Chapter 2
Natural Soil Deposits and Subsoil Exploration
Review of Effective Stress

<table>
<thead>
<tr>
<th>Point</th>
<th>Total Stress</th>
<th>Effective Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$\sigma_0 = 115 \times 6 = 690$ psf</td>
<td>$\sigma_0 = 115 \times 6 = 690$ psf</td>
</tr>
<tr>
<td>B</td>
<td>$\sigma_0 = \sigma_0@A + 95 \times 12 = 1140 + 690 = 1830$ psf</td>
<td>$\sigma_0 = \sigma_0 - u = 1830 - 12 \times 62.4 = 1101$ psf</td>
</tr>
<tr>
<td>C</td>
<td>$\sigma_0 = \sigma_0@B + 105 \times 8 = 1830 + 840 = 2670$ psf</td>
<td>$\sigma_0 = \sigma_0 - u = 2670 - (20 \times 62.4) = 1442$ psf</td>
</tr>
</tbody>
</table>
Perhaps those engineers who are well trained in geology have the advantage, for they are likely to take mother nature as she exists, rather than as has been created in the mind of the engineer.

Ralph B. Peck
Norfolk Cruise Terminal

**Notes:**
- **Stratum 1A** - Very soft to soft, silty CLAY (CL & CH)
- **Stratum 1B** - Very soft, organic CLAY (OH)
- **Stratum 2A** - Very loose to dense, slightly silty, silty & clayey SAND (SP-SM, SM & SC)
- **Stratum 2B** - Fill as Silty SAND (SM) with debris
- **Stratum 3** - Loose to firm, silty SAND (SM) – Yorktown Formation
Route 123 Bridge Over Occoquan River
DD(X) Land Based Test Facility

Bridge

Loose silty SAND (SM)

Typical groundwater

Loose silty SAND (SM)

Very loose to firm/soft silty SAND (SP-SM)

Very soft to soft silty CLAY (CH)

Very soft to stiff organic CLAY (OH)

Firm to stiff silty CLAY (CH)

Proposed Finished Floor Elevation +3.66 m

ELEVATION (meters)

ELEVATION (feet)
American Port Services

**Notices:**
- Elevations shall be considered approximate.
- Surface conditions presented are based on a comprehensive site investigation.

**Stratum 1 -** Stiff to hard CLAY (CL)
**Stratum 2 -** Very loose to firm, silty and clayey SAND (SM & SC)
**Stratum 3 -** Very soft to soft silty CLAY (CL & CH)
**Stratum 4 -** Firm to stiff silty CLAY (CL & CH)
**Stratum 5 -** Very loose to dense, slightly silty, silty & clayey SAND (SP-SM, SM & SC)

---

**Lithology & Graphics**

Key:
- **Gray area:** Clayey sand
- **Black area:** Silty clay
- **Green area:** Peat, clay, low to moderate sensitivity

**NOTES:**
- CPT Tip Resistances truncates @ 400ksf
- DMT Thrust truncates @ 6000 psf

---

**GB-04**
- 412
- 0.12
- 4
- 2
- 412
- 12
- 2
- 9672
- 28
- 40

**GB-11**
- 18
- 10
- 10
- 110
- 6628

**GB-13**
- 31
- 2
- 31
- 6
- 6241

**GB-18**
- 31
- 2
- 31
- 6
- 62419
What Do We Want To Know?

<table>
<thead>
<tr>
<th>INDICES</th>
<th>STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
<td>Void Ratio, e₀</td>
</tr>
<tr>
<td>Geologic Age</td>
<td>Unit Weight, γₜ</td>
</tr>
<tr>
<td>Grain Sizes</td>
<td>Relative Density, Dₛ</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Vertical Stress, σᵥ₀</td>
</tr>
<tr>
<td>Plasticity</td>
<td>Hydrostatic, uₒ</td>
</tr>
<tr>
<td>Shape</td>
<td>Saturation, S</td>
</tr>
<tr>
<td>Sphericity</td>
<td>Geostatic K₀ = σₒ/σᵥ₀</td>
</tr>
<tr>
<td>Roundness</td>
<td>Stiffness, G₀ = Gₘₐₓ</td>
</tr>
<tr>
<td>Angularity</td>
<td>Cementation</td>
</tr>
<tr>
<td>Packing limits</td>
<td>Fabric, void index Iᵥₒ</td>
</tr>
<tr>
<td>(eₘₐₓ and eₘᵦᵦ)</td>
<td>Intact or Fissured</td>
</tr>
</tbody>
</table>

