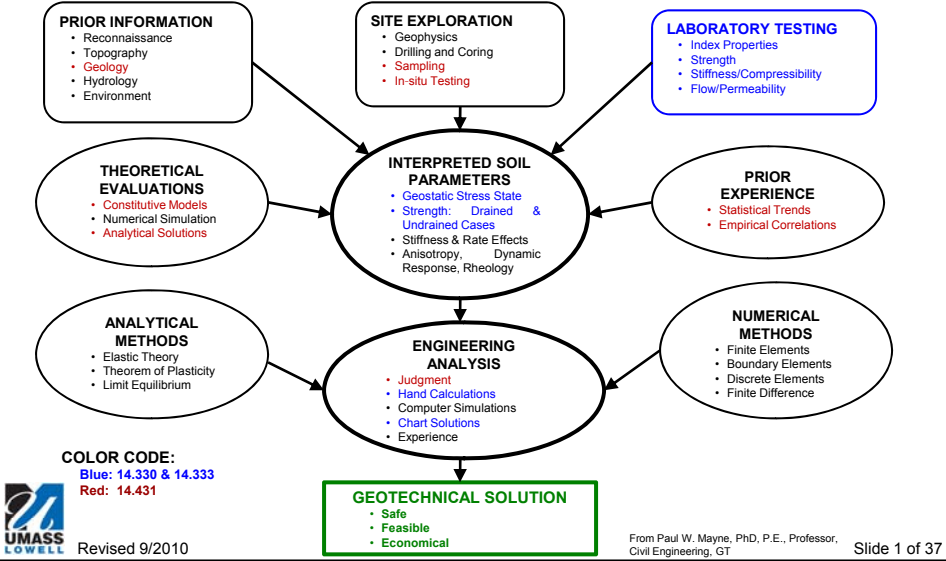


15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

DATA COLLECTION, INTERPRETATION, & ANALYSIS TO GEOTECHNICAL SOLUTIONS FLOW CHART

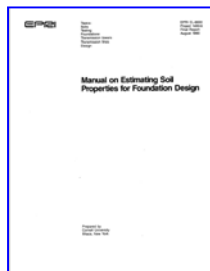


15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

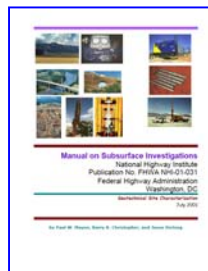
SELECTED REFERENCES YOU SHOULD HAVE IN YOUR LIBRARY



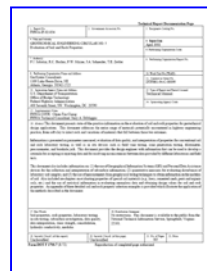
Naval Facilities Command (NAVFAC) Soil Mechanics (DM7.01, 1986)



EPRI EL-6800 Manual for Estimating Soil Properties for Foundation Design (Kulhawy & Mayne 1991)



FHWA Manual on Subsurface Investigations (NHI-01-031, 2001)



FHWA Evaluation of Soil & Rock Properties (IF-02-034, 2002)



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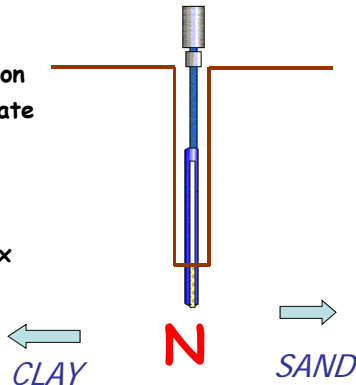
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15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

**STANDARD PENETRATION TEST**

- $c_u$  = undrained strength
- $\gamma_T$  = unit weight
- $I_R$  = rigidity index
- $\phi'$  = friction angle
- OCR = overconsolidation
- $K_0$  = lateral stress state
- $e_o$  = void ratio
- $V_s$  = shear wave
- $E'$  = Young's modulus
- $C_c$  = compression index
- $q_b$  = pile end bearing
- $f_s$  = pile skin friction
- $k$  = permeability
- $q_a$  = bearing stress

- $D_R$  = relative density
- $\gamma_T$  = unit weight
- LI = liquefaction index
- $\phi'$  = friction angle
- $c'$  = cohesion intercept
- $e_o$  = void ratio
- $q_a$  = bearing capacity
- $\sigma_p'$  = preconsolidation
- $V_s$  = shear wave
- $E'$  = Young's modulus
- $\Psi$  = dilatancy angle
- $q_b$  = pile end bearing
- $f_s$  = pile skin friction



What Do We Need? How Do We Get It?



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Interpretation of Subsurface Data

**CORRECTIONS TO SPT N VALUE**

$N_{\text{measured}}$  = Raw SPT Value from Field Test (ASTM D1586-08a)

$N_{60}$  = Corrected N values corresponding to 60% Energy Efficiency  
(i.e. The Energy Ratio (ER) = 60% (ASTM D4633-05))

Note: 30% < ER < 100% with average ER = 60% in the U.S.

$$N_{60} = C_E C_B C_S C_R N_{\text{measured}}$$

SPT Corrections  
From Table 9  
FHWA IF-02-034

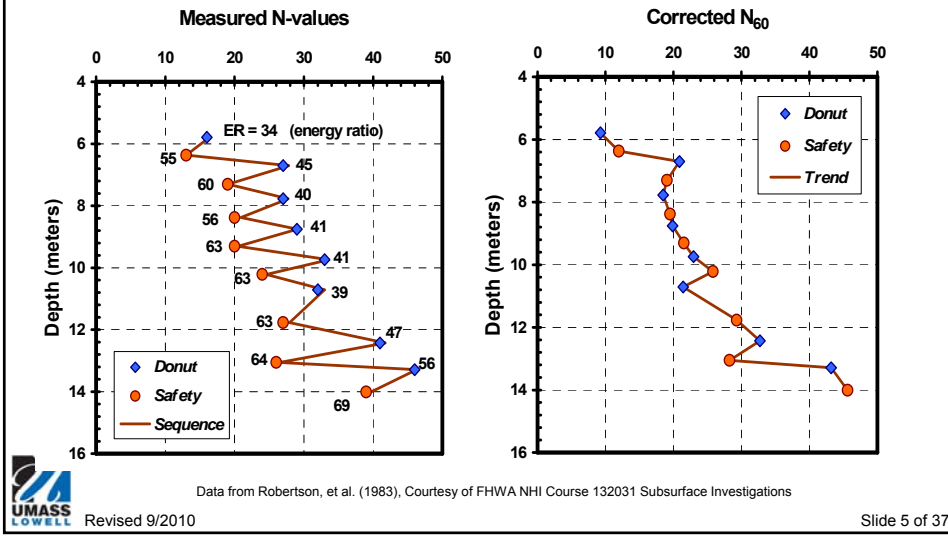
Factor	Term	Equipment Variable	Correction
Energy Ratio	$C_E = ER/60$	Donut Hammer	0.5 to 1.0
		Safety Hammer	0.7 to 1.2
		Automatic Hammer	0.8 to 1.5
Borehole Diameter	$C_B$	65 – 155 mm	1.00
		150 mm	1.05
		200 mm	1.15
Sampling Method	$C_S$	Standard Sampler	1.0
		Non-Standard Sampler	1.1 to 1.3
Rod Length	$C_R$	3 – 4 m	0.75
		4 – 6 m	0.85
		6 – 10 m	0.95
		> 10 m	1.00



