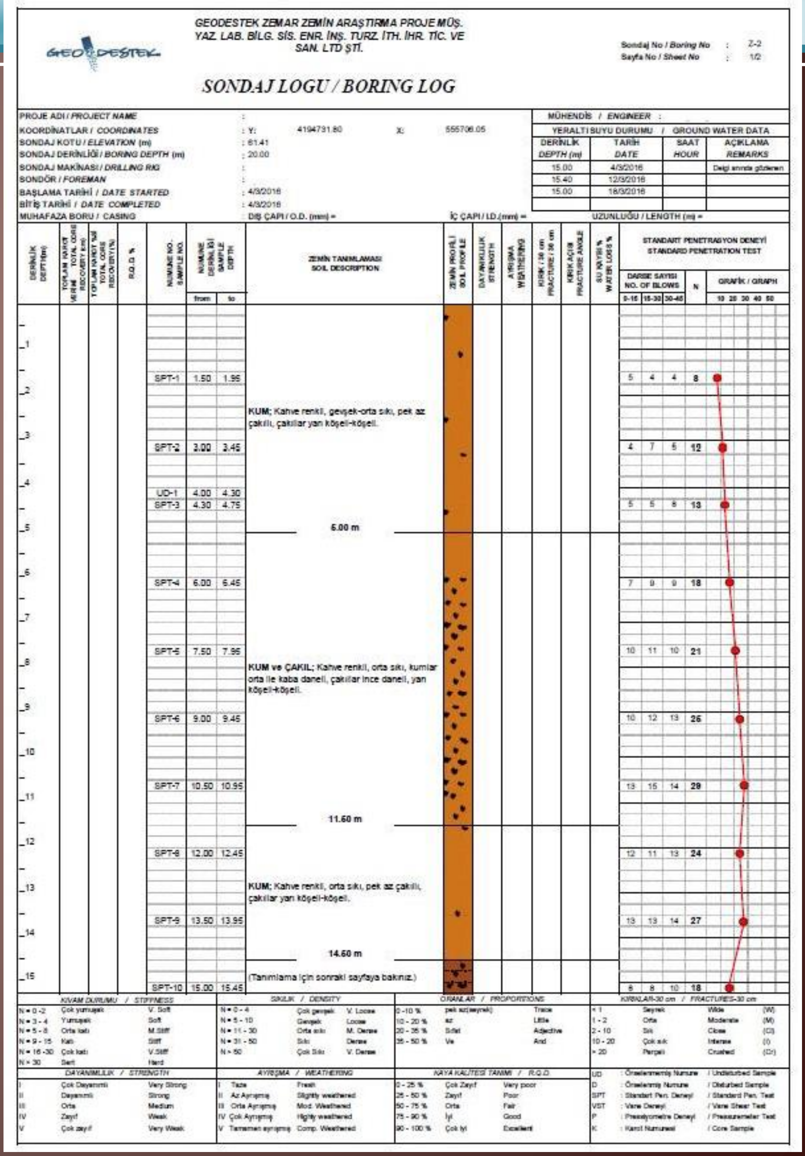
CE363 Soil Mechanics Laboratory

According TS 1900-1/March 2006

Atterberg Limit Test

IDEALIZED SOIL PROFILES





GEODESTEK ZEMAR ZEMİN ARAŞTIRMA PROJE MÜŞ. YAZ. LAB. BİLG. SİS. ENR. İNŞ. TURZ. İTH. İHR. TİC. VE SAN. LTD ŞTİ.

Sondaj No / Boring No : Z-2
Sayfa No / Sheet No : 1/2

SONDAJ LOGU / BORING LOG

PROJE ADI / PROJECT NAME :
KOORDİNATLAR / COORDINATES : Y: 4194731.80 X: 555706.05
SONDAJ KOTU / ELEVATION (m) : 61.41
SONDAJ DERİNLİĞİ / BORING DEPTH (m) : 20.00
SONDAJ MAKİNASI / DRILLING RIG :
SONDÖR / FOREMAN :
BAŞLAMA TARİHİ / DATE STARTED : 4/3/2016
BİTİŞ TARİHİ / DATE COMPLETED : 4/3/2016
MUHAFAZA BORU / CASING : DIŞ ÇAPI / O.D. (mm) = İÇ ÇAPI / I.D.(mm) = UZUNLUĞU / LENGTH (m) =

MÜHENDİS / ENGINEER :

YERALTI SUYU DURUMU / GROUND WATER DATA

DERİNLİK DEPTH (m)	TARİH DATE	SAAT HOUR	AÇIKLAMA REMARKS
15.00	4/3/2016		Delgi anında gözlenen
15.40	12/3/2016		
15.00	18/3/2016		

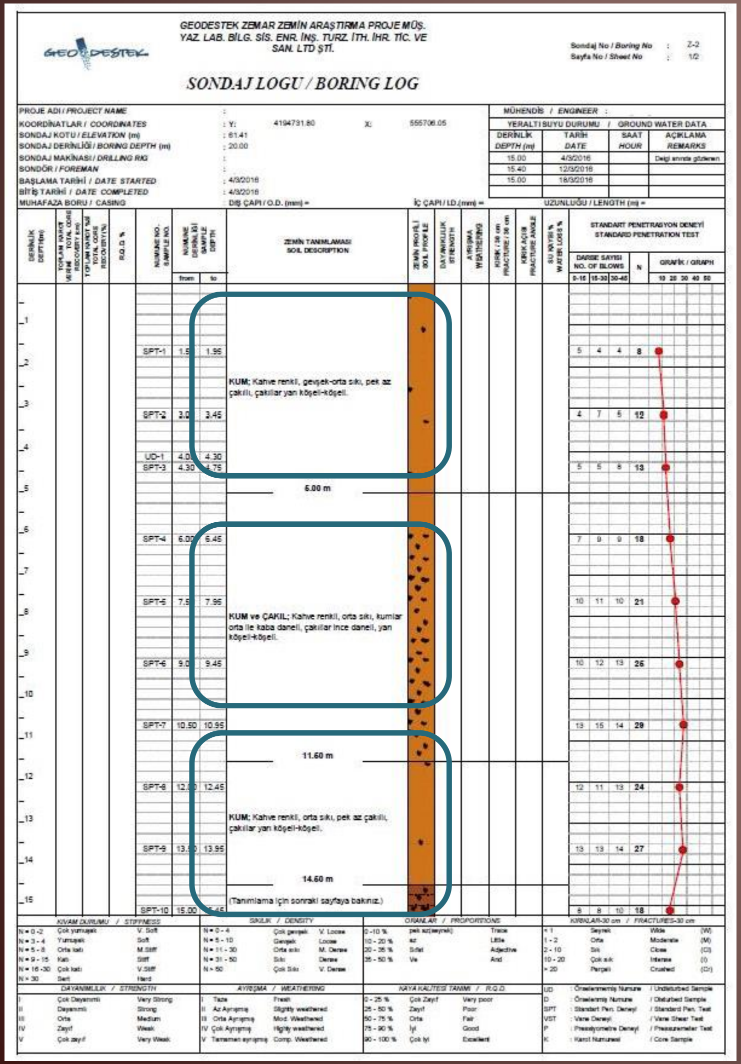
NUMUNE NO. SAMPLE NO.	NUMUNE DERİNLİĞİ SAMPLE DEPTH from	to	ZEMİN TANIMLAMASI SOIL DESCRIPTION	DARBE SAYISI NO. OF BLOWS 0-15	15-30	30-45	N
SPT-1	1.50	1.95	KUM; Kahve renkli, gevşek-orta sıkı, pek az çakıllı, çakıllar yarı köşeli-köşeli.	5	4	4	8
SPT-2	3.00	3.45		4	7	5	12
UD-1	4.00	4.30					
SPT-3	4.30	4.75		5	5	8	13
			5.00 m				
SPT-4	6.00	6.45	KUM ve ÇAKIL; Kahve renkli, orta sıkı, kumlar orta ile kaba daneli, çakıllar ince daneli, yarı köşeli-köşeli.	7	9	9	18
SPT-5	7.50	7.95		10	11	10	21
SPT-6	9.00	9.45		10	12	13	26
SPT-7	10.50	10.95		13	15	14	29
			11.60 m				
SPT-8	12.00	12.45	KUM; Kahve renkli, orta sıkı, pek az çakıllı, çakıllar yarı köşeli-köşeli.	12	11	13	24
SPT-9	13.50	13.95		13	13	14	27
			14.60 m				
SPT-10	15.00	15.45	(Tanımlama için sonraki sayfaya bakınız.)	8	8	10	18

Other columns: DERİNLİK DEPTH (m); TOPLAM KAROT VERİMİ TOTAL CORE RECOVERY (cm); TOPLAM KAROT % TOTAL CORE RECOVERY (%); R.Q.D %; ZEMİN PROFİLİ SOIL PROFILE; DAYANIMLILIK STRENGTH; AYRIŞMA WEATHERING; KIRIK / 30 cm FRACTURE / 30 cm; KIRIK AÇISI FRACTURE ANGLE; SU KAYBI % WATER LOSS %; STANDART PENETRASYON DENEYİ STANDARD PENETRATION TEST; GRAFİK / GRAPH 10 20 30 40 50

KIVAM DURUMU / STIFFNESS			SIKILIK / DENSITY			ORANLAR / PROPORTIONS			KIRIKLAR-30 cm / FRACTURES-30 cm			
N = 0-2	Çok yumuşak	V. Soft	N = 0-4	Çok gevşek	V. Loose	0-10 %	pek az(seyrek)	Trace	< 1	Seyrek	Wide	(W)
N = 3-4	Yumuşak	Soft	N = 5-10	Gevşek	Loose	10-20 %	az	Little	1-2	Orta	Moderate	(M)
N = 5-8	Orta katı	M.Stiff	N = 11-30	Orta sıkı	M. Dense	20-35 %	Sıfat	Adjective	2-10	Sık	Close	(Cl)
N = 9-15	Katı	Stiff	N = 31-50	Sıkı	Dense	35-50 %	Ve	And	10-20	Çok sık	Intense	(I)
N = 16-30	Çok katı	V.Stiff	N > 50	Çok Sıkı	V. Dense				> 20	Parçalı	Crushed	(Cr)
N > 30	Sert	Hard										

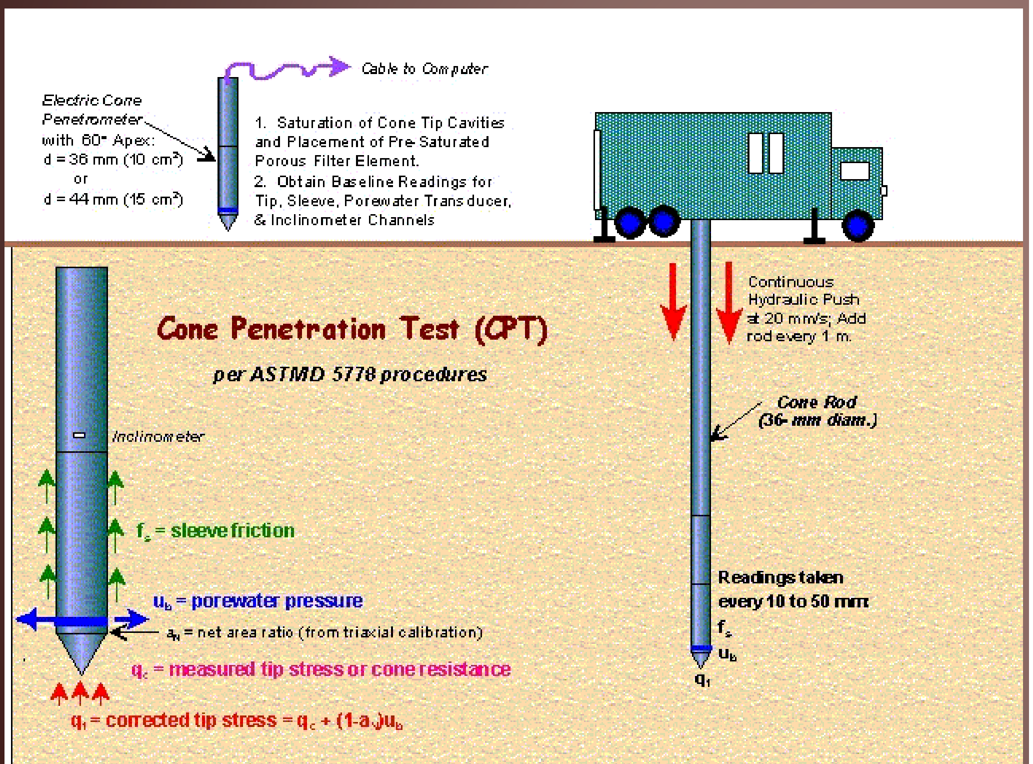
DAYANIMLILIK / STRENGTH			AYRIŞMA / WEATHERING		KAYA KALİTESİ TANIMI / R.Q.D.					
I	Çok Dayanımlı	Very Strong	I Taze	Fresh	0-25 %	Çok Zayıf	Very poor	UD	: Örselenmemiş Numune	/ Undisturbed Sample
II	Dayanımlı	Strong	II Az Ayrışmış	Slightly weathered	25-50 %	Zayıf	Poor	D	: Örselenmiş Numune	/ Disturbed Sample
III	Orta	Medium	III Orta Ayrışmış	Mod. Weathered	50-75 %	Orta	Fair	SPT	: Standart Pen. Deneyi	/ Standard Pen. Test
IV	Zayıf	Weak	IV Çok Ayrışmış	Highly weathered	75-90 %	İyi	Good	VST	: Vane Deneyi	/ Vane Shear Test
V	Çok zayıf	Very Weak	V Tamamen ayrışmış	Comp. Weathered	90-100 %	Çok İyi	Excellent	P	: Presiyometre Deneyi	/ Pressuremeter Test
								K	: Karot Numunesi	/ Core Sample