Initial Conditions

- z_w
- z

Soil Element A
In-Situ Geotechnical Tests for Soils

- **SPT**: Standard Penetration Test
- **CPT**: Cone Penetration Test
- **DMT**: Flat Plate Dilatometer Test
- **PMT**: Prebored Pressuremeter Test
- **VST**: Vane Shear Test
Determination of the minimum depth of testing

Square footings stress twice the footing width. Strip footings stress four times the footing width. Add another 10 feet for total boring depth.
Pile Foundation Testing Depth

How deep do you test?
- Most important - Local knowledge
- Rough rule - 1 usable ton/foot
  50 ton pile - 50 feet
- Add 15 feet to explore below pile tip.
Hand Tools

Limited by strength of operator.

Limited by groundwater level.
Hollow Stem Auger Drilling
Hollow Stem Auger
Mud Rotary Boring
Split Spoon Sampler

(a) Standard split-spoon sampler;
(b) Spring core catcher
Configuration of SPT Hammers

(a) safety hammer;
(b) donut hammer

(after Seed et al., 1985)

Automatic hammers now being used.
Standard Penetration Test

The number of blows of a 140 lb. hammer dropping 30 inches measured over 1 foot.

• Very crude
• Very dependent on operator
• Better with automatic hammer
• Numerous correlations & corrections
• Not as reliable as other in-situ tests
\( c_u = \) 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
\( qa = \) 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

Is One Number Enough???
Table 1 Summary of Factors in the Variability of SPT expressed in typical N values

<table>
<thead>
<tr>
<th>Cause</th>
<th>Typical SPT value in Clean Sand N = 20</th>
<th>Typical SPT value in Clay N=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Detailed</td>
<td></td>
</tr>
<tr>
<td>Drilling method</td>
<td>1. Use of drilling mud and fluid bypass. 20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2. Use of drill mud and no fluid bypass. 6-20</td>
<td>8-10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>3. Use of clear water with or without bypass. 6-20</td>
<td>8-10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>4. Use of hollow-stem augers with or without fluid. 0-20</td>
<td>8-10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>5. 6-inch diameter hole compared to 4 inch. 17</td>
<td>8-10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sampler</td>
<td>6. Use of the larger ID barrel, without the liners 17</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>7. Use of a 3-inch OD barrel versus a 2-inch barrel 25-30&lt;sup&gt;4&lt;/sup&gt;</td>
<td>10</td>
</tr>
<tr>
<td>Procedure</td>
<td>8. Use of a blow count rate of 55 bpm as opposed to 30 bpm 20&lt;sup&gt;4&lt;/sup&gt;</td>
<td>10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Energy Transmission Factors:

<table>
<thead>
<tr>
<th>Drill Rods</th>
<th>Typical SPT value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Rods</td>
<td>9. AW rod versus NW rod 14-22&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Drill Rods</td>
<td>10. SPT at 200 ft as opposed to 50 ft 18&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Drill Rods</td>
<td>11. SPT at less than 10 ft as opposed to 50 ft with AW rods 30</td>
</tr>
<tr>
<td>Drill Rods</td>
<td>12. SPT at less than 10 ft as opposed to 50 ft with NW rods 25</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>13. Three wraps versus two wraps around the cathode 22</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>14. Using new rope as opposed to old rope 19</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>15. Free fall string cut drops versus 2 wrap on cathode 16</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>16. Use of high efficiency automatic hammer versus 2 wrap safety hammer 14</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>17. Use of a dusk hammer with large anvil as opposed to safety hammer 24</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>18. Failure to obtain 30 inch drop height (28-in) 22</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>19. Failure to obtain a 30 inch drop height (32 in) 18</td>
</tr>
<tr>
<td>Hammer Operation</td>
<td>20. Back tapping of safety hammer during testing 25</td>
</tr>
</tbody>
</table>