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For Guidance Only. Actual ER values should be measured per ASTM D4633 Slide 4 of 37

**CORRECTIONS TO SPT N VALUE  
EXAMPLE OF DATA FROM SAME SITE**



**NORMALIZED SPT N VALUE  $(N_1)_{60}$**

$(N_1)_{60} = N_{60}$  values normalized to 1 atmosphere overburden stress.

$$(N_1)_{60} = C_N N_{60}$$

Where:

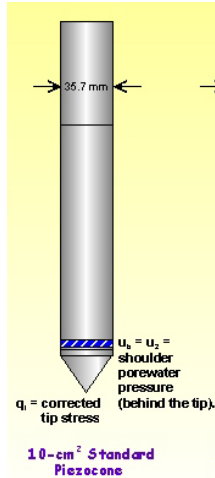
$$C_N = (P_a / \sigma'_{v0})^n$$

$P_a$  = Atmospheric Pressure (1 atm = 14.7 psi = 2116 psf = 1.06 tsf)

$\sigma'_{v0}$  = Insitu Vertical Effective Stress

$n = 1$  (clays) and 0.5 to 0.6 (sands)

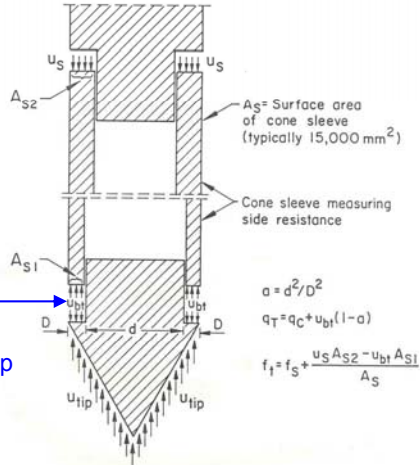
**CORRECTIONS TO CPT MEASUREMENTS (WITH  $U_2$ )**



Need to correct tip resistance ( $q_c$ ) for pore pressure @  $U_2$  location.

$$q_c \rightarrow q_t$$

$U_2 = U_b$   
Pore Pressure Measurement behind Tip



$$\alpha = d^2/D^2$$

$$q_t = q_c + u_{bt}(1-\alpha)$$

$$f_t = f_s + \frac{u_s A_{s2} - u_{bt} A_{s1}}{A_s}$$

**Porous Element for  $U_2$**

Materials: Sintered Metals, Ceramics, Plastics (disposable)

Saturation of Porous Elements: Water, Glycerine, Silicone

Procedures: Vacuum for 24-hours, Pre-Saturated Elements, Prophylactic to maintain fluids



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Courtesy of FHWA IF-02-034

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**WHAT DO WE NEED FOR GEOTECHNICAL DESIGN?**

1. **Geostratigraphy:**
  - Layering
  - Soil Types
  - Depth to Strata
2. **Total and Effective Soil Stresses:**
  - Soil Unit Weight ( $\gamma$  or  $\gamma_{sat} = \gamma_t$ )
  - GWT Location ( $u$ )
3. **Shear Strength:**
  - Effective Friction Angle ( $\phi'$ )
  - Effective Cohesion Intercept ( $c'$ )
  - Undrained Shear Strength ( $S_u$ )
4. **Stress State:**
  - Maximum Past Pressure ( $\sigma'_{vm}$ )
  - Overconsolidation Ratio (OCR)
  - Coefficient of Earth Pressure at Rest ( $K_0$ )
5. **Stiffness and Moduli:**
  - Elastic Modulus (E)
  - Shear Modulus (G)
  - Compression Index ( $C_c$ )
6. **Consistency:**
  - Void Ratio (e)
  - Relative Density ( $D_r$ )
7. **Flow Parameters:**
  - Coefficient of Permeability (k)
  - Coefficient of Consolidation ( $c_v, c_h$ )



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15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

**INSITU TESTS – APPLICABLE SOIL PROPERTIES**

Soil Property	SPT	CPT	DMT
Soil Classification	USCS	Behavior	Behavior
Groundwater Table	Yes	Yes	Possible
Effective Friction Angle ( $\phi'$ ) (Sands)	Yes	Yes	Yes
Relative Density ( $D_r$ ) (Sands)	Yes	Yes	Yes
Unit Weight ( $\gamma$ )	Yes	Yes	Yes
Undrained Shear Strength ( $S_u$ )	Possible <sup>1</sup>	Yes	Yes
Maximum Past Pressure ( $\sigma'_{vm}$ or $\sigma'_p$ )	Possible <sup>1</sup>	Yes	Yes
Overconsolidation Ratio (OCR)		Yes	
Shear Wave Velocity ( $V_s$ )		Yes (SCPTu)	Yes (SDMT)
Small Strain Shear Modulus ( $G_{max}$ )		Yes (SCPTu)	Yes (SDMT)
Small Strain Young's Modulus ( $E_{max}$ )		Yes (SCPTu)	Yes (SDMT)
E (Young's Modulus)	Possible <sup>1</sup>	Possible <sup>1</sup>	Yes
Coefficient of At-Rest Earth Pressure ( $K_0$ )		Yes	Yes
IBC Site Classification	Yes (N)	Yes ( $V_s$ , $S_u$ )	Yes ( $S_u$ )



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NOTES:

1. Possible, but not recommended for use.

After Table 10. FHWA IF-02-034

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Interpretation of Subsurface Data

**COEFFICIENT OF VARIATION (V) FOR GEOTECHNICAL PROPERTIES AND INSITU TESTS (after Duncan, 2000)**

Coefficient of Variation: A measure of dispersion of a probability distribution.