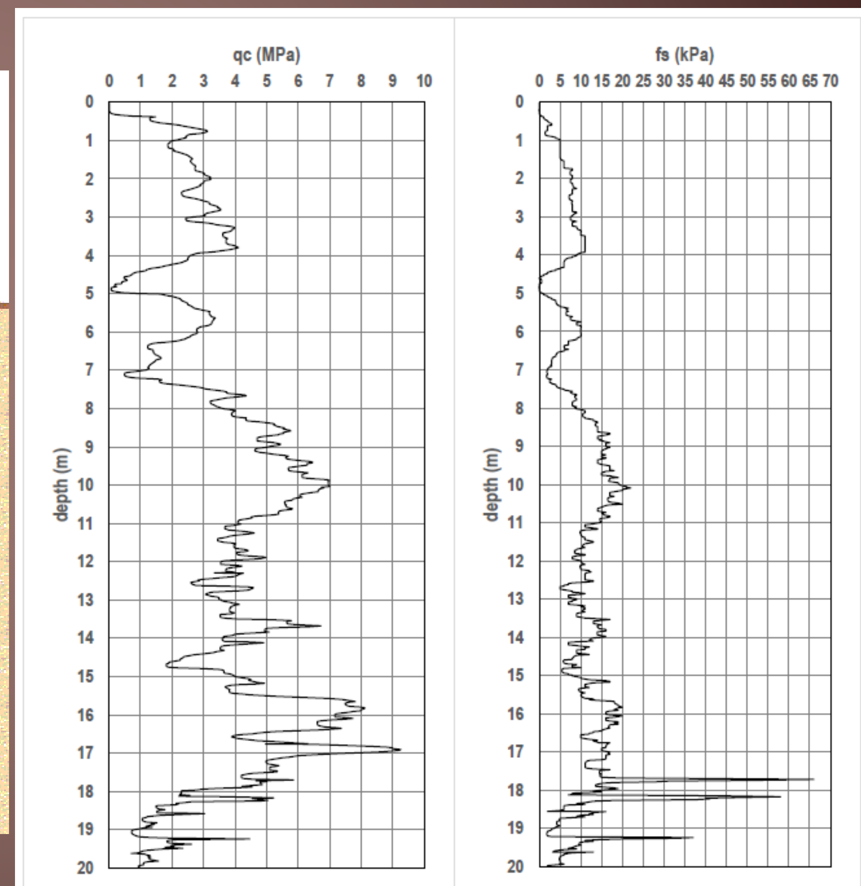
IDEALIZED SOIL PROFILES



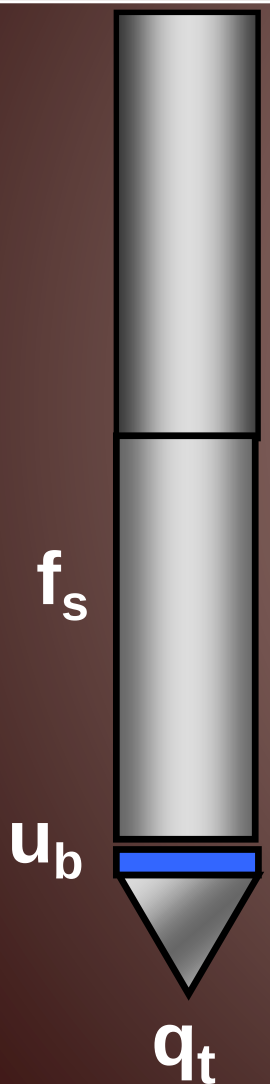
d (m)	SPT-N	σ'_v	C_N	C_E	C_B	C_R	C_S	$N_{1.60}$
1.50	8	27	1.92	1.00	1.00	0.75	1.00	12
3.00	12	54	1.36	1.00	1.00	0.75	1.00	12
4.30	13	77.4	1.14	1.00	1.00	0.85	1.00	13
6.00	18	108	0.96	1.00	1.00	0.85	1.00	15
7.50	21	135	0.86	1.00	1.00	0.95	1.00	17
9.00	26	162	0.79	1.00	1.00	0.95	1.00	20
10.50	28	189	0.73	1.00	1.00	1.00	1.00	20
12.00	24	216	0.68	1.00	1.00	1.00	1.00	16
13.50	27	243	0.64	1.00	1.00	1.00	1.00	17
15.00	18	270	0.61	1.00	1.00	1.00	1.00	11
16.50	32	309	0.57	1.00	1.00	1.00	1.00	18
18.00	31	348	0.54	1.00	1.00	1.00	1.00	17
19.50	82	387	0.51	1.00	1.00	1.00	1.00	42

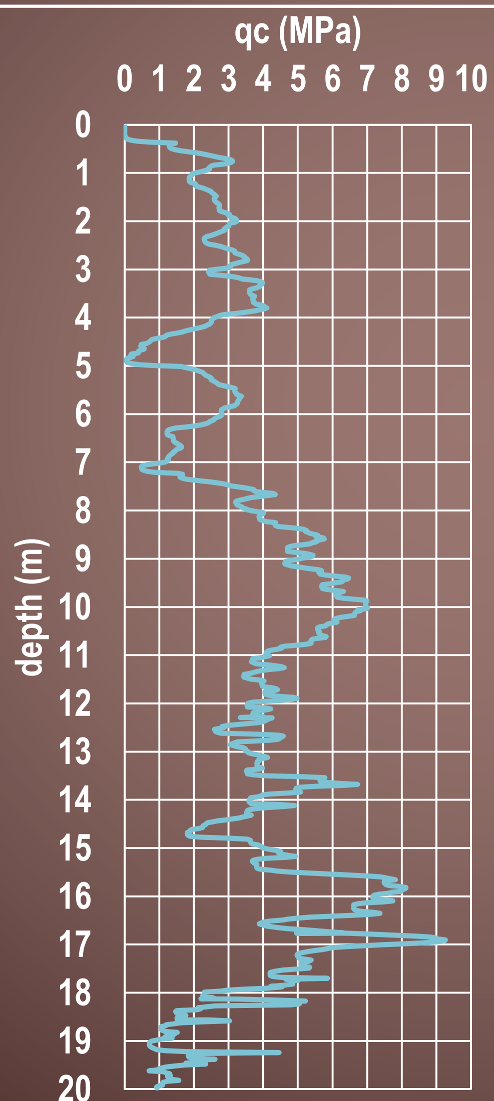
IDEALIZED SOIL PROFILES

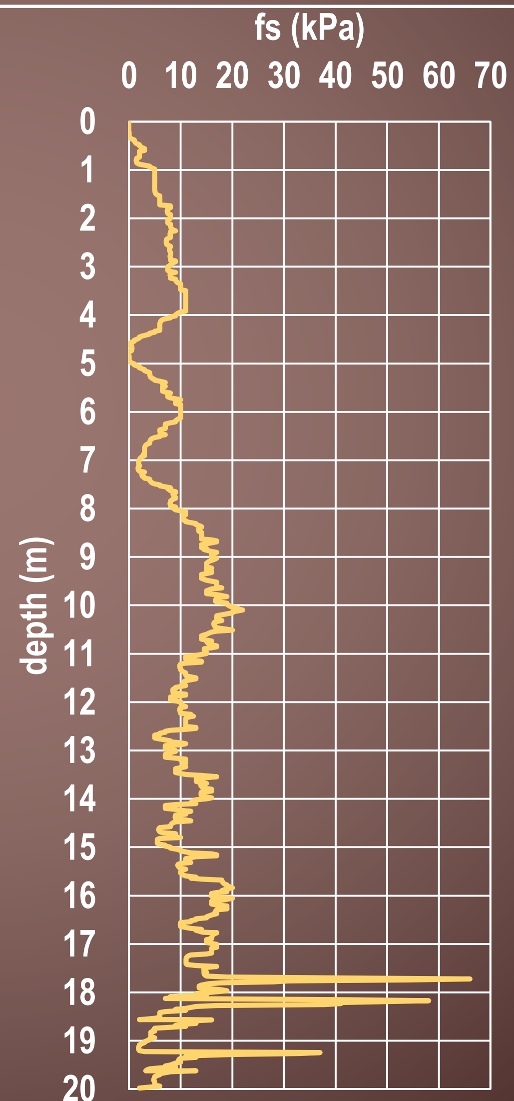




IDEALIZED SOIL PROFILES







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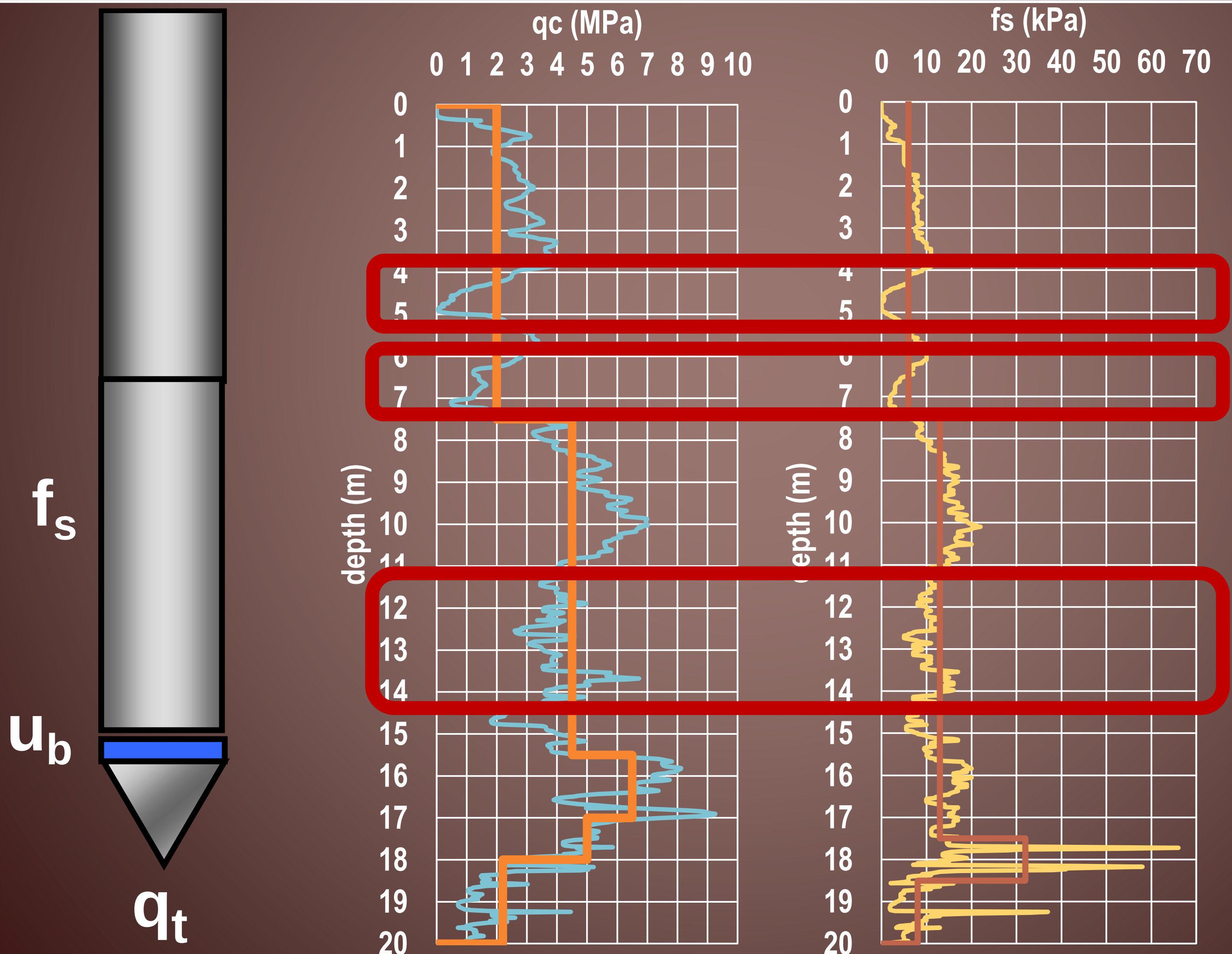
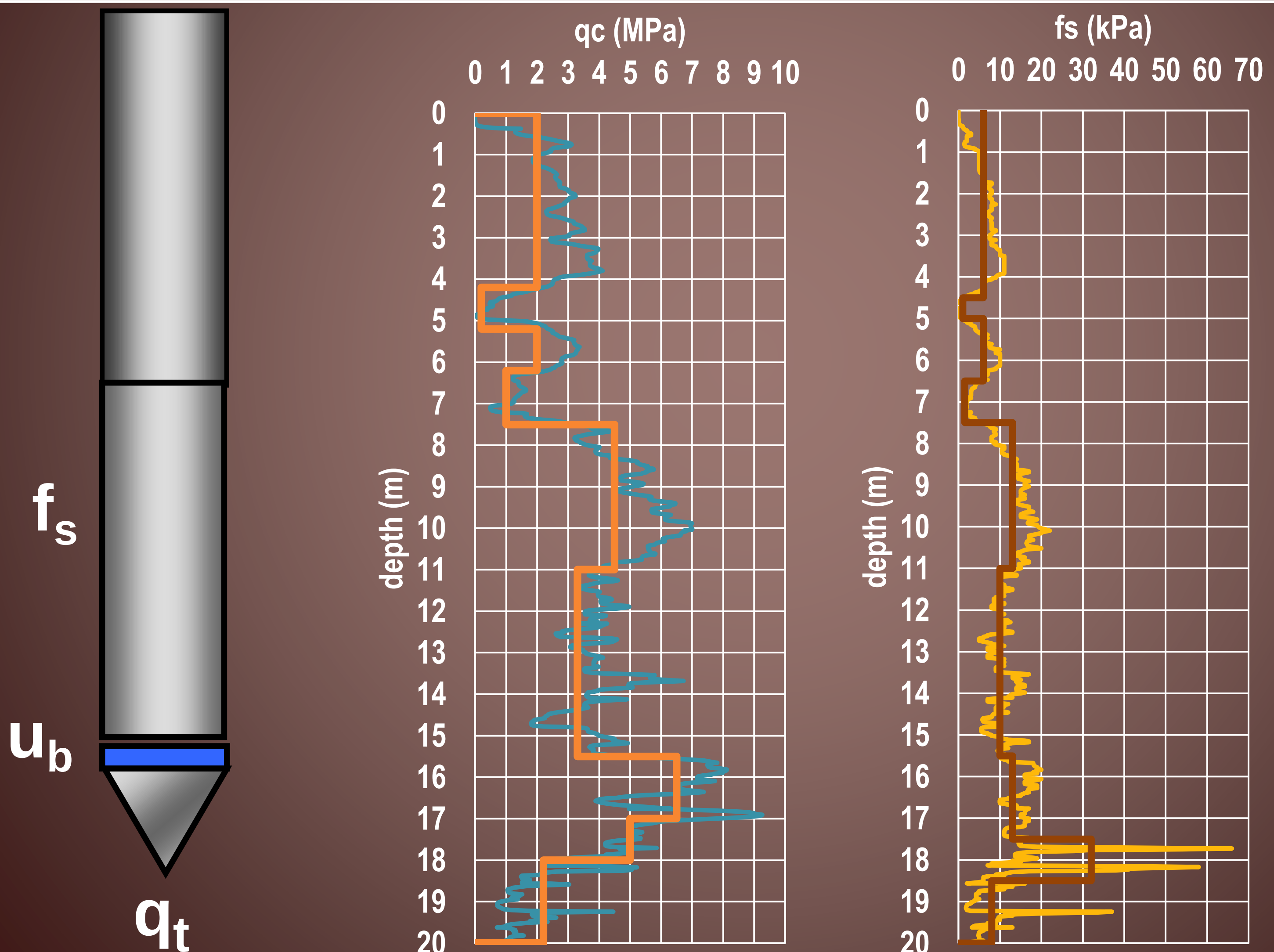