<sup>4</sup> = Estimated value
<sup>1</sup> = Difference occurs in sandy sands only
<sup>2</sup> = It is not known whether small drill rods are less or more efficient, with larger rods N may be less in clay due to weight.
<sup>3</sup> = N in clay may be lower due to weight of the rods
<sup>4</sup> = Actual N value will be much higher due to higher confining pressure at great depth, i.e. the difference shown here is from energy only, and confining pressure was not considered
ASCE Study

Summary of Raw N Values Vs. Depth
Seattle ASCE Study
Raw N Value

- A2 - Safety Hammer BW Rod
- A3 - CME Automatic Hammer AWJ rods
- A4 - Safety Hammer - 300 lb, NWJ rod
- B2 - BK-B1 Automatic Hammer - AWJ rod
- B3 - Spooling winch, safety hammer, NWJ rod
- B6 - CME Automatic Hammer, mud rotary, AWJ rod
Corrected SPT

\[ N_{60} = \frac{(N \cdot \eta_H \cdot \eta_B \cdot \eta_S \cdot \eta_R)}{60} \]

- \( N_{60} \) = SPT corrected for field conditions
- \( N \) = uncorrected SPT from field test
- \( \eta_H \) = hammer efficiency
- \( \eta_B \) = correction for borehole diameter
- \( \eta_S \) = sampler correction
- \( \eta_R \) = correction for rod length

**Example**

\[ N = 9 \]
\[ \eta_H = 60\% \text{ (American safety hammer & pulley)} \]
\[ \eta_B = 1 \text{ (4 inch diameter hole)} \]
\[ \eta_S = 1 \text{ (Standard sampler)} \]
\[ \eta_R = 0.85 \text{ (15 foot sample)} \]

\[ N_{60} = \frac{(9 \cdot 60 \cdot 1 \cdot 1 \cdot 0.85)}{60} = 7.6 \text{ round to 8} \]
\[ N_{60} = \frac{(9 \cdot 100 \cdot 1 \cdot 1 \cdot 0.85)}{60} = 12.8 \text{ round to 13 for automatic hammer} \]
Corrected SPT

\[ N_{60} = (N \cdot \eta_H \cdot \eta_B \cdot \eta_S \cdot \eta_R)/60 \]

Table 2.5 Variations of \( \eta_H, \eta_B, \eta_S, \) and \( \eta_R \) [Eq. (2.6)]

1. Variation of \( \eta_H \)

<table>
<thead>
<tr>
<th>Country</th>
<th>Hammer type</th>
<th>Hammer release</th>
<th>( \eta_H ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>Donut</td>
<td>Free fall</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Donut</td>
<td>Rope and pulley</td>
<td>67</td>
</tr>
<tr>
<td>United States</td>
<td>Safety</td>
<td>Rope and pulley</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Automatic Hammer</td>
<td>Free Fall</td>
<td>85</td>
</tr>
<tr>
<td>Argentina</td>
<td>Donut</td>
<td>Rope and pulley</td>
<td>45</td>
</tr>
<tr>
<td>China</td>
<td>Donut</td>
<td>Free fall</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Donut</td>
<td>Rope and pulley</td>
<td>50</td>
</tr>
</tbody>
</table>

2. Variation of \( \eta_B \)

<table>
<thead>
<tr>
<th>Diameter</th>
<th>( \eta_B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm  in.</td>
<td></td>
</tr>
<tr>
<td>60–120 2.4–4.7</td>
<td>1</td>
</tr>
<tr>
<td>150 6</td>
<td>1.05</td>
</tr>
<tr>
<td>200 8</td>
<td>1.15</td>
</tr>
</tbody>
</table>

3. Variation of \( \eta_S \)

<table>
<thead>
<tr>
<th>Variable</th>
<th>( \eta_S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard sampler</td>
<td>1.0</td>
</tr>
<tr>
<td>With liner for dense sand and clay</td>
<td>0.8</td>
</tr>
<tr>
<td>With liner for loose sand</td>
<td>0.9</td>
</tr>
</tbody>
</table>

4. Variation of \( \eta_R \)

<table>
<thead>
<tr>
<th>Rod length</th>
<th>( \eta_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>m  ft</td>
<td></td>
</tr>
<tr>
<td>&gt;10 &gt;30</td>
<td>1.0</td>
</tr>
<tr>
<td>6–10 20–30</td>
<td>0.95</td>
</tr>
<tr>
<td>4–6 12–20</td>
<td>0.85</td>
</tr>
<tr>
<td>0–4 0–12</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Effects of Corrected SPT