Measured or Interpreted Parameter	V (%)
Unit Weight ( $\gamma$ )	3 to 7
Effective Friction Angle ( $\phi'$ )	2 to 13
Undrained Shear Strength ( $S_u$ )	13 to 40
Undrained Shear Ratio ( $S_u/\sigma'_{vo}$ )	5 to 15
SPT N Value	15 to 45
Electric CPT Tip Resistance ( $q_t$ )	5 to 15

after Table 52. FHWA IF-02-034



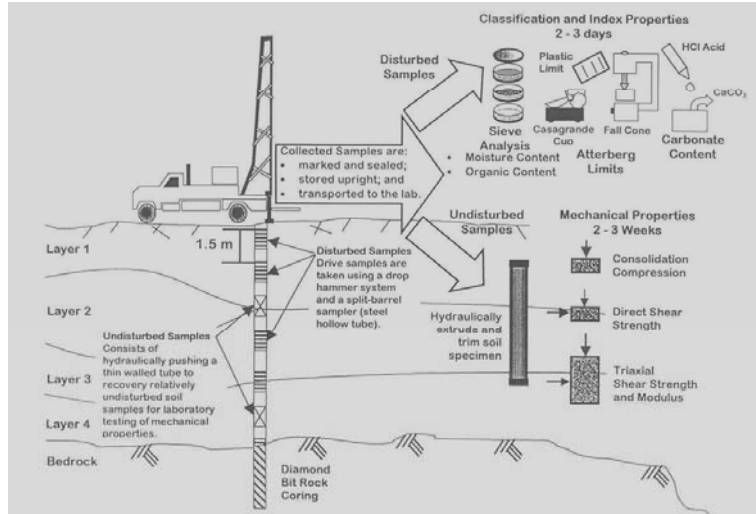
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Also see Chapter 8 – Applying Judgment in Selecting Soil and Rock Properties for Design (FHWA IF-02-034).

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Interpretation of Subsurface Data

SOIL BORINGS – DETERMINATION OF SOIL STRATIGRAPHY



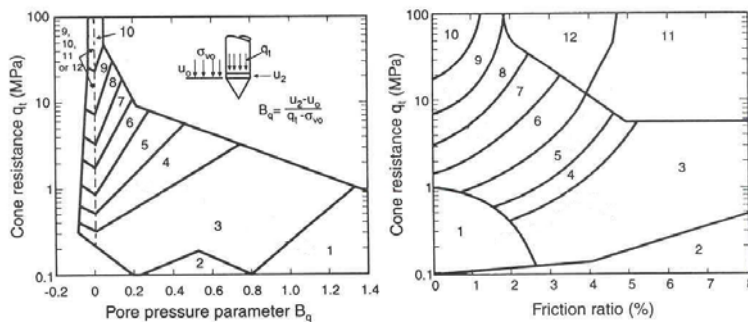
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Figure 9-1. FHWA NHI Course 132031 Subsurface Investigations

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Interpretation of Subsurface Data

CONE PENETRATION TEST (CPT)  
DETERMINATION OF SOIL STRATIGRAPHY



Zone: Soil Behaviour Type:

- |                           |                              |                              |
|---------------------------|------------------------------|------------------------------|
| 1. Sensitive fine grained | 5. Clayey silt to silty clay | 9. Sand                      |
| 2. Organic material       | 6. Sandy silt to clayey silt | 10. Gravelly sand to sand    |
| 3. Clay                   | 7. Silty sand to sandy silt  | 11. Very stiff fine grained* |
| 4. Silty clay to clay     | 8. Sand to silty sand        | 12. Sand to clayey sand*     |

\* Overconsolidated or cemented.

CPT Soil Behavior Classification  
(Based on  $q_t$ , FR or  $B_q$ )

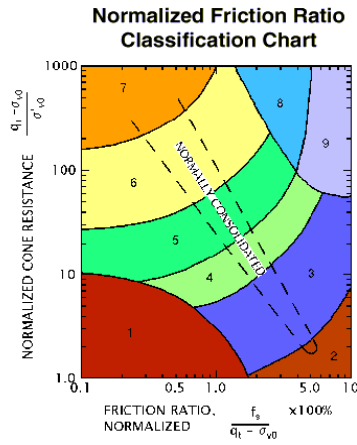


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Figure 9-3. FHWA NHI Course 132031 Subsurface Investigations

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**CONE PENETRATION TEST (CPT)  
DETERMINATION OF SOIL STRATIGRAPHY**



Zone	Q <sub>t</sub> /N	Description
1	2	Sensitive, Fine Grained
2	1	Organic Soils-Peats
3	1.5	Clays-Clay to Silty Clay
4	2	Silt Mixtures-Clayey Silt to Silty Clay
5	3	Sand Mixtures-Silty Sand to Sandy Silt
6	4.5	Sands-Clean Sand to Silty Sand
7	6	Gravelly Sand to Sand
8	1	Very Stiff Sand to Clayey Sand *
9	2	Very Stiff, Fine Grained *

(Ref. Robertson, 1990)

(\*) Heavily Overconsolidated or Cemented

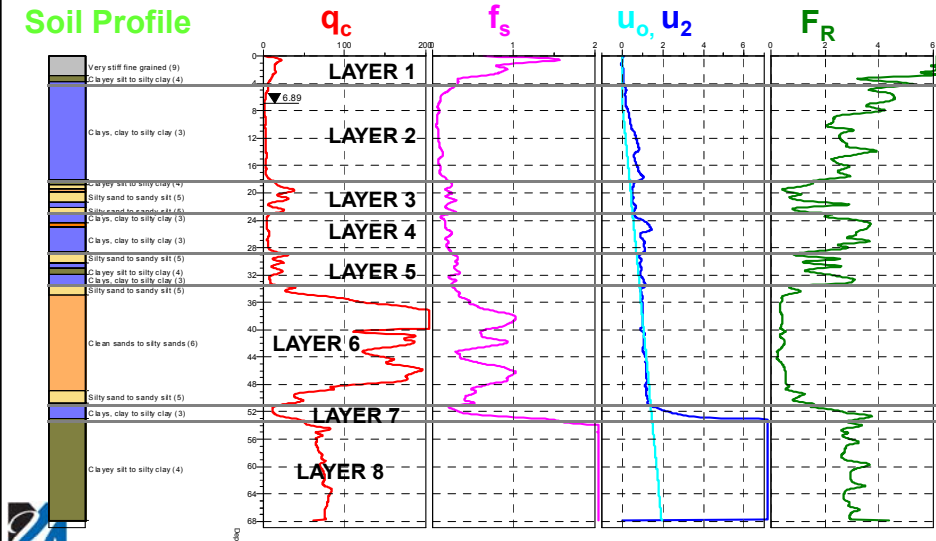


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**CONE PENETRATION TESTING (CPT) RESULTS**