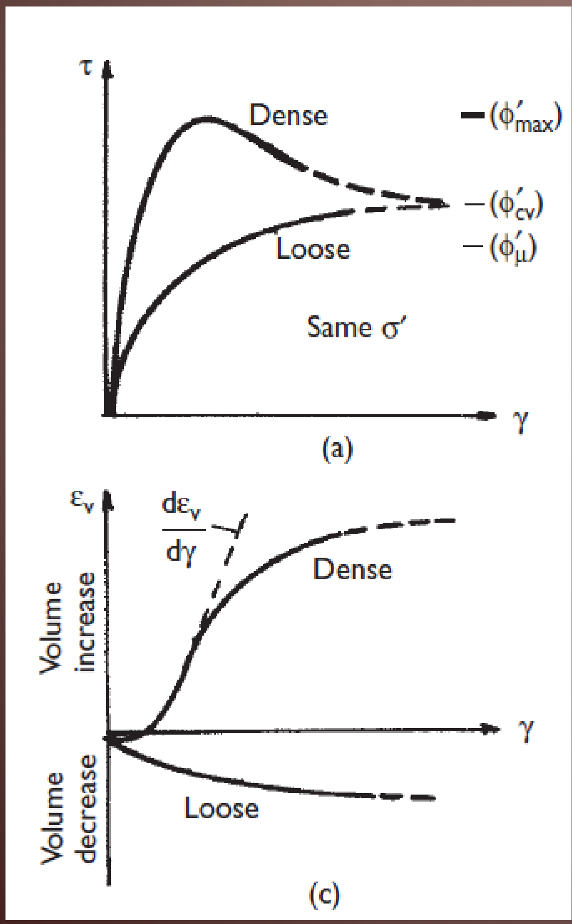
IDEALIZED SOIL PROFILES

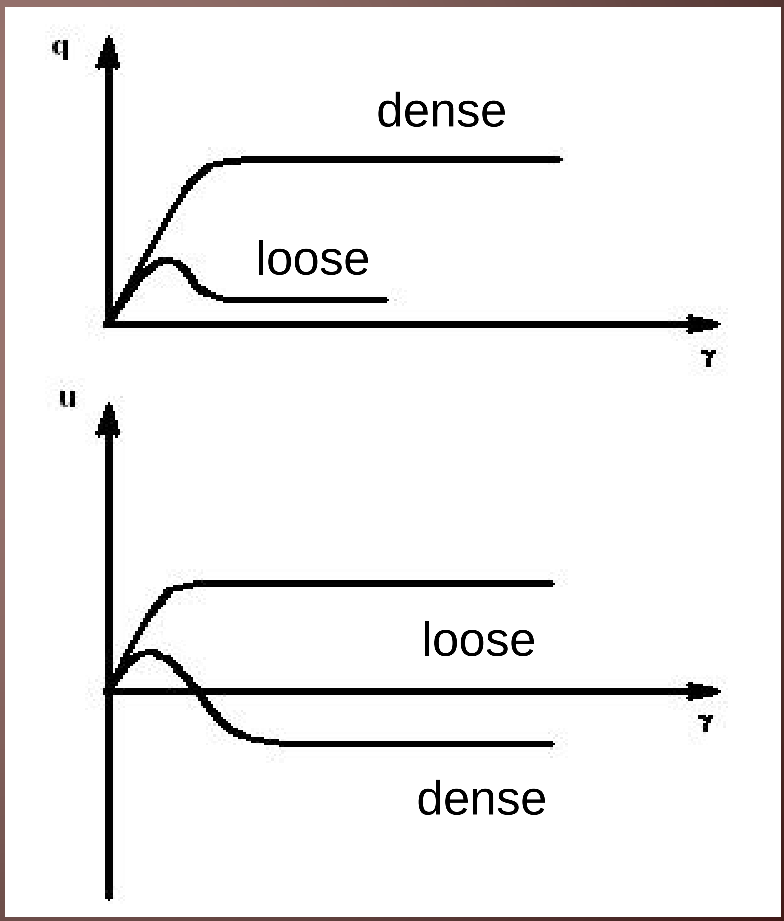


STATIC SOIL BEHAVIOR

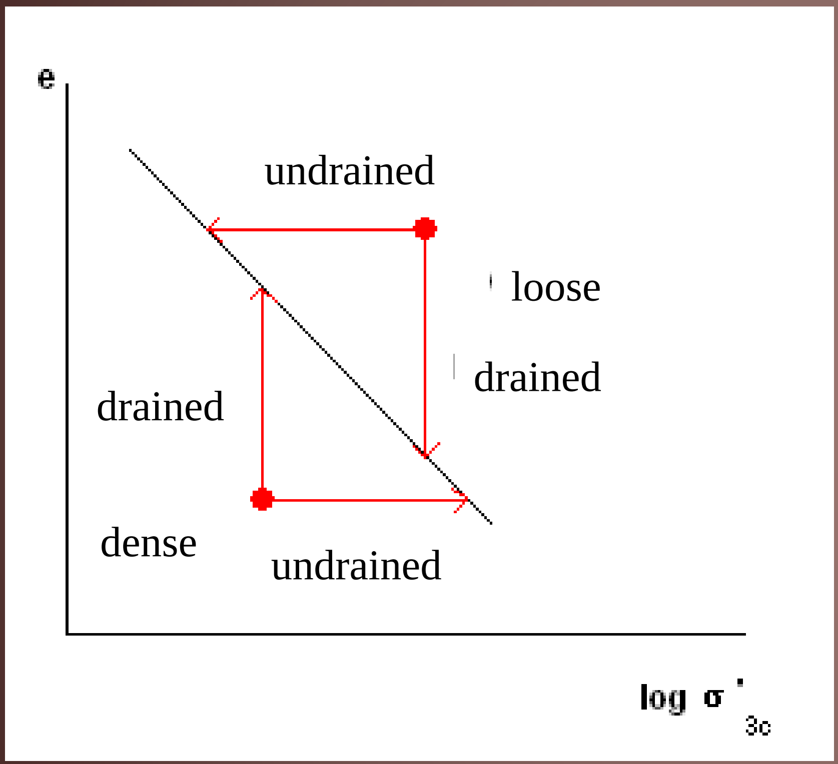
Drained

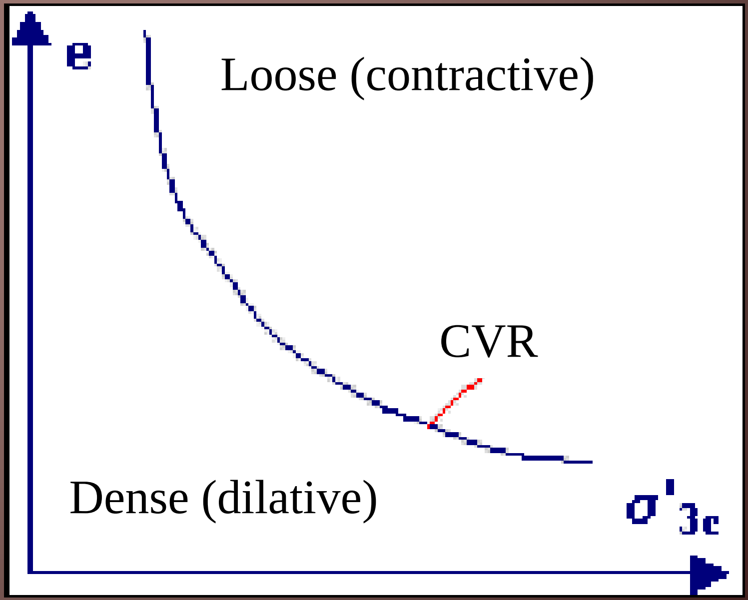
Undrained



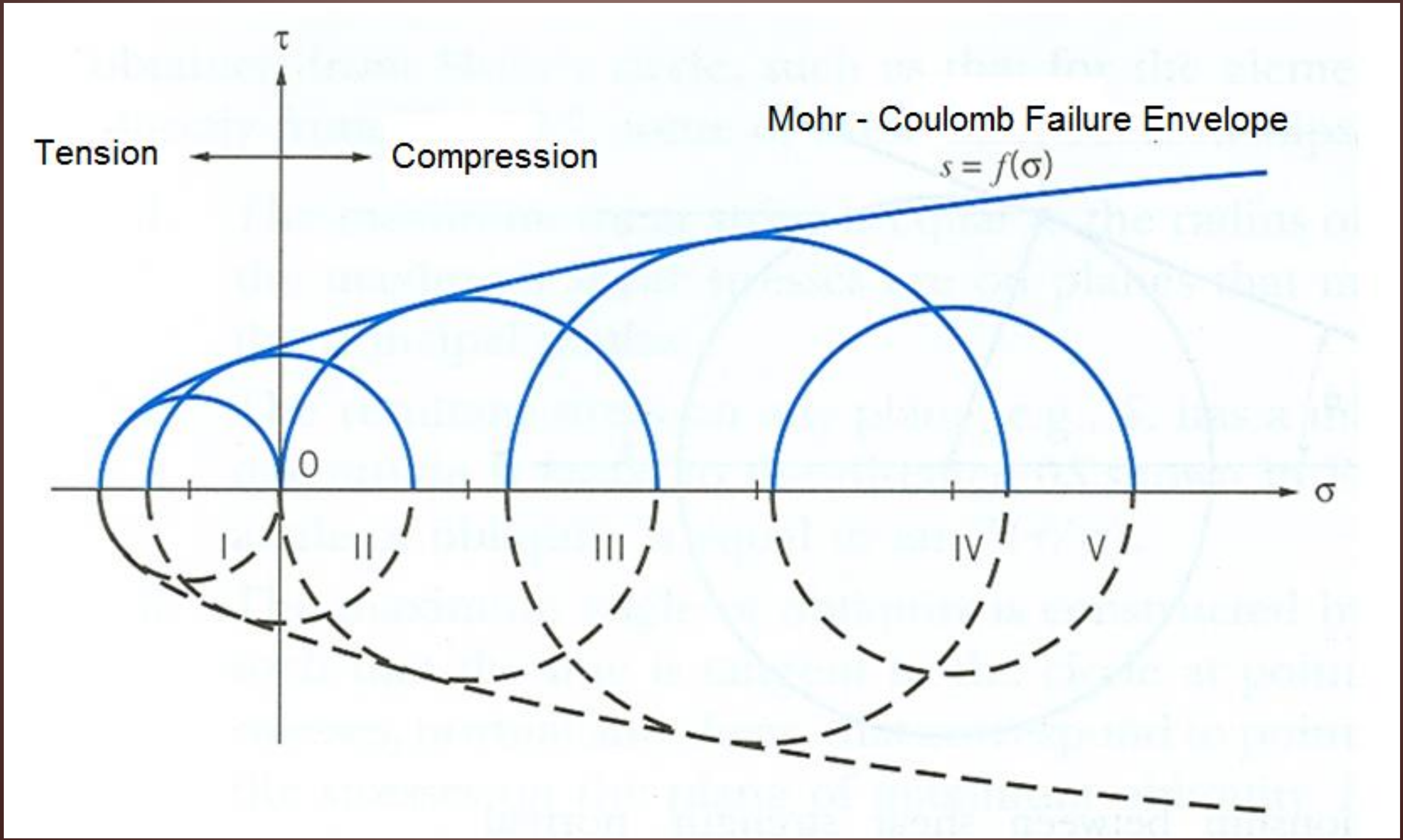


STATIC SOIL BEHAVIOR



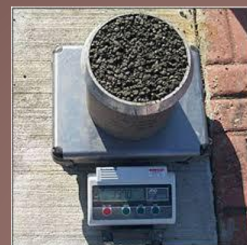


MOHR-COULOMB CIRCLES AT DIFFERENT STRESS LEVELS



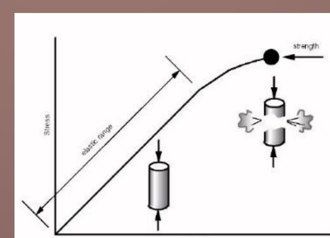
SELECTION OF SOIL PARAMETERS

- Unit weight



- Shear strength $\tau = c + \sigma_v'.\,tan\emptyset$

- Modulus



- Permeability

UNIT WEIGHT

Bowles (1996)

Table 1.3. Relation between SPT-$(N_1)_{70}$ - D_r - ϕ' - γ_s (Bowles, 1996)

Definition		*Very loose*	*Loose*	*Medium dense*	*Dense*	*Very dense*
D_r		0	0.15	0.35	0.65	0.85
$(N_1)_{70}$	Fine	1 – 2	3 – 6	7 – 15	16 – 30	-
	Medium	2 – 3	4 – 7	8 – 20	21 – 40	> 40
	Coarse	3 – 6	5 – 9	10 – 25	26 – 45	> 45
ϕ'	Fine	26 – 28	28 – 30	30 – 34	33 – 38	< 50
	Medium	27 – 28	30 – 32	32 – 36	36 – 42	
	Coarse	28 – 30	30 – 34	33 – 40	40 – 50	
$\gamma_s(kN/m^3)$		11 – 16	14 – 18	17 – 20	17 – 22	20 – 23

Rock Fill: 22 – 24 kN/m^3

Rocks: 23 – 25 kN/m^3

Erol and Cekinmez (2014)

Cetin et al. (2016)

SPT-N_{60} (blows/ft)	γ_{moist} (lb/ft^3)	γ_{moist} (kN/m^3)	γ_{sat} (lb/ft^3)	γ_{sat} (kN/m^3)
(a) Coarse-grained soil layers				
0 - 4	100	16.0	110	17.6
5 - 10	110	17.6	120	19.2
11 - 30	120	19.2	125	20.0
30 - 50	125	20.0	135	21.6
(b) Fine-grained soil layers				
0 - 4	100	16.0	110	17.6
5 - 8	110	17.6	120	19.2
9 - 16	115	18.4	125	20.0

SELECTION OF MODEL PARAMETERS

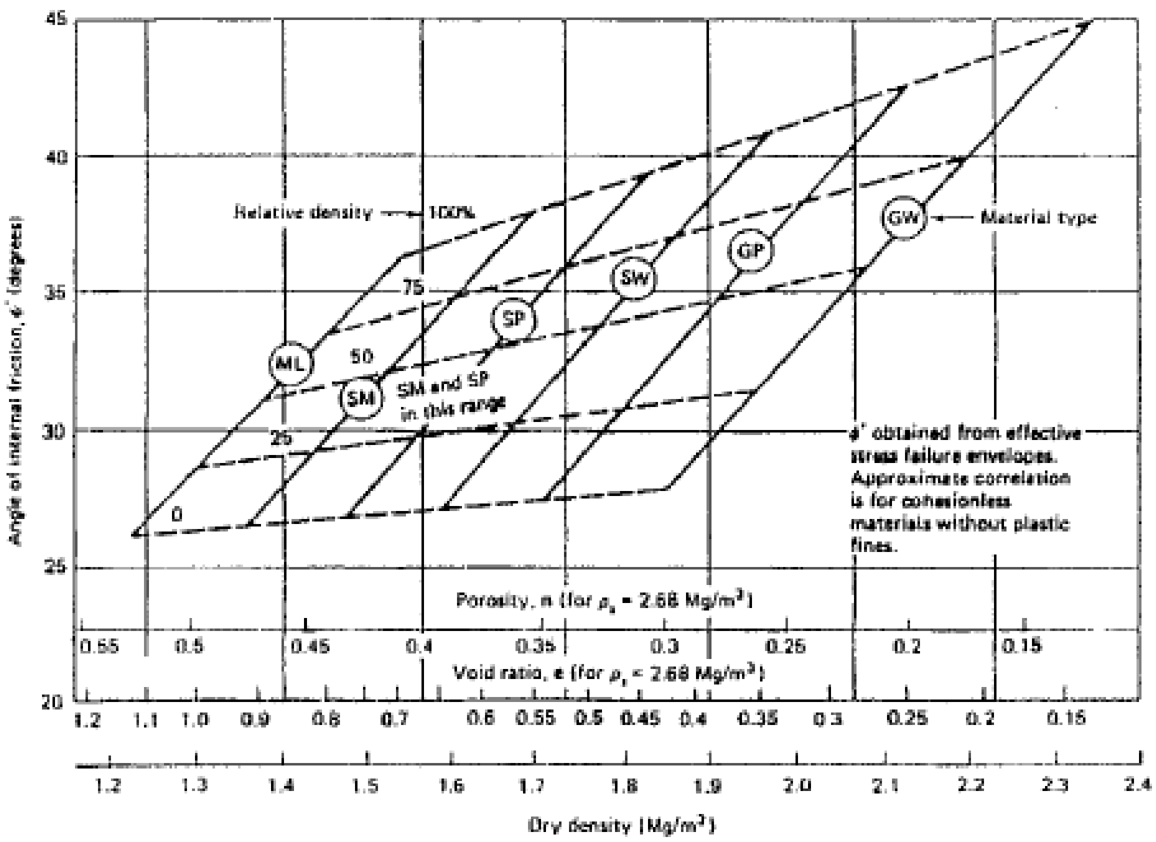


FIG.11. Angle of internal friction depending on soil density or void ratio (sands) (from NAVFAC, 1982)

FORMULAS FOR SAND

$$\gamma_{unsat} = 15 + 4.0\,RD/100 \quad [kN/m^3]$$

$$\gamma_{sat} = 19 + 1.6\,RD/100 \quad [kN/m^3]$$

σ'_v ?