SPT (blows per foot)

Depth (feet)

Uncorrected N
Corrected N - Das
Corrected N Das (AH)
Correction for Overburden

\[(N_1)_{60} = C_N \cdot N_{60}\]

**Liao and Whitman**

\[C_N := \left[ \frac{1}{\left( \frac{\sigma_0}{p_a} \right)^{0.5}} \right]\]

**Skempton**

\[C_N := \left[ \frac{2}{\left( 1 + \frac{\sigma_0}{p_a} \right)^2} \right]\]

**Seed**

\[C_N := 1 - 1.25 \log \left( \frac{\sigma_0}{p_a} \right)\]

**Peck**

\[C_N := 0.77 \log \left( \frac{20}{\sigma_0 \cdot \frac{p_a}{p_a}} \right)\]

\(p_a\) is a normalizing pressure

\(p_a = 1\) atmosphere

or about 1 tsf

or about 100 kPa

Pay attention to units
Correction for Overburden in Sand
Correcting SPT

It’s like polishing a turd. When you are finished, it’s still a turd.

Ethan Cargill - ConeTec
# Consistency

## SANDS

<table>
<thead>
<tr>
<th>SPT Resistance, bpf</th>
<th>RELATIVE DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>Very Loose</td>
</tr>
<tr>
<td>5-10</td>
<td>Loose</td>
</tr>
<tr>
<td>11-30</td>
<td>Firm</td>
</tr>
<tr>
<td>31-50</td>
<td>Dense</td>
</tr>
<tr>
<td>OVER 50</td>
<td>Very Dense</td>
</tr>
</tbody>
</table>

## SILTS AND CLAYS

<table>
<thead>
<tr>
<th>SPT Resistance, bpf</th>
<th>CONSISTENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>Very Soft</td>
</tr>
<tr>
<td>3-4</td>
<td>Soft</td>
</tr>
<tr>
<td>5-8</td>
<td>Firm</td>
</tr>
<tr>
<td>9-15</td>
<td>Stiff</td>
</tr>
<tr>
<td>16-30</td>
<td>Very stiff</td>
</tr>
<tr>
<td>31-50</td>
<td>Hard</td>
</tr>
<tr>
<td>OVER 50</td>
<td>Very Hard</td>
</tr>
</tbody>
</table>
Correlations – Real Data

Saturated Soil Materials:

\[ \gamma_f (\text{kN/m}^3) = 8.32 \log V_s - 1.61 \log z \]

with \( V_s \) (m/s) and depth \( z \) (m)

- \( n = 727 \)
- \( r^2 = 0.808 \)
- S.E. = 1.05
Correlations

**Hara**

\[ S_u := 29 \left( N_{60} \right)^{0.72} \]

**Mayne & Kemper**

\[ OCR := 0.193 \left( \frac{N_{60}}{\sigma_o} \right)^{0.689} \]

**Mayne & Kulhawy**

\[ \phi := \tan \left( \frac{N_{60}}{12.2 + 20.3 \frac{\sigma_o}{\sigma_p}} \right)^{0.34} \]

**Hatanaka et al**

\[ \phi := \sqrt{20 \cdot \frac{N_{160}}{60} + 20} \]

**Marcuson & Bieganousky**

\[ D_r := 11.7 + 0.76 \left[ 222 N_{60} + 1600 - 53 \sigma_o - 50 \left( \frac{C_u}{2} \right)^{0.5} \right] \]

**Mayne & Kulhawy**

\[ D_r := 12.2 + 0.75 \left[ 222 N_{60} + 2311 - 711OCR - 779 \frac{\sigma_o}{\sigma_p} - 50 \left( \frac{C_u}{2} \right)^{0.5} \right] \]

**Cubrinsky & Ishihara**

\[ D_r := \left[ \frac{N_{60} \left( 0.23 + \frac{0.06}{D_{50}} \right)}{9} \right]^{1.7} \cdot \frac{1}{\frac{\sigma_o}{\sigma_p}} \cdot 100 \]