**Soil Profile**



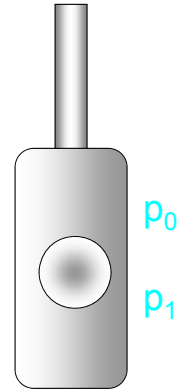
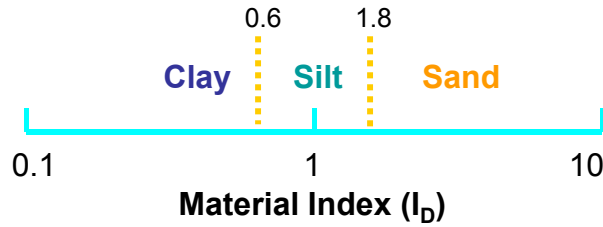
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CPT Results courtesy of WPC Engineering Inc.

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**FLAT PLATE DILATOMETER  
DETERMINATION OF SUBSURFACE DATA**

$$\text{Material Index, } I_D = \frac{p_1 - p_0}{p_0 - u_0}$$



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Courtesy of FHWA NHI Course 132031 Subsurface Investigations

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**FLAT PLATE DILATOMETER  
DETERMINATION OF SUBSURFACE DATA**

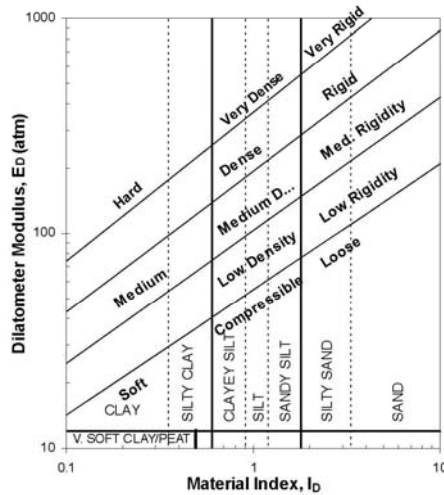


Figure 43. FHWA IF-02-034



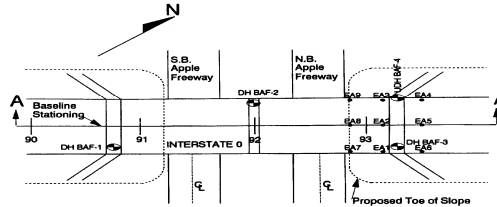
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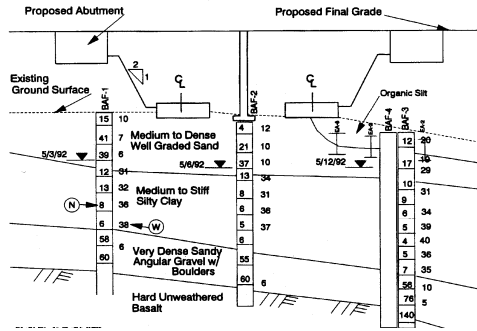
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Interpretation of Subsurface Data

SOIL PROFILE (EXAMPLE)

Plan View  
(Boring Locations)



Soil Profile  
(Cross-Section)



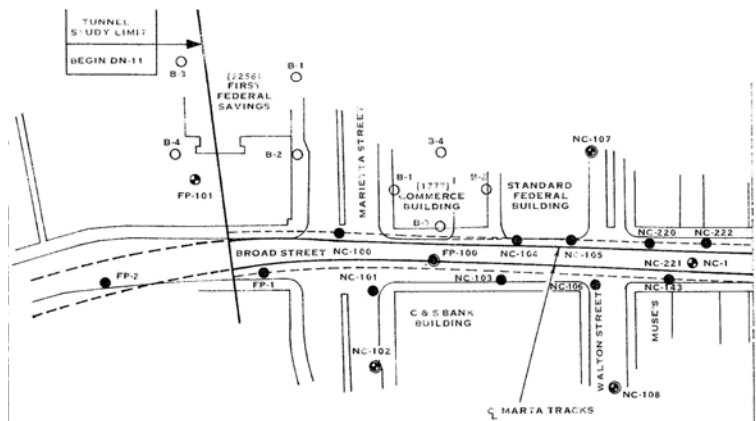
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Figure courtesy of FHWA

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Interpretation of Subsurface Data

SOIL PROFILE (EXAMPLE)



Boring Location Plan



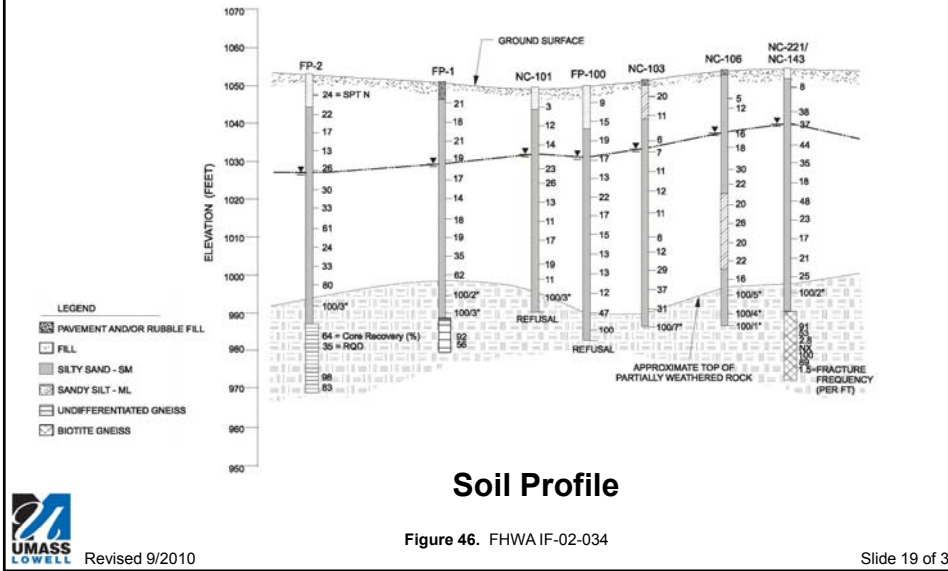
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Figure 45. FHWA IF-02-034