SHEAR STRENGTH PARAMETERS

Cohesive Soils

- Undrained shear strength (c_u)
- Effective internal friction of angle (ϕ')

Cohesionless Soils

- Effective internal friction of angle (ϕ')

MOHR CIRCLES

Strength parameters

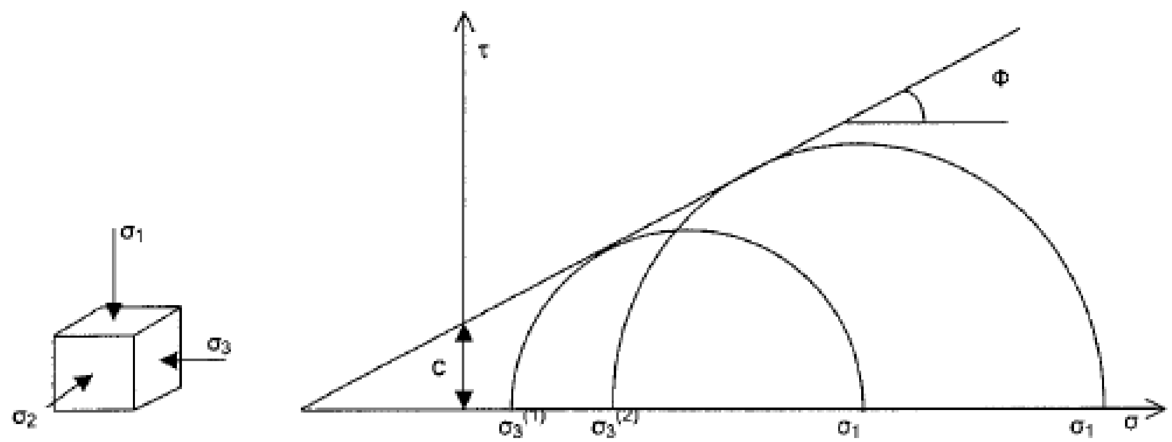
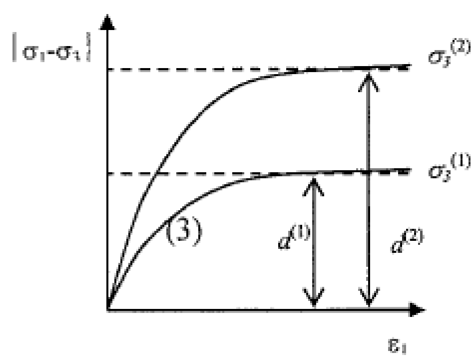


FIG. 9. Selection of φ'and c' based on two Mohr stress circles



$$d = \frac{2c'\cos\varphi' + 2\sigma'_3 \sin\varphi'}{1 - \sin\varphi'}$$

FIG. 10. Calculation of φ' and c' from triaxial tests at different confining pressures σ_3

MOHR CIRCLES

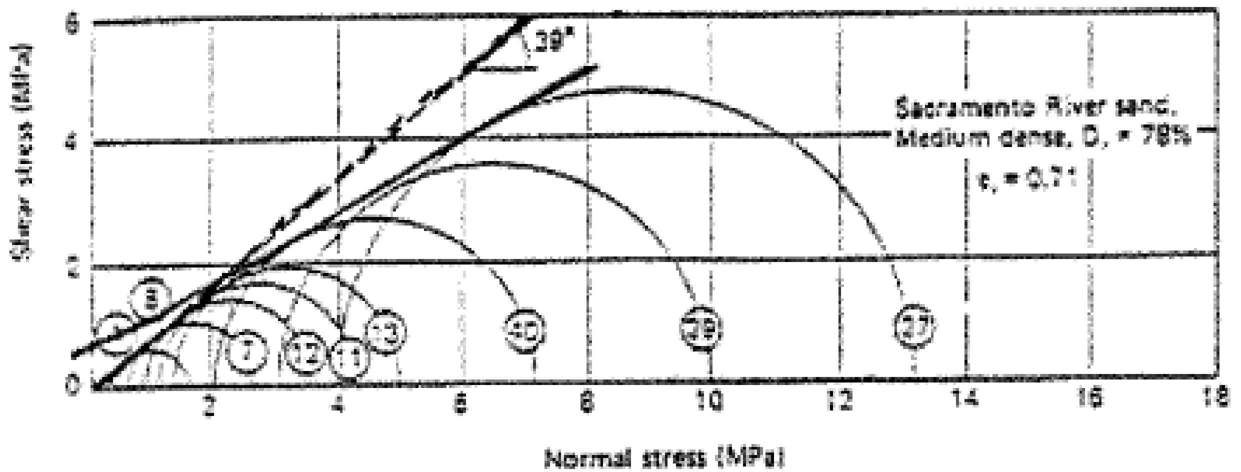


FIG. 12. Example showing that a combination of φ' and *c'* is only valid in a certain stress range

COHESIVE SOILS

CLAY

DRAINED OR UNDRAINED?

Drained or undrained conditions

A simple formula can help to determine if undrained behaviour applies:

$$T = \frac{k\,E_{oed}}{\gamma_w\,D^2}\,t$$

where

T	=	hydrodynamic period
k	=	soil permeability
E_{oed}	=	oedometer stiffness
γ_w	=	unit weight of water
D	=	drainage length
t	=	time (construction time or loading time)

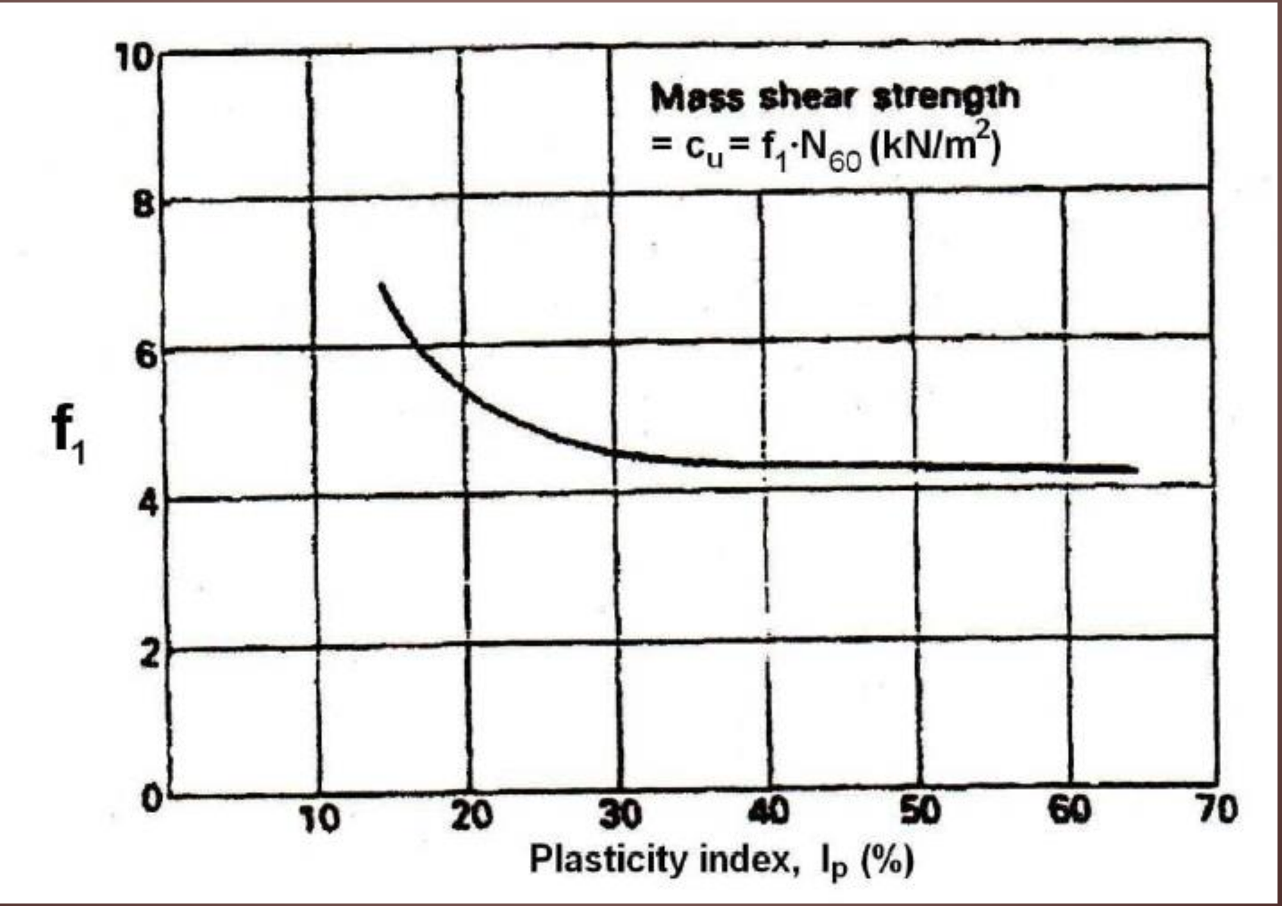
COHESIVE SOILS
UNDRAINED SHEAR STRENGTH

$s_u = \left[\frac{1}{10} .. \frac{1}{20}\right](q_c - q_0)$	Correlation with cone resistance q_c from CPT; q_0 is the external load
$s_u \approx (0.11 + 0.0037 I_p)\sigma'_1$	Skempton's correlation with vertical effective stress, involving the plasticity index I_p (Skempton, 1957).
$s_u \approx 0.3\sigma'_1$	Approximation of the above correlation for medium plastic soils
$s_u \approx 0.2\sigma'_1 (OCR)^{0.8}$	Ladd's correlation for over-consolidated clays (Ladd, 1991)

$s_u = c'\cos\varphi' + (\sigma'_1 + \sigma'_3)\sin\varphi'$	Relationship between undrained shear strength and effective strength properties for plane strain applications using the Mohr-Coulomb model.

COHESIVE SOILS
UNDRAINED SHEAR STRENGTH

Undrained shear strength (c_u)



Stroud (1974)

COHESIVE SOILS UNDRAINED SHEAR STRENGTH

Undrained shear strength (c_u)

$$c_u = (q_c - P_0)/N_k$$

q_c : CPT tip resistance (kN/m^2)

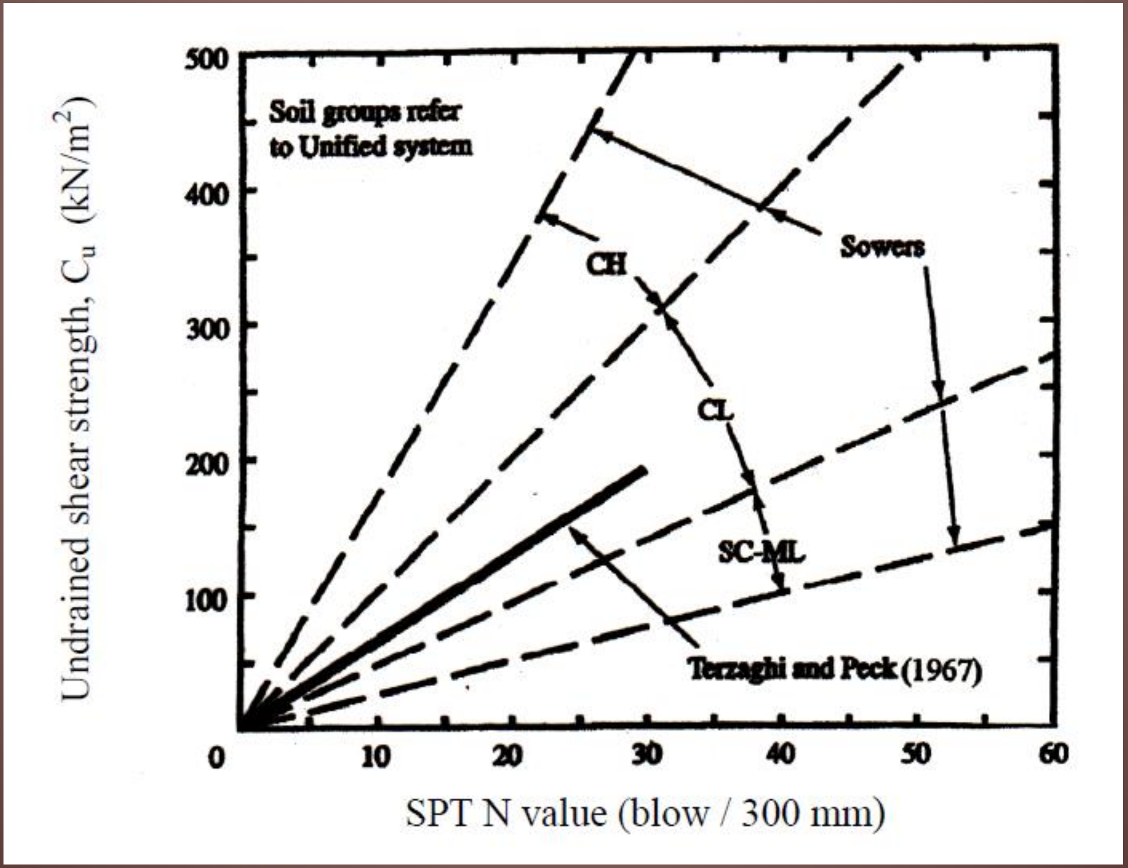
P_0 : Total stress (kN/m^2)

N_k : Typically N_{kt} varies from 10 to 18, with 14 as an average for $c_{u(ave).}$ N_{kt} tends to increase with increasing plasticity and decrease with increasing soil sensitivity.

N_k =17 (Lunne et al. 1997)

UNDRAINED PARAMETERS

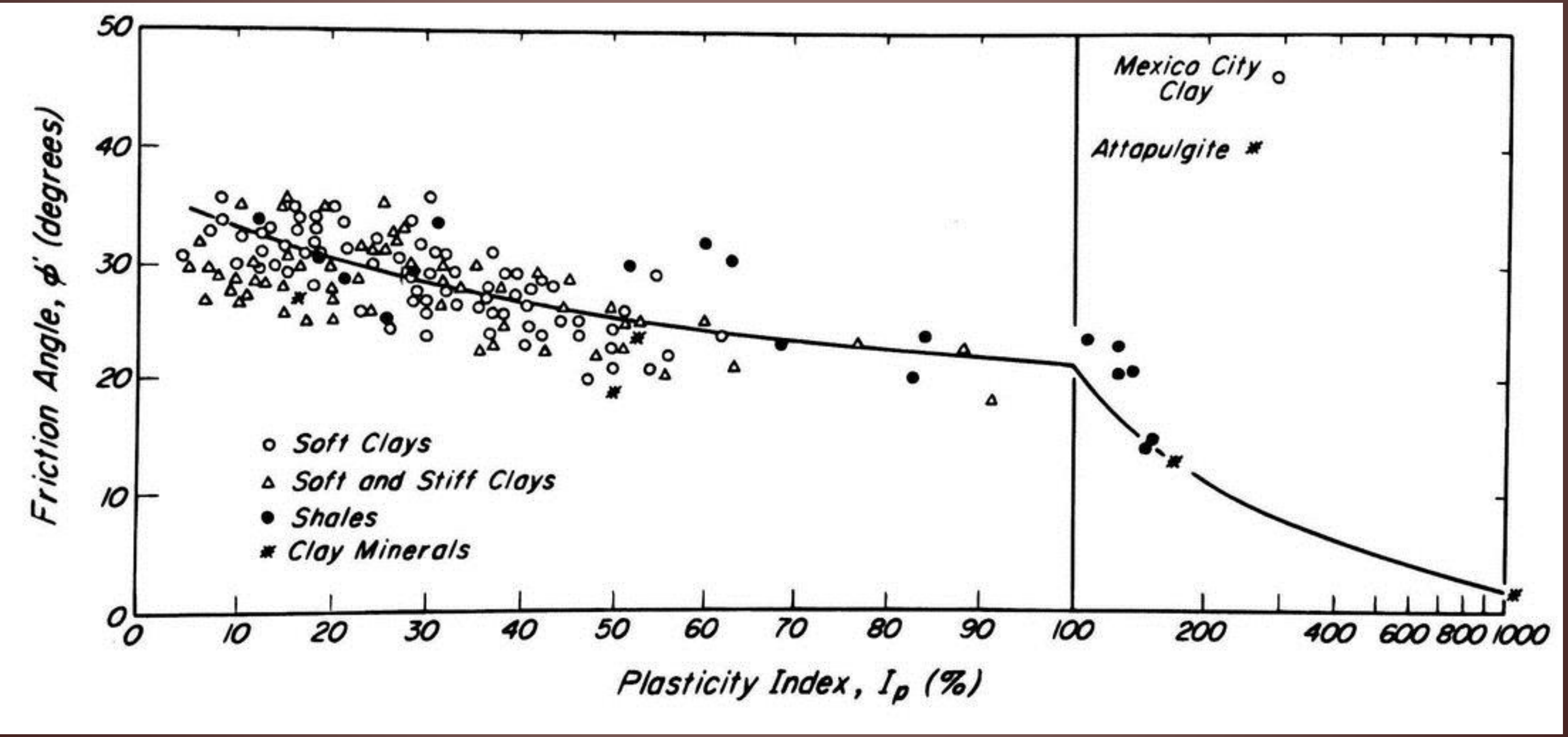
Undrained shear strength (c_u)