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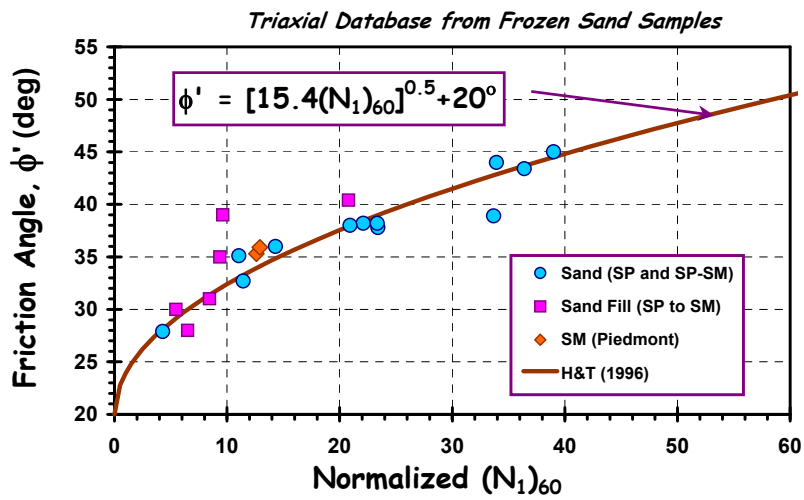
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Interpretation of Subsurface Data

SOIL PROFILE (EXAMPLE)



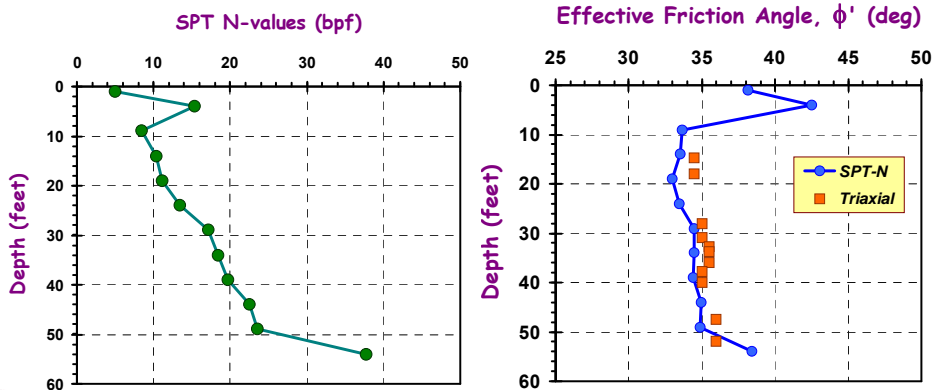
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Interpretation of Subsurface Data

EFFECTIVE FRICTION ANGLE ( $\phi'$ ) FOR SANDS - SPT



**EFFECTIVE FRICTION ANGLE ( $\phi'$ ) FOR SANDS - SPT**

Comparison of  $\phi'$  from SPT and Laboratory Tests  
Piedmont Residuum (GT Campus) – Silty Sand (SM)



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Courtesy FHWA NHI Course 132031 Subsurface Investigations

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**EFFECTIVE FRICTION ANGLE ( $\phi'$ ) FOR SANDS - CPT**

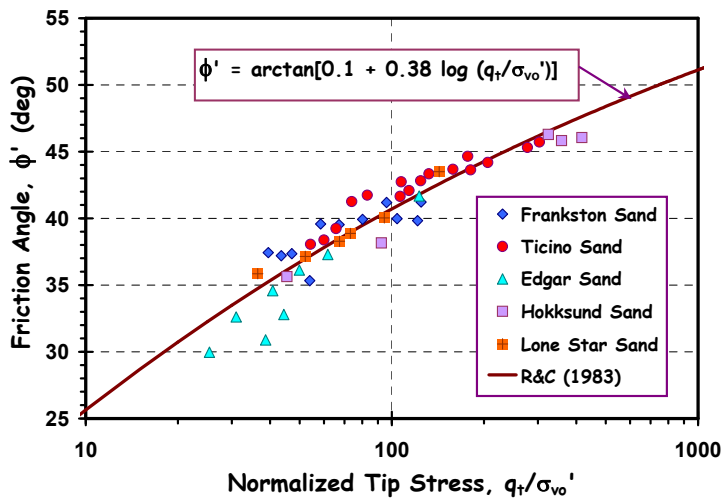
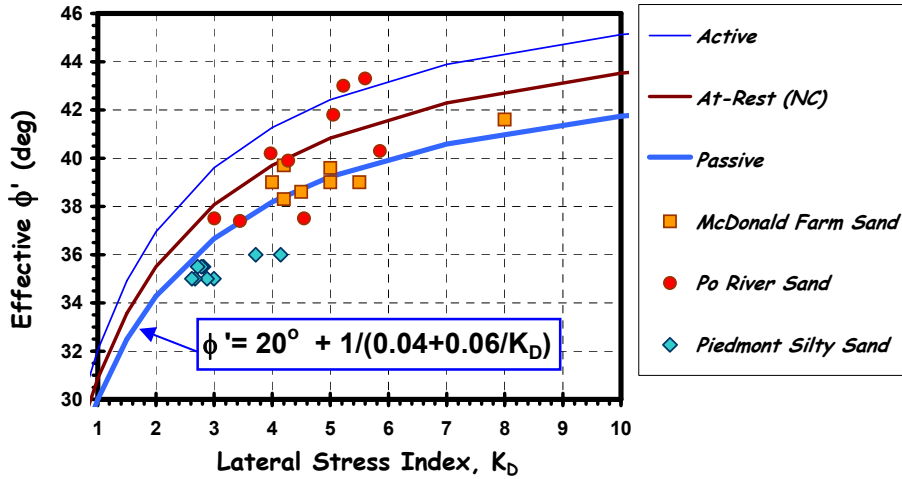


Figure 9-13. FHWA NHI Course 132031 Subsurface Investigations

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**EFFECTIVE FRICTION ANGLE ( $\phi'$ ) FOR SANDS - DMT**



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Figure 9-14. FHWA NHI Course 132031 Subsurface Investigations

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**SOIL SHEAR STRENGTH CORRELATIONS FROM INSITU TESTING**

Shear Strength Parameter	Insitu Testing Method		
	SPT	CPT	DMT
Effective Soil Friction Angle ( $\phi'$ )	See Slide 25	$\arctan[0.1 + 0.38 \log(q_t/\sigma'_{vo})]$	$28^\circ + 14.6^\circ \log(K_D) - 2.1^\circ \log^2 K_D$
	See Slide 25	Robertson and Campanella (1983)	Marchetti et al. (2001) ISSMGE TC 16 Report
Undrained Shear Strength ( $S_u$ )	NO ACCEPTABLE CORRELATIONS	$(q_t - \sigma_{vo})/N_{kt}$ ( $N_{kt} = 15$ for CHS)	$0.22 \sigma'_{vo} (0.5 K_D)^{1.25}$
		Aas et al. (1986)	Marchetti et al. (2001) ISSMGE TC 16 Report

**NOTES:**

- $(N_1)_{60} = N_{60} (P_a/\sigma'_{vo})^{0.5}$  for sands.  $P_a$  = Atmospheric Pressure = 1 bar  $\approx$  1 tsf.
- $\sigma'_{vo}$  = Insitu Effective Overburden Pressure = Insitu Vertical Effective Stress.
- $\sigma_{vo}$  = Total Overburden Pressure = Insitu Vertical Total Stress.



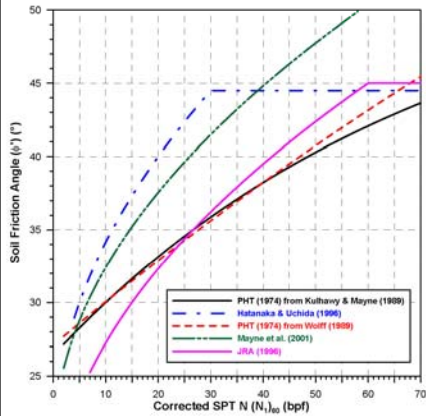
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Interpretation of Subsurface Data

**SOIL SHEAR STRENGTH CORRELATIONS  
FROM INSITU TESTING**

Effective Soil Friction Angle ( $\phi'$ ) summary from NCHRP Report 651 (2010)



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Equation	Reference
$54^\circ - 27.6034 \cdot \exp(-0.014(N_1)_{60})$	Peck, Hanson, & Thorton (1974) from Kulhawy & Mayne (1990)
$\phi' = [20 \cdot (N_1)_{60}]^{0.5} + 20^\circ$ for $3.5 \leq (N_1)_{60} \leq 30$	Hatanaka & Uchida (1996)
$\phi' = 27.1^\circ + 0.3 \cdot (N_1)_{60} - 0.00054 \cdot (N_1)_{60}^2$	Peck, Hanson, & Thorton (1974) from Wolff (1989)
$\phi' = [15.4 \cdot (N_1)_{60}]^{0.5} + 20^\circ$	Mayne et al. (2001) based on Hatanaka & Uchida (1996)
$\phi' = [15 \cdot (N_1)_{60}]^{0.5} + 15^\circ$ for $(N_1)_{60} > 5$ and $\phi \leq 45^\circ$	JRA (1996)

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15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

**SOIL ENGINEERING PROPERTY CORRELATIONS  
FROM INSITU TESTING (TABLE 1)**

Soil	Density/Consistency	N	$q_t$ (MPa)	$\gamma_t$ (pcf)	$\phi'$ ( $^\circ$ )
SANDS	V. Loose	0-4	0-2	90-105	<30
	Loose	5-10	2-5	95-110	30-35
	Medium Dense	11-30	5-15	105-120	35-38
	Dense	31-50	15-25	115-130	38-41
	Very Dense	>50	>25	125-140	41-44
COHESIVE SOILS	Very Soft	0-2	0-0.5	90-100	NA
	Firm	2-8	0.5-1.5	90-110	
	Stiff	9-15	1.5-3	105-125	
	Very Stiff	15-30	3-6	115-135	
	Hard	>30	>6	120-140	



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after Fang et al. (1991) and EM 1110-1-1905.

NOTE: 1 MPa = 10.44 tsf

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15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

**SOIL ENGINEERING PROPERTIES DETERMINATION**  
**Maximum Allowable Shear Strengths (SCDOT, 2010)**

Table 7-15, Maximum Allowable Total Soil Shear Strengths

Soil Type		Peak		Residual	
		c (psf)	$\phi$ (degrees)	$c_r$ (psf)	$\phi_r$ (degrees)
USCS	Description				
GW, GP, GM, GC	Stone and Gravel	0	34	0	18
	Coarse Grained Sand	0	17	0	7
SM, SP	Fine Grained Sand	0	17	0	7
	Uniform Rounded Sand	0	15	0	6
ML, MH, SC	Silt, Clayey Sand, Clayey Silt	1,500	15	1,200	6
	Residual Soils	900	14	700	6
CL-ML	NC Clay (Low Plasticity)	1,500	0	900	0
CL, CH	NC Clay (Med-High Plasticity)	2,500	0	1250	0
CL-ML	OC Clay (Low Plasticity)	2,500	0	1400	0
CL, CH	OC Clay (Med-High Plasticity)	4,000	0	2000	0

**Cannot be exceeded with laboratory testing**  
**AND**  
**written permission from SCDOT**



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15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

**SOIL ENGINEERING PROPERTIES DETERMINATION**  
**Maximum Allowable Shear Strengths (SCDOT, 2010)**

Table 7-16, Maximum Allowable Effective Soil Shear Strengths

Soil Description		Peak <sup>(1)</sup>		Residual	
		c (psf)	$\phi$ (degrees)	c (psf)	$\phi$ (degrees)
USCS	Description				
GW, GP, GM, GC	Stone and Gravel	0	40	0	34
	Coarse Grained Sand	0	38	0	32
SM, SP	Fine Grained Sand	0	36	0	30
	Uniform Rounded Sand	0	32	0	32
ML, MH, SC	Silt, Clayey Sand, Clayey Silt	0	30	0	27
	Residual Soils	0	27	0	22
CL-ML	NC Clay (Low Plasticity)	0	35	0	31
CL, CH	NC Clay (Med-High Plasticity)	0	26	0	16
CL-ML	OC Clay (Low Plasticity)	0	34	0	31
CL, CH	OC Clay (Med-High Plasticity)	0	28	0	16

(1) The same maximum peak effective shear strength parameters shall be used for peak effective internal friction angle of normally consolidated cohesive soils and to the fully-softened internal friction angle of overconsolidated cohesive soils.