Terzaghi and Peck (1967), Sowers (1979)

COHESIVE SOILS
DRAINED SHEAR STRENGTH

Effective internal friction of angle (ϕ')



Terzaghi (1966)

COHESIONLESS SOILS

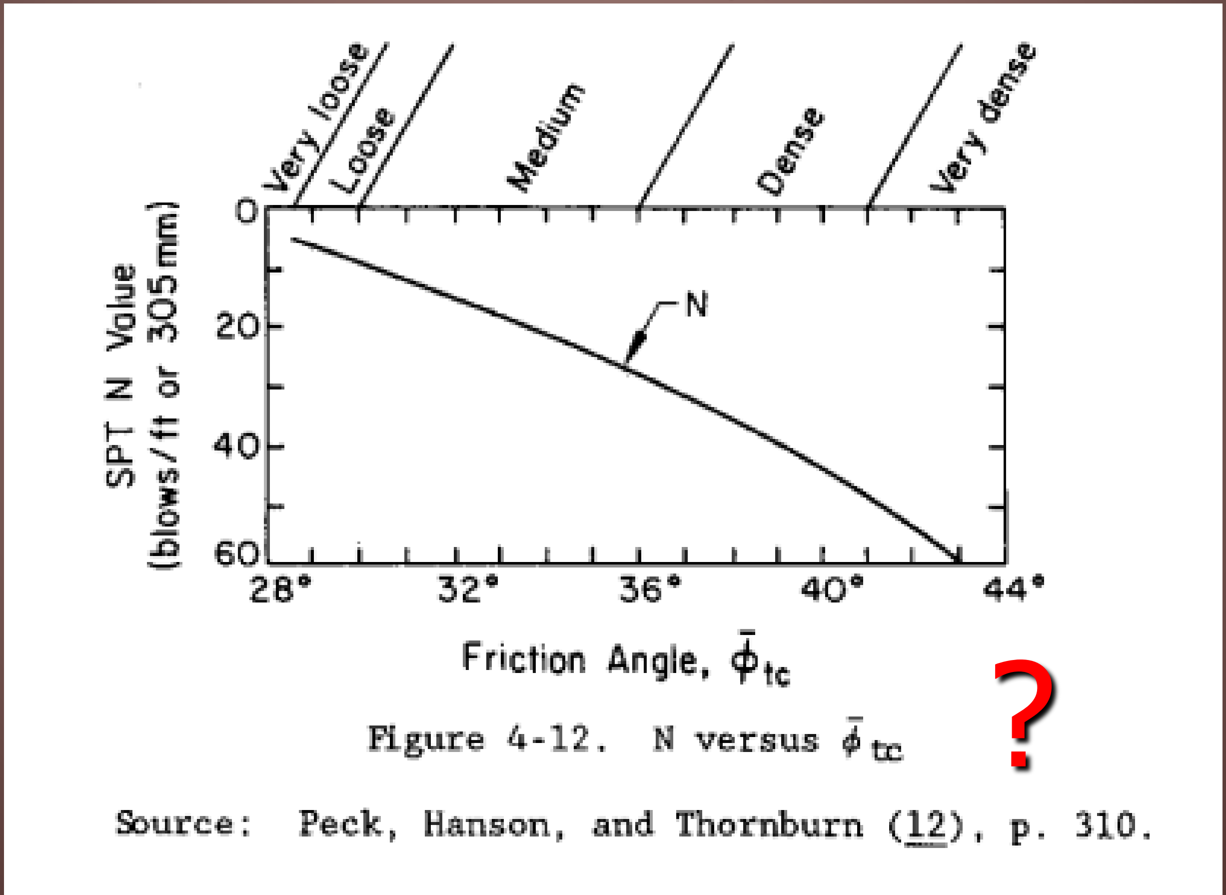
SILT

SAND

GRAVEL

COHESIONLESS SOILS

Effective internal friction of angle (ϕ')



Peck et al. (1974)

COHESIONLESS SOILS

Effective internal friction of angle (ϕ')

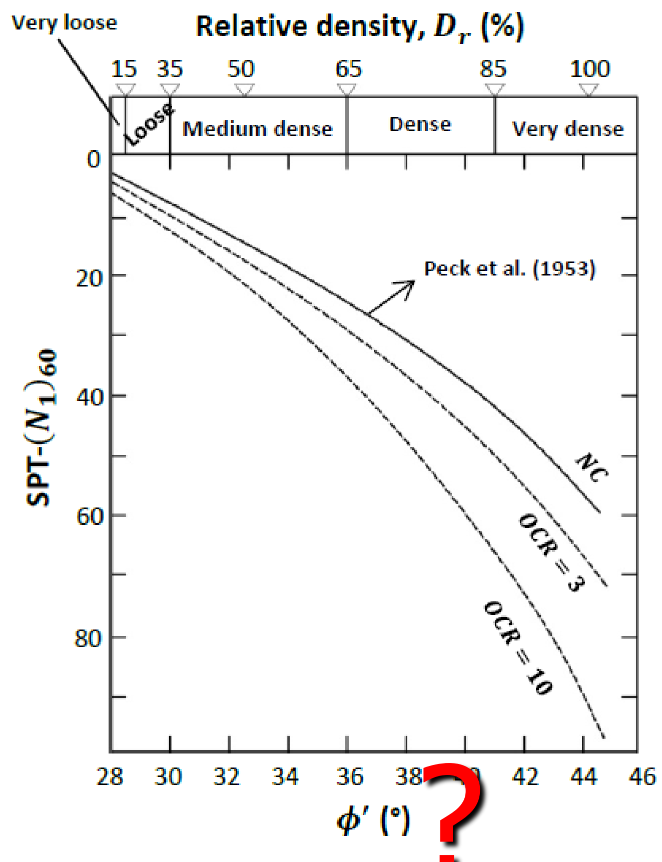


Figure 1.2. Relation between SPT-$(N_1)_{60}$ - ϕ' - OCR (Stroud, 1988)

Erol and Cekinmez (2014)

COHESIONLESS SOILS

Effective internal friction of angle (ϕ')

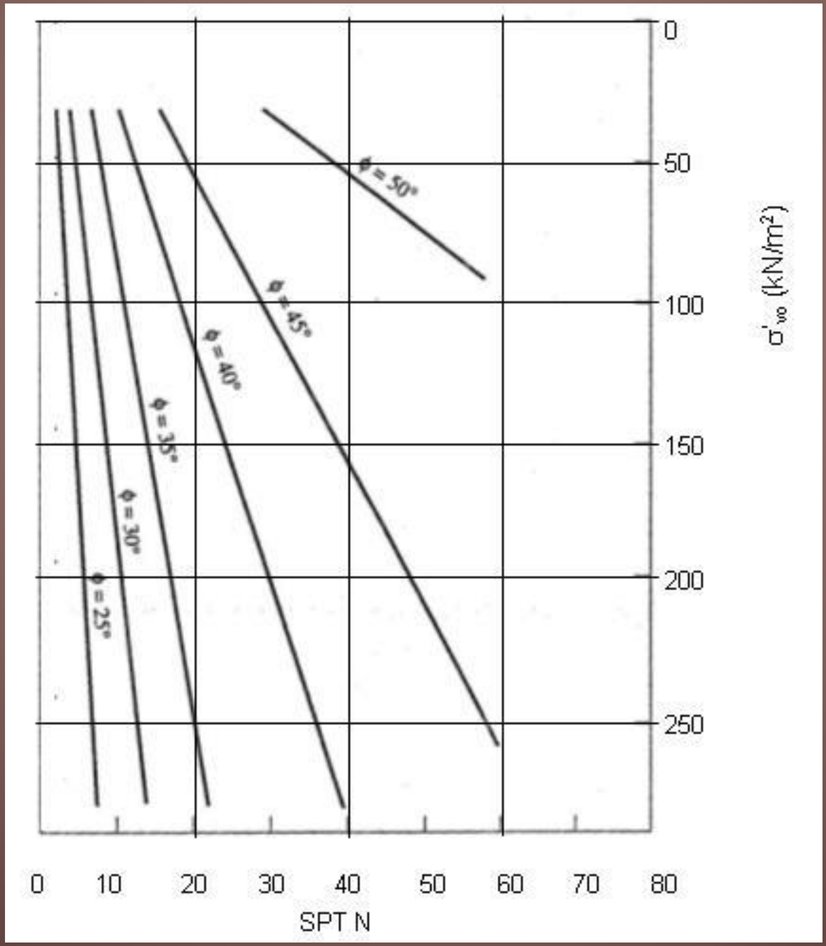
$$\phi' = 25 + 3.2\sqrt{\frac{100N}{70 + \sigma'_{v0}}}$$ (OCDI- Japan 2002)

$N_{1,60,CS} = 0.0046 * D_R^2$

Boulanger and Idriss (2004)

COHESIONLESS SOILS

Effective internal friction of angle (ϕ')



Coduto (1994)

COHESIONLESS SOILS

Effective internal friction of angle (ϕ')

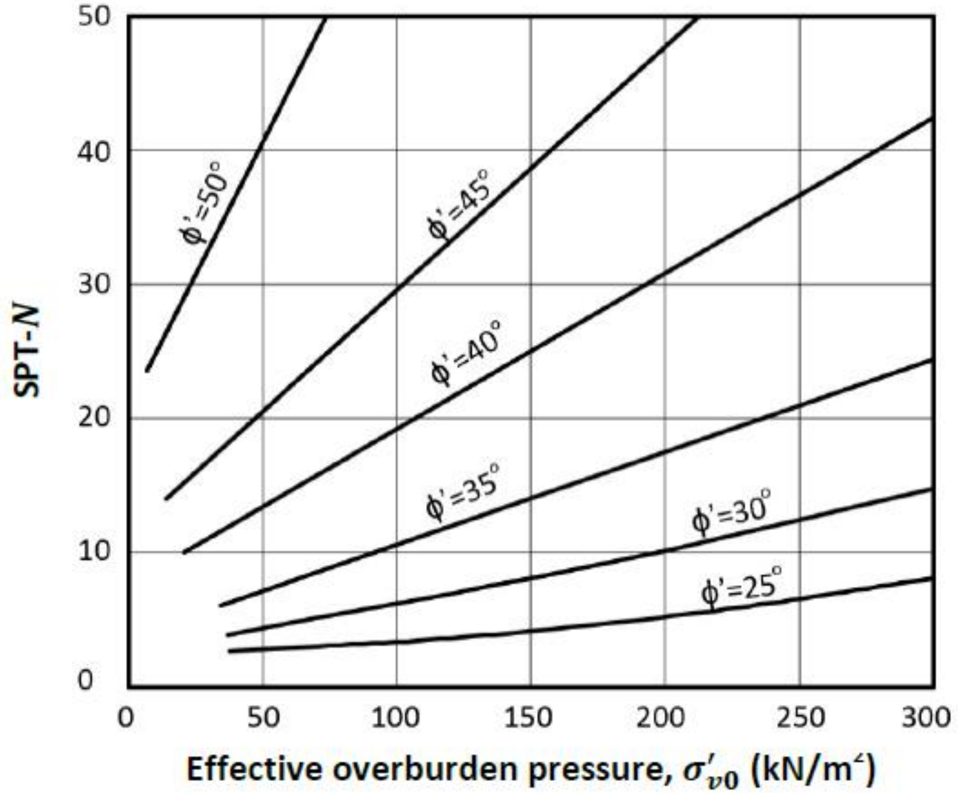
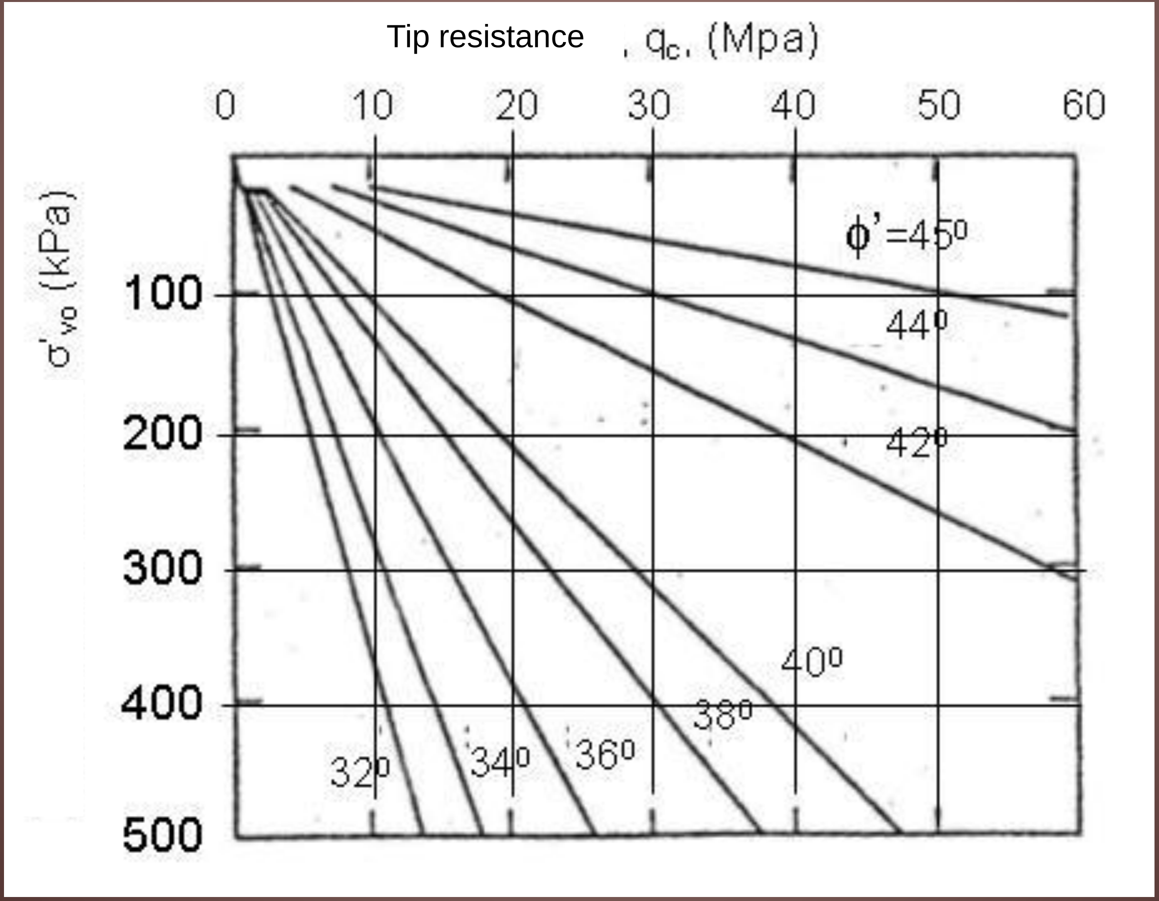


Figure 1.3. Relation between σ'_{v0} - SPT-N - ϕ' (Schmertmann, 1975)

Erol and Cekinmez (2014)