**Cannot be exceeded with laboratory testing**  
**AND**  
**written permission from SCDOT**



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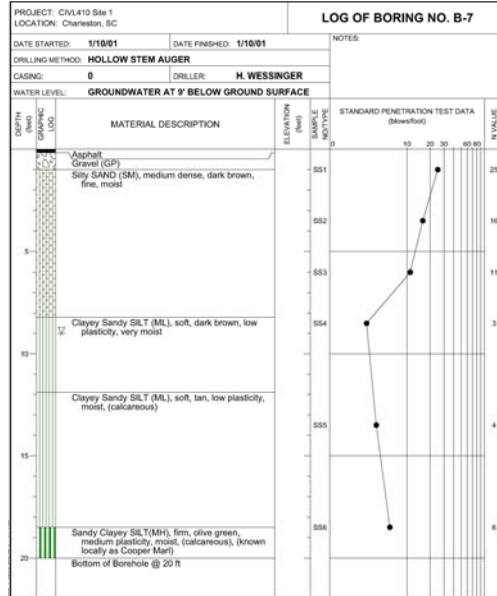
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15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

**EXAMPLE INTERPRETATION - SPT Given Data**

**Provided:**

- Soil Stratigraphy
- USCS Classification
- Groundwater Table (@ Time of Testing)
- SPT N Values (No Energy Measurements)
- Drilling Method (HSA)
- Date Started/Ended

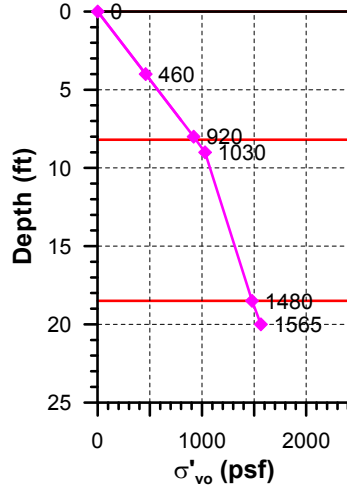
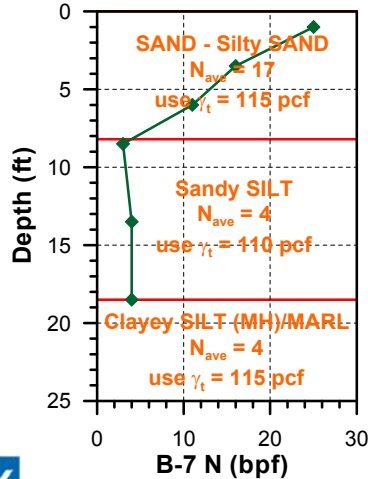


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15.533 ADVANCED FOUNDATION ENGINEERING  
Interpretation of Subsurface Data

**EXAMPLE INTERPRETATION - SPT Determination of  $N_{ave}$ ,  $\gamma_t$ , and  $\sigma'_{vo}$**

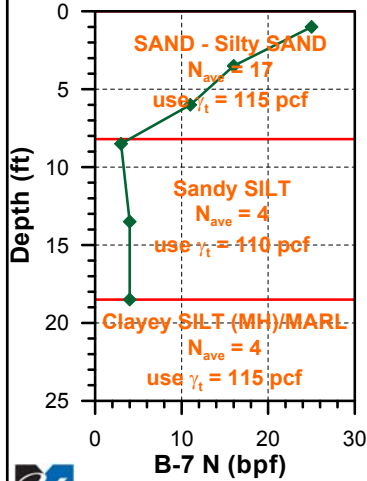


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Interpretation of Subsurface Data

**EXAMPLE INTERPRETATION – SPT**  
**Determination of Effective Friction Angle ( $\phi'$ )**



Calculate  $N_{ave}$  for sand layer from 0 to 8 ft.

**Simple Way:**  
Using Table 1 (Lecture Notes)

$N_{ave} = 17$ , therefore  $\phi' \approx 36^\circ$

**Formula Way:**  
Use Mayne et al. (2001)

$$\phi' = [15.4(N_1)_{60}]^{0.5} + 20^\circ \text{ and } (N_1)_{60} = N_{60}(P_a/\sigma'_{vo})^{0.5}$$

Use  $N_{ave} = 17$ ,  $\sigma'_{vo,ave} = 460$  psf, and  $P_a = 2115$  psf  
Therefore,  $(N_1)_{60} = 17(2115/460)^{0.5} = 36$

Using equation  $\phi' = [15.4(N_1)_{60}]^{0.5} + 20^\circ$ ,  $\phi' = 44^\circ$

**USE  $\phi' = 36^\circ$**

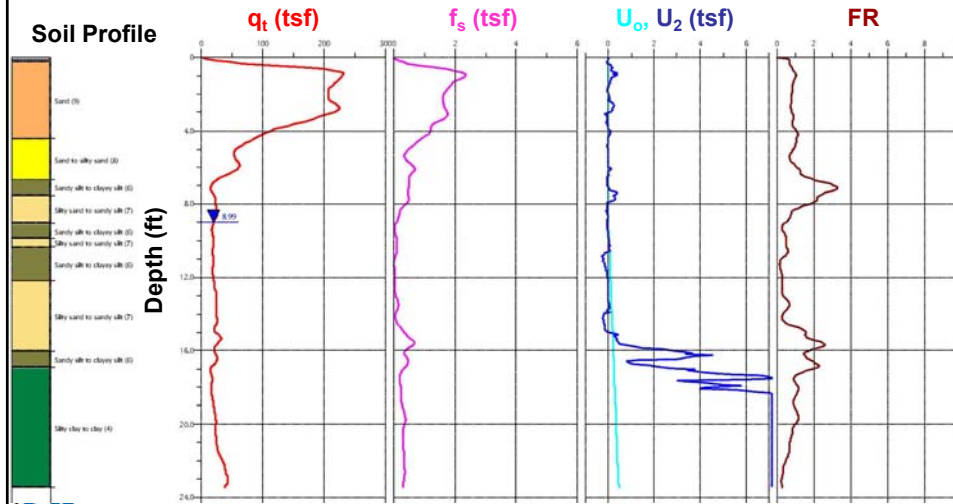


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Interpretation of Subsurface Data

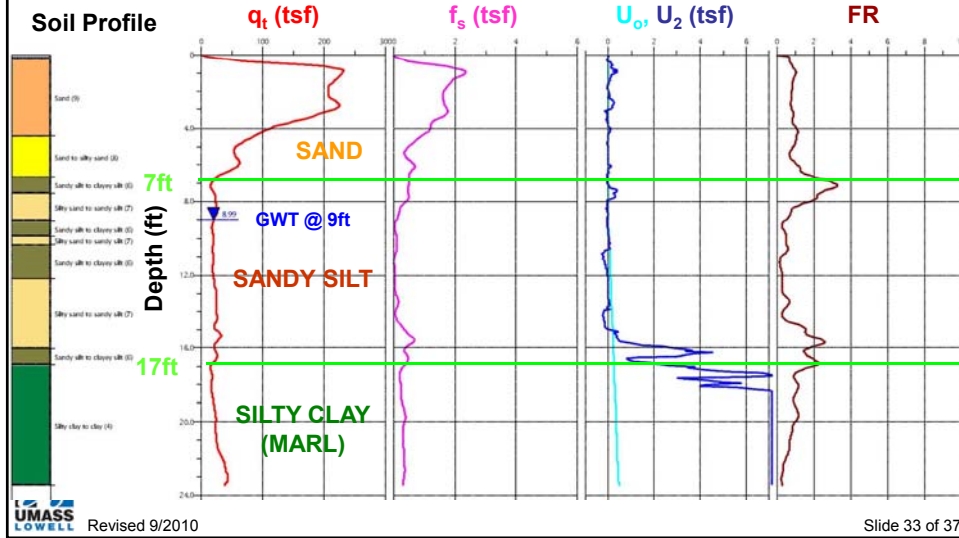
**EXAMPLE INTERPRETATION – CPT**  
**Given Data**



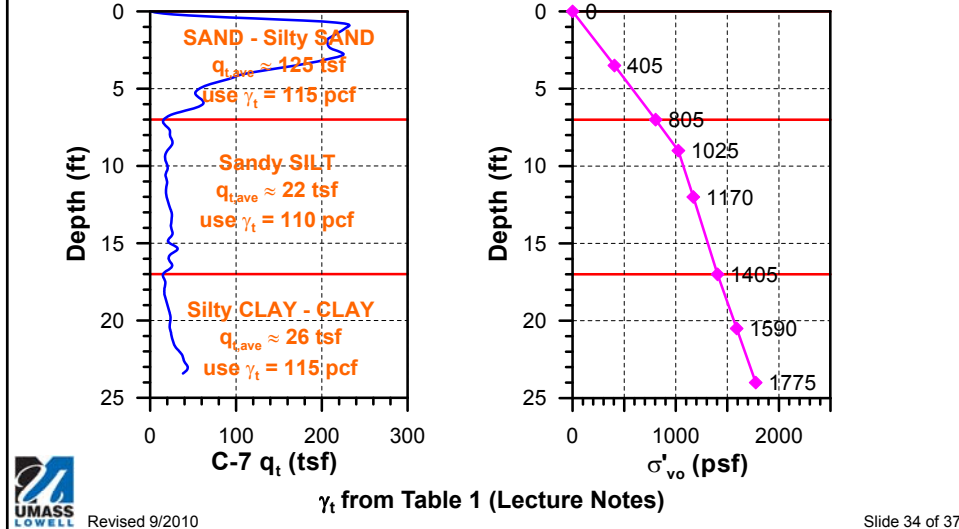
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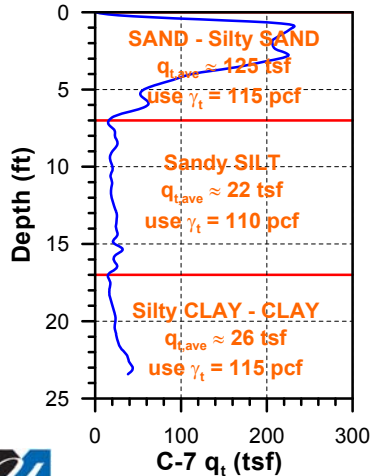
**EXAMPLE INTERPRETATION – CPT**  
**Determination of Soil Layers**



**EXAMPLE INTERPRETATION – CPT**  
**Determination of  $q_{t,ave}$ ,  $\gamma_t$  and  $\sigma'_{vo}$**



**EXAMPLE INTERPRETATION – CPT**  
**Determination of Effective Friction Angle ( $\phi'$ )**



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Calculate  $q_{t,ave}$  for sand layer from 0 to 7 ft

**Simple Way:**  
Using Table 1 (Lecture Notes)

$q_{t,ave} \approx 125$  tsf  $\approx 12$  MPa  
therefore  $\phi' \approx 37^\circ$

**Formula Way:**  
Using Robertson and Campanella (1983) formula.

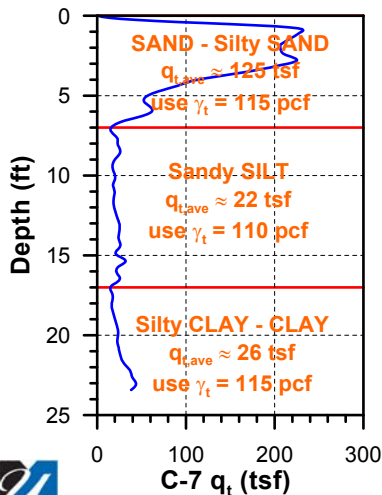
$$\phi' = \arctan[0.1 + 0.38 \log(q_t / \sigma'_{vo})]$$

Use  $q_{t,ave} \approx 12$  MPa (250000 psf) &  
 $\sigma'_{vo,ave} = 405$  psf for layer.  
Using equation,  $\phi' = 49^\circ$

**USE  $\phi' \approx 37^\circ$**

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**EXAMPLE INTERPRETATION – CPT**  
**Determination of Undrained Shear Strength ( $S_u$ )**



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Calculate  $q_{t,ave}$  for Sandy Silt from 7 to 17 ft  
Calculate  $q_{t,ave}$  for Silty Clay from 17 to 24 ft

**Formula Way:**  
use Aas et al. (1986)

$$S_u = (q_t - \sigma_{vo}) / N_{kt}$$

$N_{kt} = 15$  for CHS (Lecture Slides)

Sandy SILT Layer  
Use  $q_{t,ave} \approx 22$  tsf &  $\sigma_{vo,ave} = 1355$  psf  
 **$S_u = 2850$  psf**

Silty CLAY Layer  
Use  $q_{t,ave} \approx 26$  tsf &  $\sigma_{vo,ave} = 2310$  psf  
 **$S_u = 3300$  psf**

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**EXAMPLE INTERPRETATION – SPT & CPT**  
**Comparison of Soil Engineering Properties**