COHESIONLESS SOILS

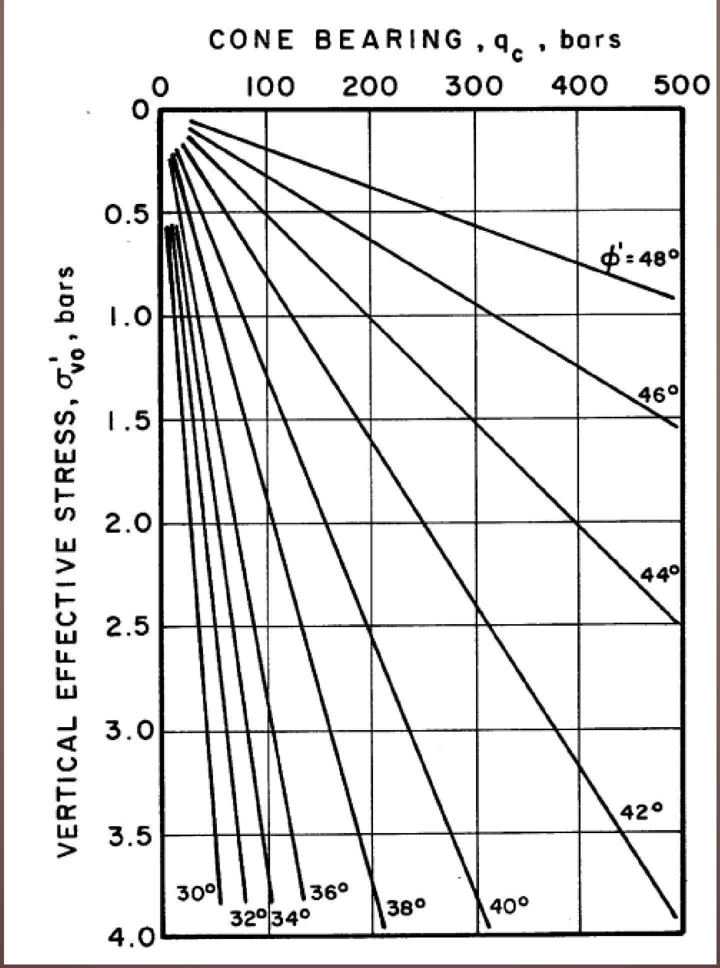
Effective internal friction of angle (ϕ')



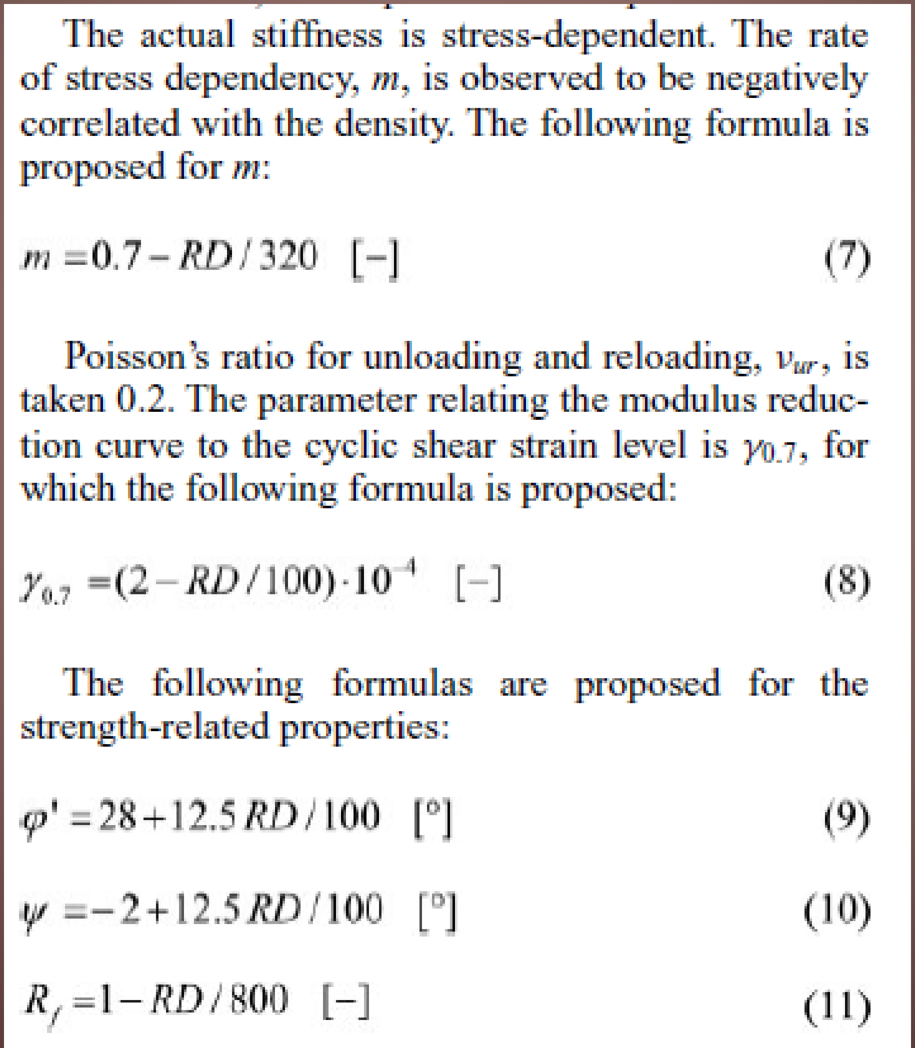
Durgunoğlu and Mitchell (1974)

COHESIONLESS SOILS

Effective internal friction of angle (ϕ')



FORMULAS FOR SAND


The actual stiffness is stress-dependent. The rate of stress dependency, m, is observed to be negatively correlated with the density. The following formula is proposed for m:

$$m = 0.7 - RD / 320 \quad [-] \tag{7}$$

Poisson's ratio for unloading and reloading, ν_{ur}, is taken 0.2. The parameter relating the modulus reduction curve to the cyclic shear strain level is $\gamma_{0.7}$, for which the following formula is proposed:

$$\gamma_{0.7} = (2 - RD / 100) \cdot 10^{-4} \quad [-] \tag{8}$$

The following formulas are proposed for the strength-related properties:

$$\varphi' = 28 + 12.5\, RD / 100 \quad [°] \tag{9}$$

$$\psi = -2 + 12.5\, RD / 100 \quad [°] \tag{10}$$

$$R_f = 1 - RD / 800 \quad [-] \tag{11}$$

ROCK FILL

Effective internal friction of angle (ϕ')
(Seed et al. (1985))

Normal Stress (kPa)	$\phi'_{(TX)}$	$\phi'_{(PS)}$
14	53	57
35	50.5	54
70	48.5	52
140	46.5	50
350	44	47.5
700	42	45.5
1400	39.5	43
3500	37.5	41

MODULUS

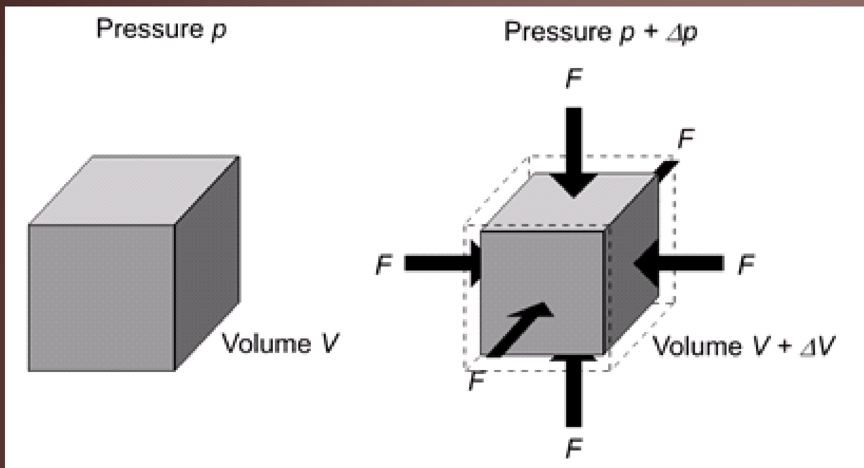
Elastic Solution

$$K = \frac{E}{3(1-2\upsilon)} \qquad G = \frac{E}{2(1+\upsilon)}$$

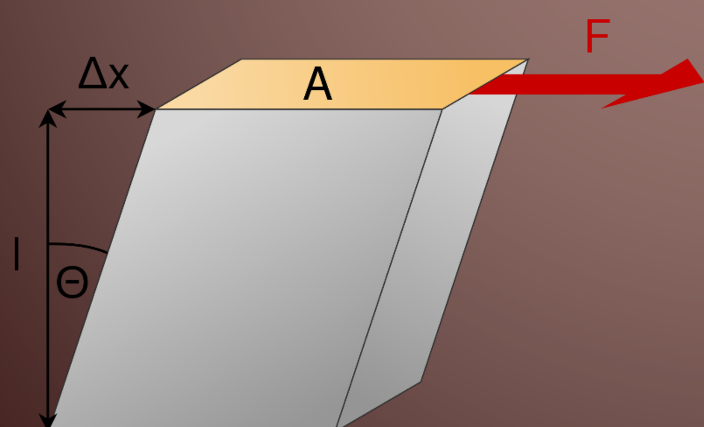
E : Elasticity modulus
K : Bulk modulus
G : Shear modulus
v : Poisson's ratio

E, G, K $\propto (\sigma'_m)^m$
m=0.5 (sands)
m=1.0 (clays)

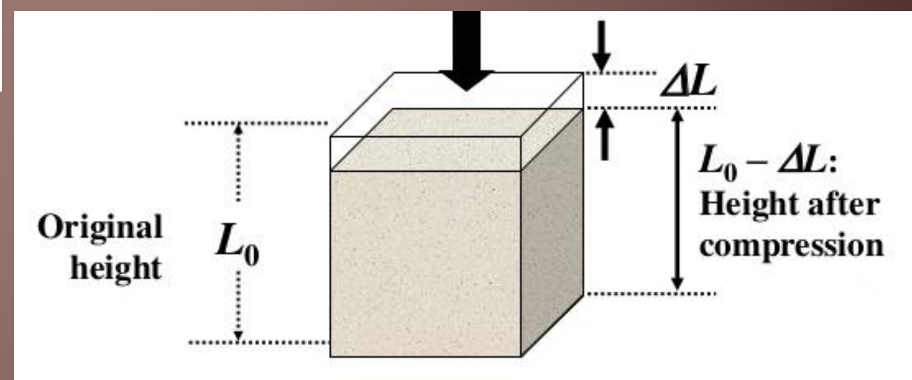
MODULUS



K : Bulk modulus



G : Shear modulus



E : Elasticity modulus

MODULUS

Stiffness parameters for sand

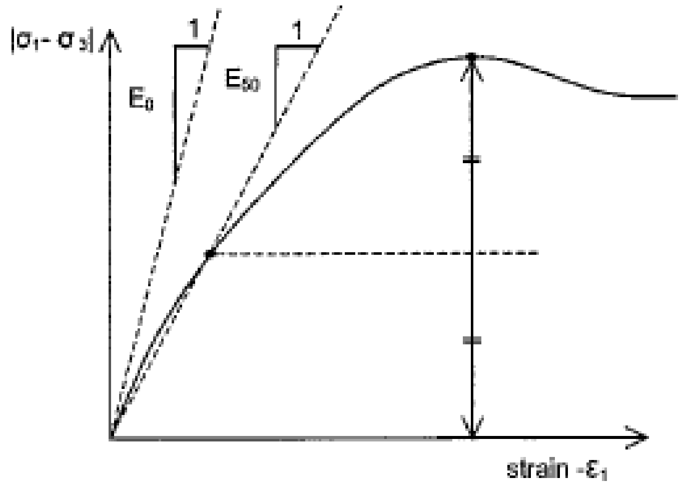
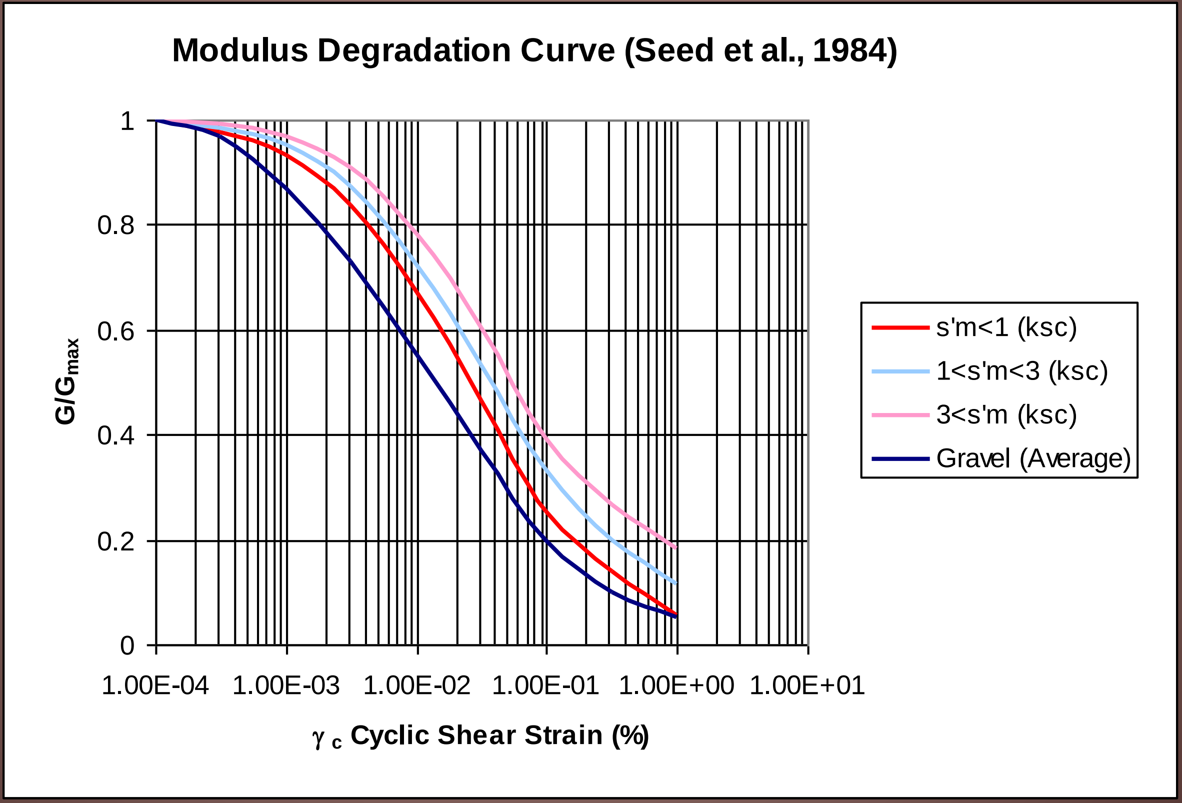


FIG.17. Selection of sand stiffness from standard drained triaxial test

$E_{50}^{ref} \approx RD \cdot 60MPa$ Correlation of triaxial stiffness by Lengkeek

$E_{50} = E_{50}^{ref} \sqrt{\frac{\sigma'_3}{p^{ref}}}$ Stress-dependent triaxial stiffness of sands

MODULUS



Modulus Degradation Curve (Seed et al., 1984)
1
0.8
0.6
0.4
0.2
0
G/G$_{max}$
1.00E-04
1.00E-03
1.00E-02
1.00E-01
1.00E+00
1.00E+01
γ_c Cyclic Shear Strain (%)
s'm<1 (ksc)
1<s'm<3 (ksc)
3<s'm (ksc)
Gravel (Average)

MODULUS

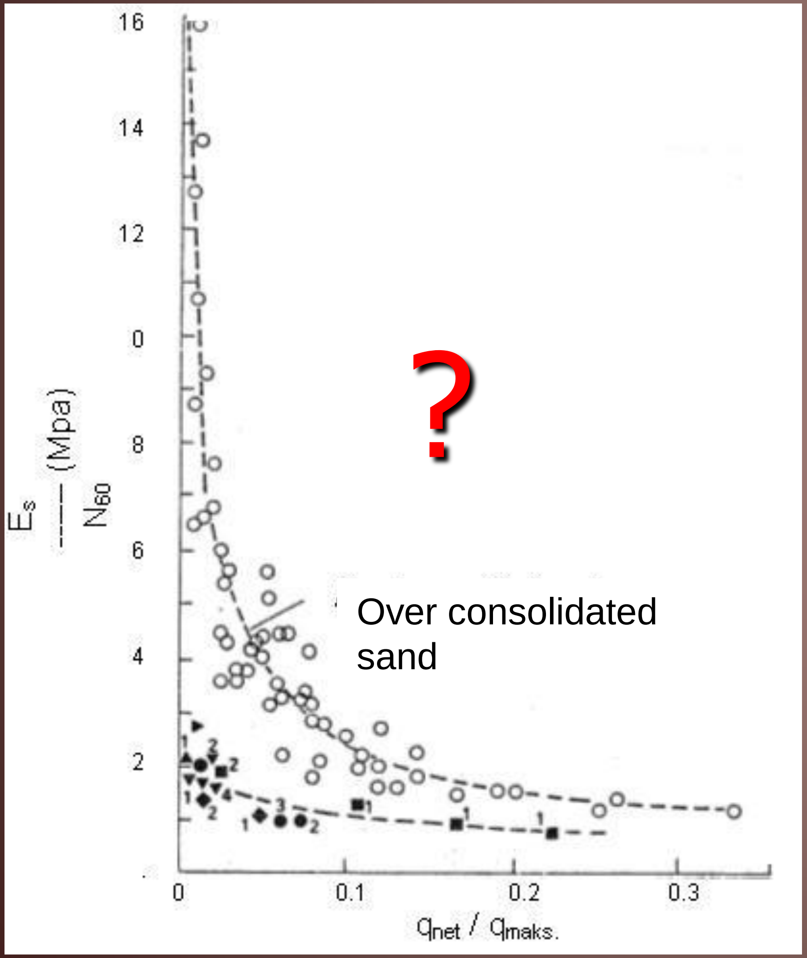
<u>Bowles (1996);</u>

Sand (normally consolidated)	Es = 500 (N + 15)	kN/m^2
Clayey Sand	Es = 320 (N + 15)	kN/m^2
Silt, sandy silt	Es = 300 (N + 6)	kN/m^2
Gravelly sand	Es =1200 (N + 6)	kN/m^2

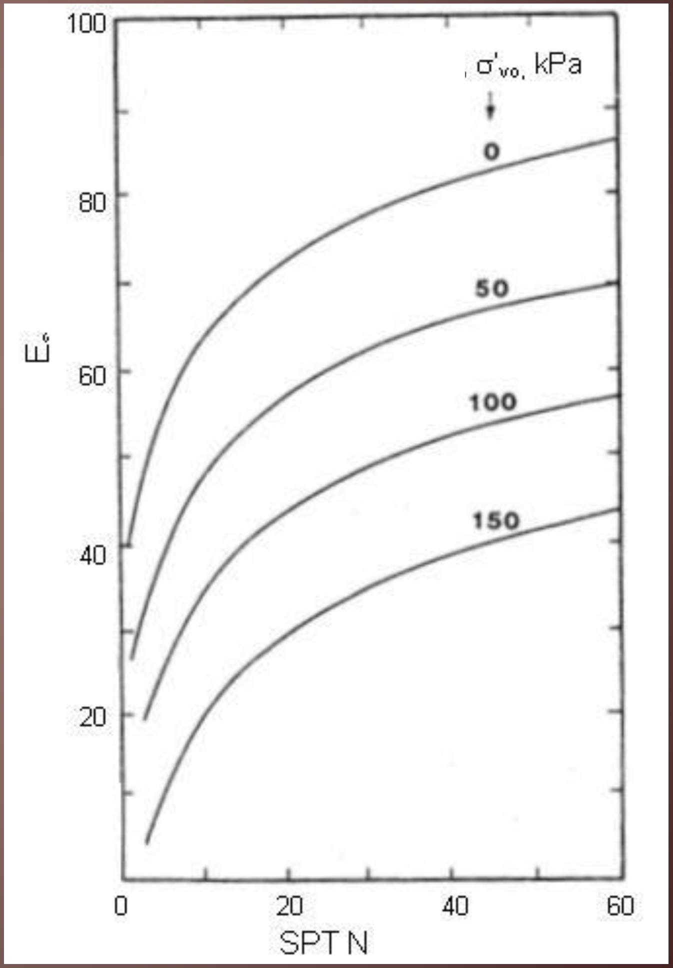
<u>Kulhawy and Mayne (1990);</u>

Silty and clayey sand	Es = 500 N_{60}	kN/m^2
Clean sand	Es = 1000 N_{60}	kN/m^2
Over consolidated clean sand	Es = 1500 N_{60}	kN/m^2

MODULUS

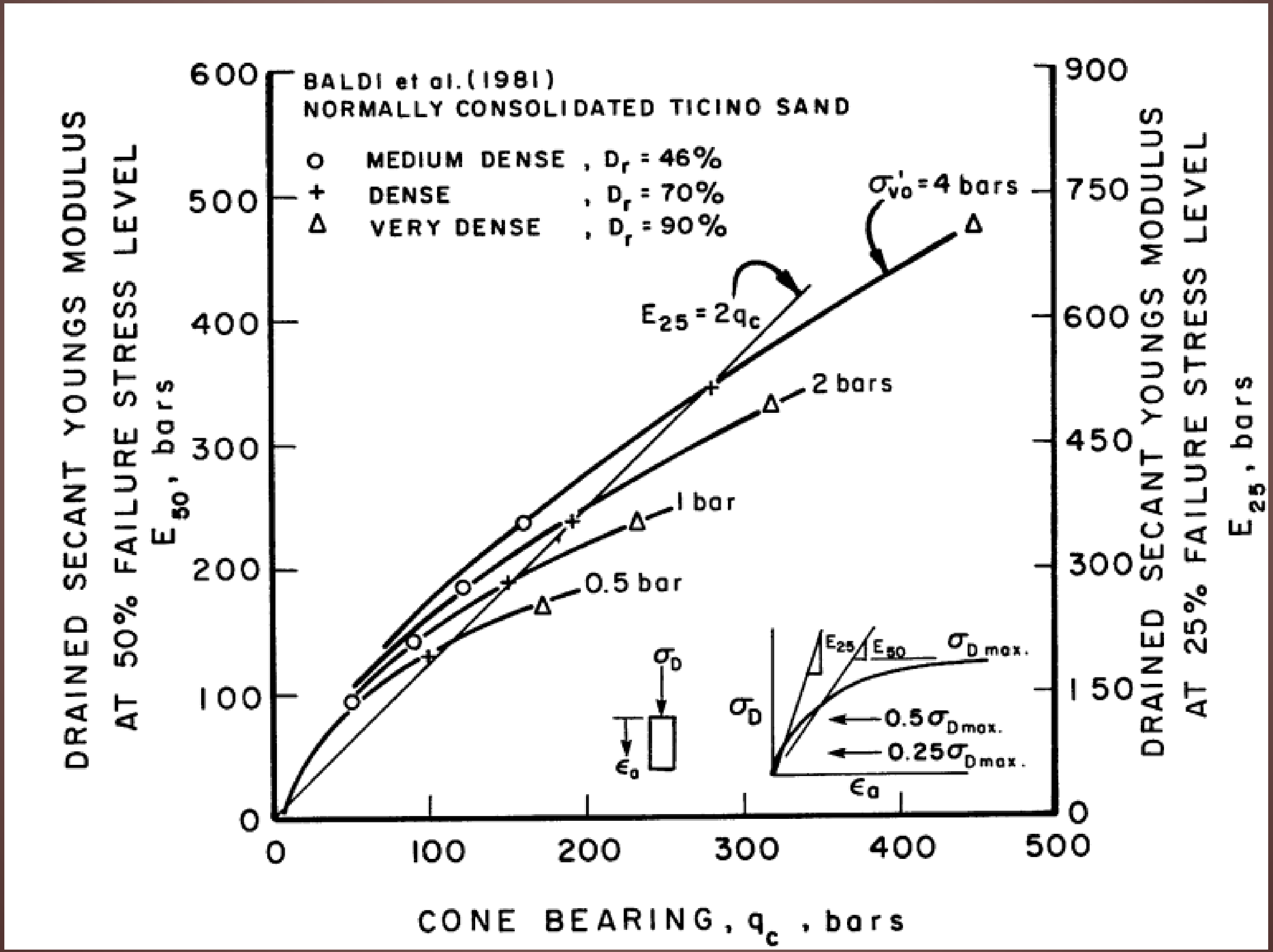


Stroud (1989)



Menzenbach (1967)

MODULUS



Robertson and Campanella (1981)

SHEAR MODULUS

$$G_{max} = 1000 \cdot K_2 \cdot (\sigma_m')^{1/2}$$

G_{max}, σ_m' in psf (2000 psf = 100 kPa)

K_2 : 120 – 170 (rock fills)

K_2 (sands)

D_R (%)	K_2
30	34
40	40
45	43
60	52
75	59
90	70

FORMULAS FOR SAND

$p^{ref} = 100\,\mathrm{kN/m^2}$:

$$E_{50}^{ref} = 60000\,RD/100 \quad [kN/m^2]$$

$$E_{oed}^{ref} = 60000\,RD/100 \quad [kN/m^2]$$

$$E_{ur}^{ref} = 180000\,RD/100 \quad [kN/m^2]$$

$$G_0^{ref} = 60000 + 68000\,RD/100 \quad [kN/m^2]$$

FORMULAS FOR SAND

Figure 1 shows the variation of G_0^{ref} with RD for different sands, in comparison with Equation 6.

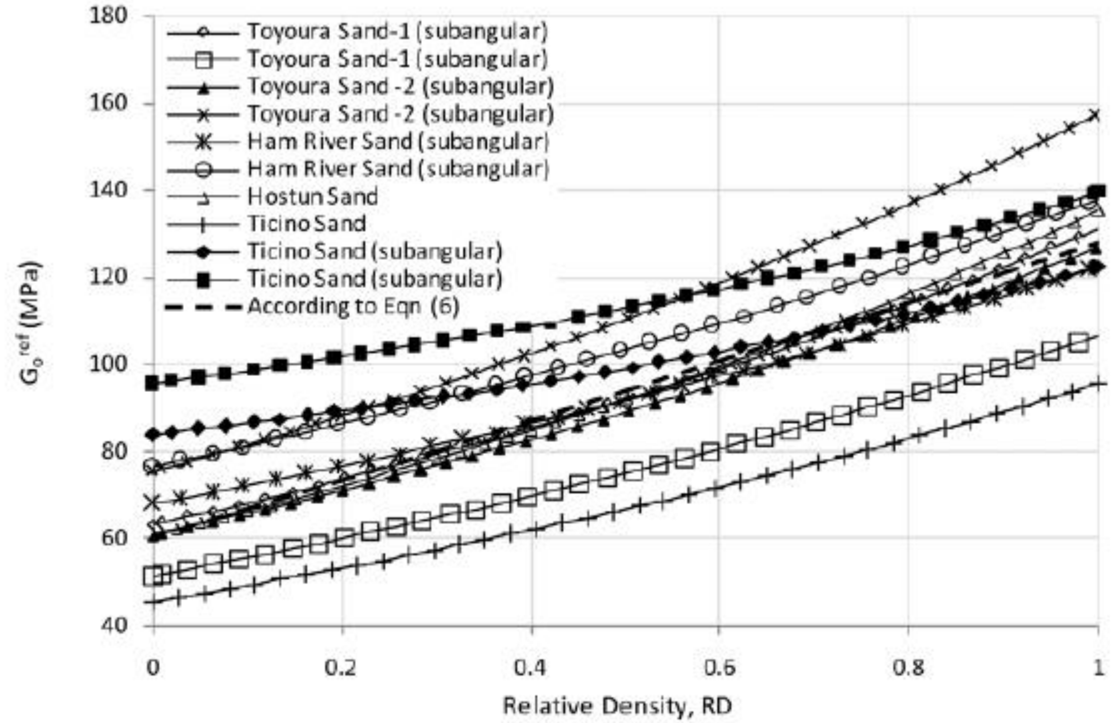


Figure 1. Comparison of formula for small-strain stiffness for different sands at different densities.

FORMULAS FOR SAND

The actual stiffness is stress-dependent. The rate of stress dependency, m, is observed to be negatively correlated with the density. The following formula is proposed for m:

$$m = 0.7 - RD / 320 \quad [-] \tag{7}$$

Poisson's ratio for unloading and reloading, ν_{ur}, is taken 0.2. The parameter relating the modulus reduction curve to the cyclic shear strain level is $\gamma_{0.7}$, for which the following formula is proposed:

$$\gamma_{0.7} = (2 - RD / 100) \cdot 10^{-4} \quad [-] \tag{8}$$

The following formulas are proposed for the strength-related properties:

$$\varphi' = 28 + 12.5\, RD / 100 \quad [^\circ] \tag{9}$$

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$$R_f = 1 - RD / 800 \quad [-] \tag{11}$$

FORMULAS FOR CLAY

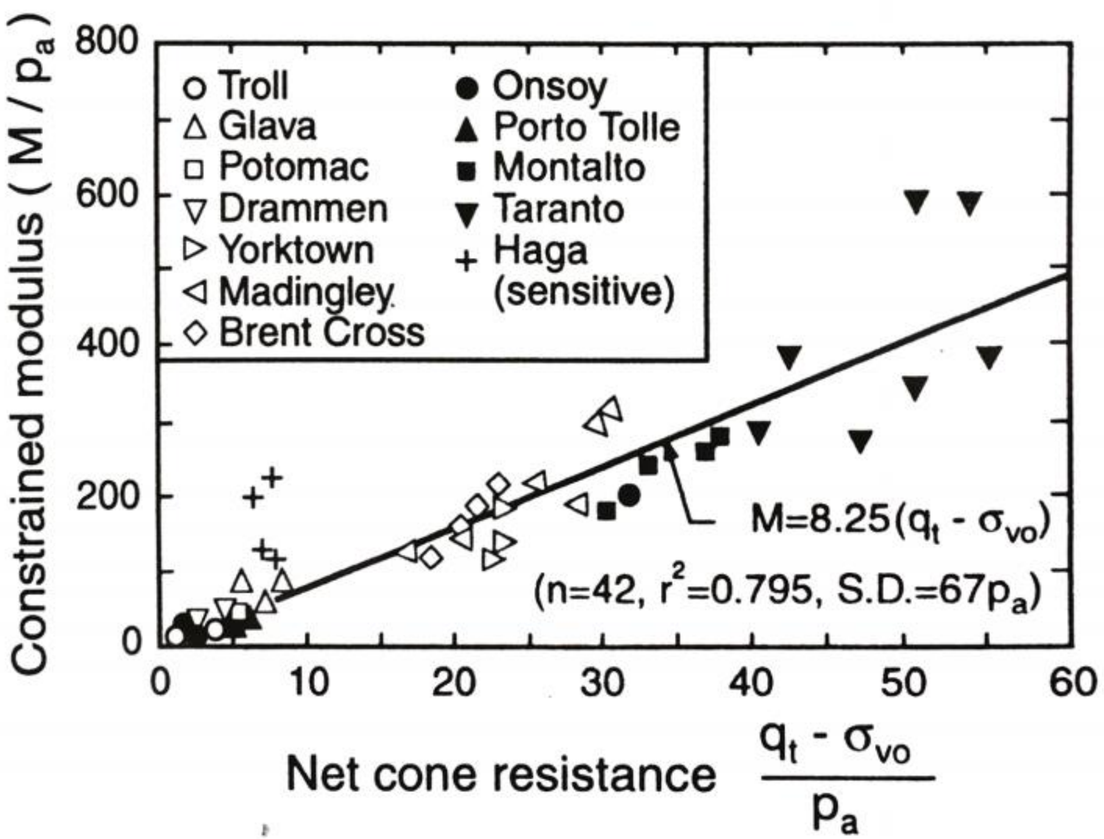


Figure 5.34 General relationship between constrained modulus and net cone resistance (from Kulhawy and Mayne, 1990).

$$G_o = 99.5\,(p_a)^{0.305}\,\frac{(q_t)^{0.695}}{(e_o)^{1.130}}$$

FORMULAS FOR CLAY

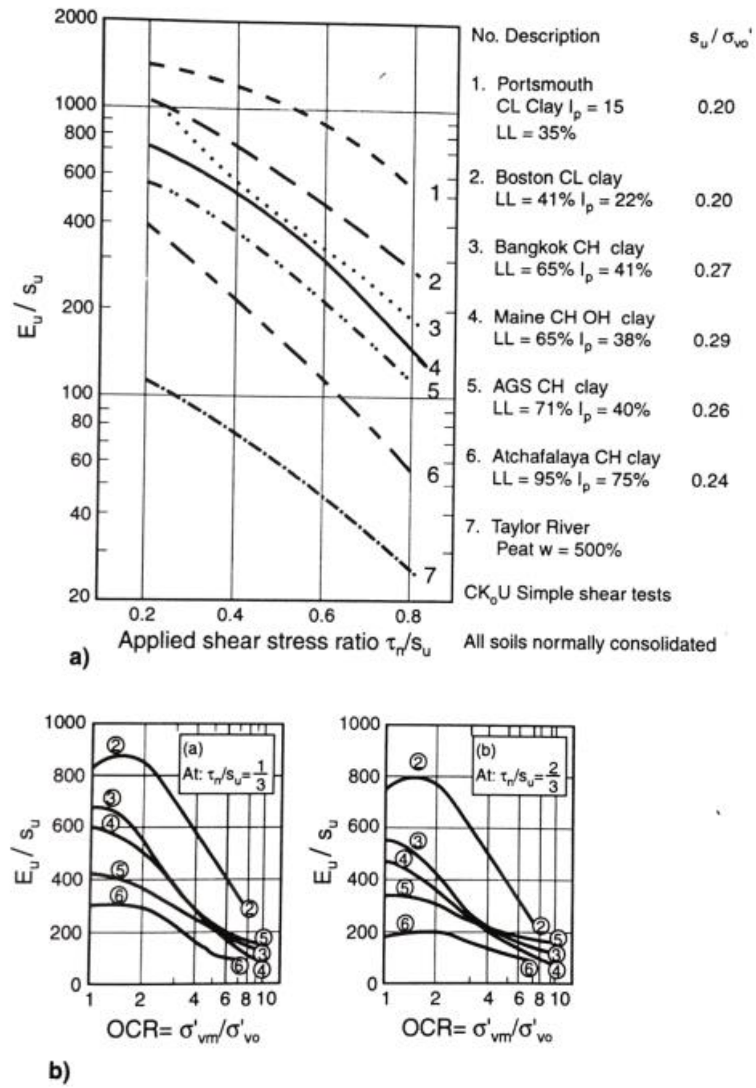


Figure 5.35 Stiffness ratio, E/s_u, as function of I_p (adapted from Ladd *et al.*, 1977).

FORMULAS FOR CLAY

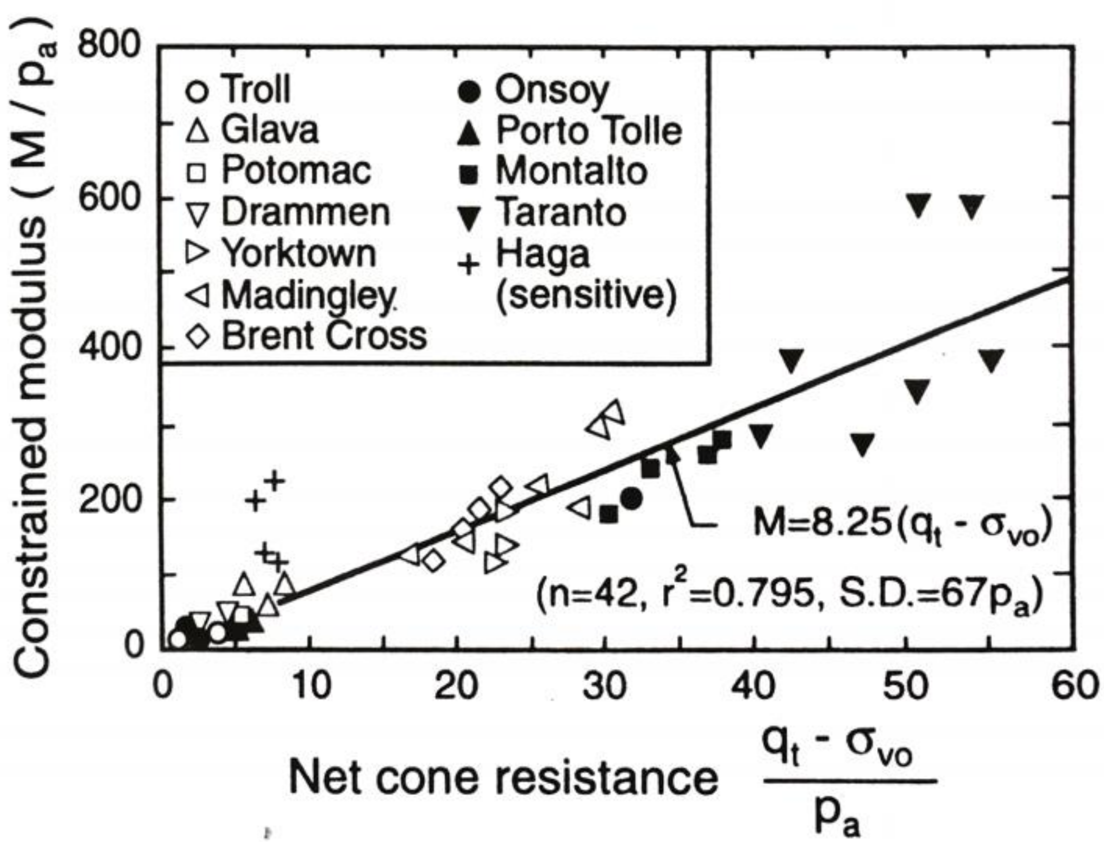


Figure 5.34 General relationship between constrained modulus and net cone resistance (from Kulhawy and Mayne, 1990).

FORMULAS FOR CLAY

Stiffness parameters for clay

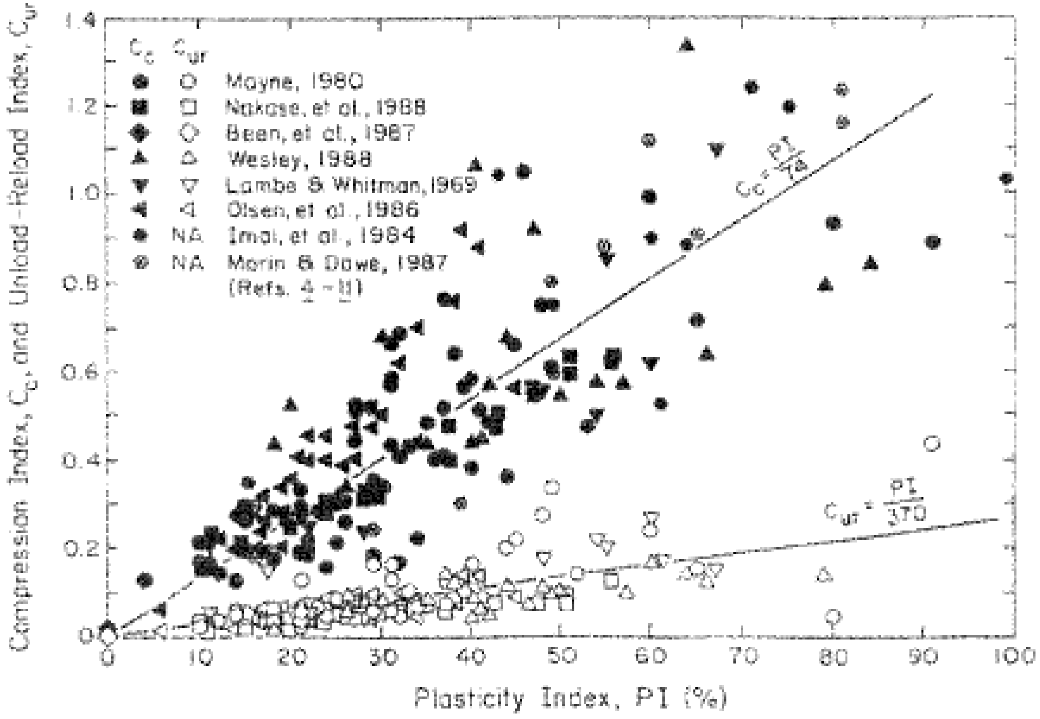


FIG. 16. Correlation for C_c and C_{ur} (C_s) based on plasticity index (Kulhawy & Maine, 1990)

FORMULAS FOR CLAY

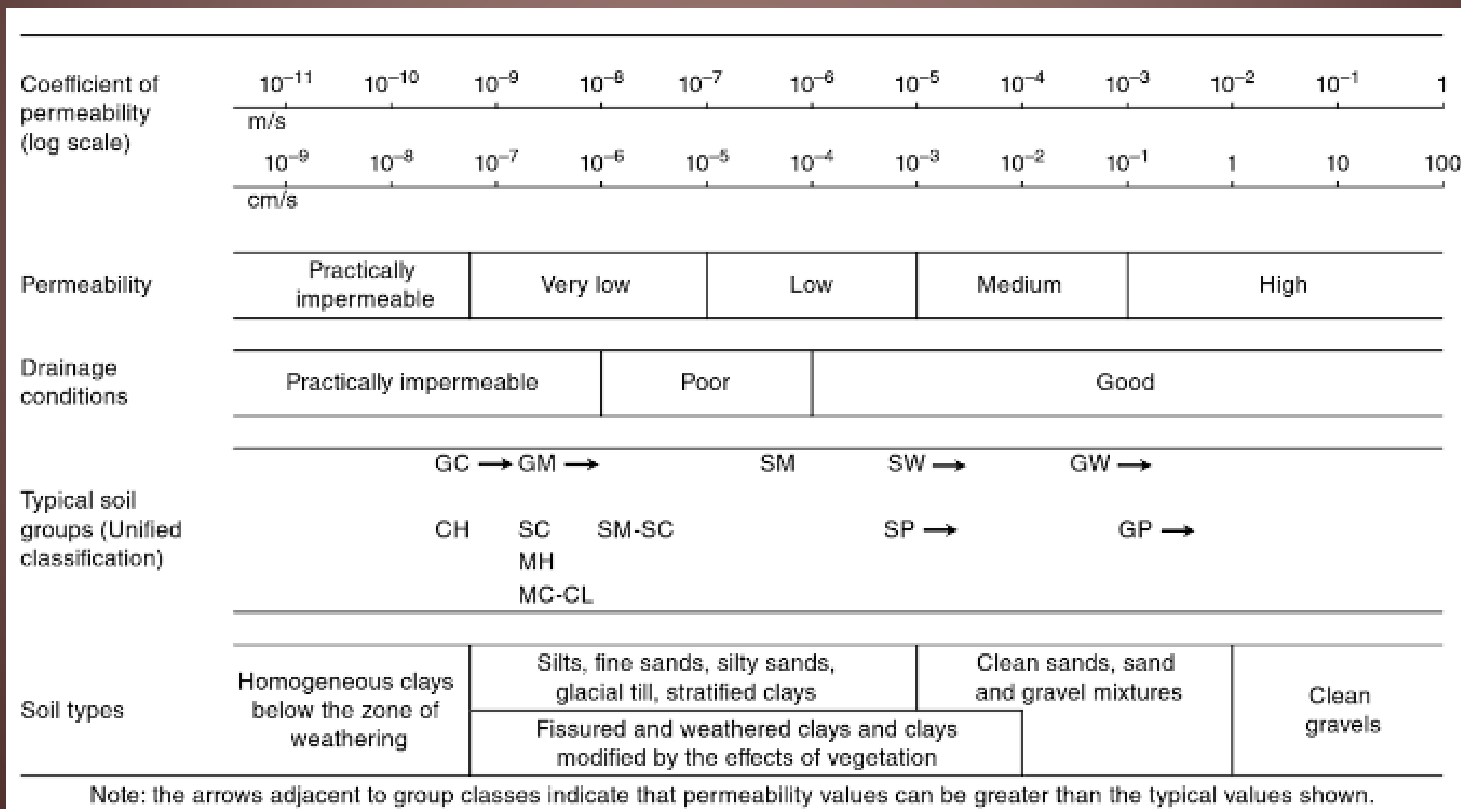
Stiffness parameters for clay

$$E_{oed}^{ref} \approx \frac{500kPa}{w_L - 0.1}$$

Correlation by Vermeer for HS model (NC clays and silts)

PERMEABILITY

Typical permeability values for soils



Casagrande and Fadum (1940)

PERMEABILITY

$$k = D_s^{\,2} \frac{\gamma}{\mu} \frac{e^3}{(1+e)} c$$

Taylor (1948)

k   Permeability constant

D_s Effective grain size

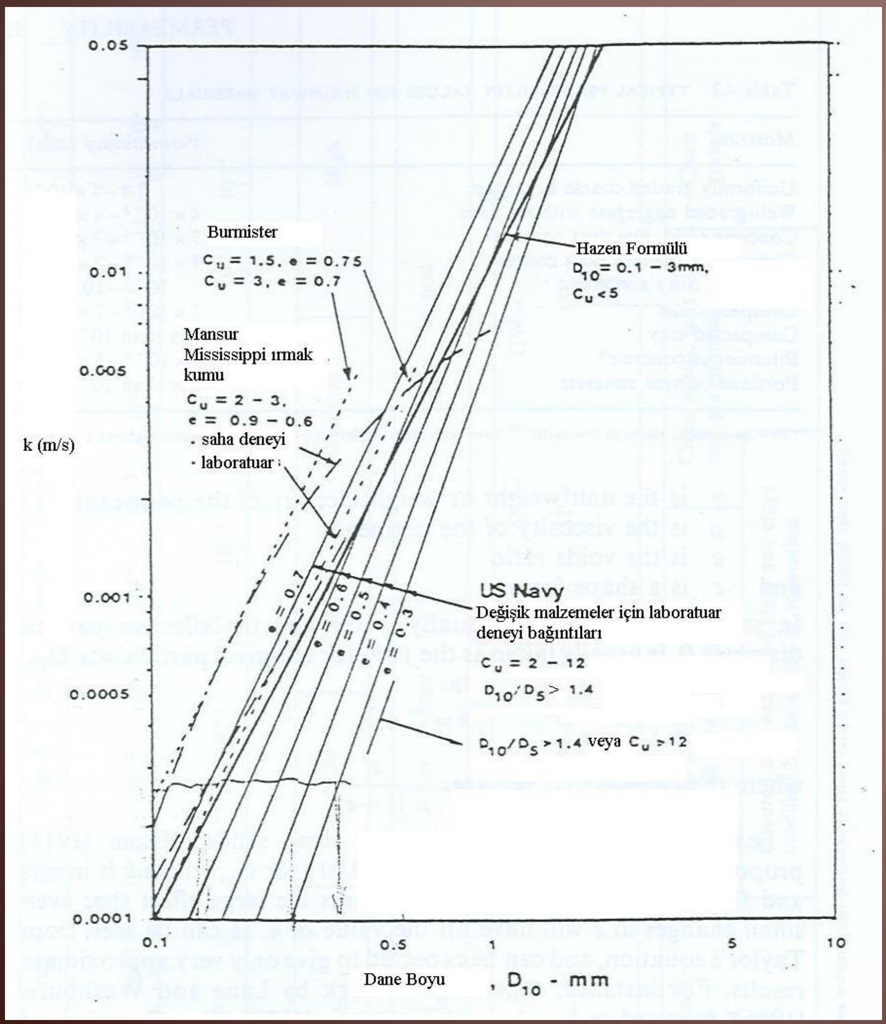
γ   Unit weight

μ   Viscocity

e   Void ratio

c   Shape factor

PERMEABILITY



Carter and Bentley (1991)