**Peck et al**

\[ \phi := 27.1 + 0.3 \left( N_{60} \right) - 0.00054 \left( N_{160} \right)^2 \]

**Hara**

\[ \phi := \tan \left( \frac{N_{60}}{12.2 + 20.3 \frac{\sigma_o}{\sigma_p}} \right)^{0.34} \]

**Hatanaka et al**

\[ \phi := \sqrt{20 \cdot \frac{N_{160}}{60} + 20} \]

**Pay attention to units**

**Mayne & Kulhawy**

\[ S_{10} := 29 \left( N_{60} \right)^{0.72} \]
Undisturbed Sampling Devices

(b) thin-walled tube;
(c) and (d) piston sampler
Boring Log
A Data Boring Log
Drilling Rigs
Groundwater

Why do you always measure groundwater?

- Calculation of effective stress
- Can impact the bearing capacity of shallow foundations
- Can impact the pressures against retaining walls
- Impacts the capacity of pile foundations
- Impacts the in-situ permeability
- Impacts construction that may be below groundwater table

How do you measure groundwater levels?

- In the borehole immediately after and 24 hours
- In a piezometer (simple well)
- Pore water pressure transducers (data over time)
Special Groundwater Cases

Perched Conditions

- High permeability sands

Actual groundwater

- Very low permeability soil (silts and clays)

Groundwater encountered at interface

- High permeability sands

“Artesian” Conditions

Actual groundwater

- Very low permeability soil (silts and clays)
Casagrande-type Piezometer

(courtesy of N. Sivakugan, James Cook University, Australia)
Pore Pressure Transducer
Settlement Monitoring

Maintain 300 mm to 1200 mm above surface.

Fill / surcharge surface.

75 mm to 100 mm protective casing, PVC or steel pipe sections, resting loose on top of steel plate.

38 mm dia. steel pipe sections, threaded both ends.

Couplings as req’d.

Standard pipe coupling welded to plate.

600 mm square x 6.5 mm thick steel plate.

Install plate on firm subgrade.

Top cap.

Reservoir on stable ground.

Head of water increases with settlement.
A Look at Time

1920

2015
A Look at Time

1920

2015
State of The Art in SPT Testing - 1920
State of The Art in SPT Testing - 2015
SPT Testing Gives One Number – Blowcount
Is One Number Enough for What We Need?

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
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f_s = pile skin friction
k = permeability
q_a = bearing stress

D_R = relative density
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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
In-Situ Testing

- Seismic Piezocone – SCPTu
- Flat Plate Dilatometer – DMT
- Cone Pressuremeter
- Dilatocone
- Resistivity Cone
- Vane Shear
- Prebored Pressuremeter
Various In-Situ Methods

- **SPT** - Standard Penetration Test
- **CPT** - Cone Penetration Test
- **DMT** - Flat Plate Dilatometer Test
- **PMT** - Prebored Pressuremeter Test
- **VST** - Vane Shear Test
Cone Penetration Test (CPT)

**Advantages**
- Measures soil properties in-situ
- Provides data essentially continuously thru subsurface
- Can measure pore water pressures & conduct dissipation tests
- Can measure downhole geophysics (shear wave velocities, etc.)
- Can sample for contaminants

**Disadvantages**
- Does not provide a soil sample for visual classification or lab testing
- Can be difficult to penetrate very dense sands and gravels
- Unknown to some clients
CPT Measurements - 4

$V_s = \text{shear wave velocity}$

$u_b = \text{porewater pressure}$

$B_q = \frac{u_b - u_0}{q_T - \sigma_{vo}}$

$f_s = \text{sleeve resistance}$

$Friction\ ratio = \frac{f_s}{q_T}$

$q_T = \text{cone tip stress}$
SCPTu Sounding

Real-Time readings in computer screen

Penetration at 2 cm/s

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>( q_t ) (MPa)</th>
<th>( f_s ) (kPa)</th>
<th>( u_s ) (kPa)</th>
<th>( V_s ) (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
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<td></td>
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<tr>
<td>15</td>
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<td>20</td>
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<td>25</td>
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<tr>
<td>30</td>
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<tr>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CONE TIP STRESS | SLEEVE FRICTION | PORE PRESSURE | SHEAR WAVE VELOCITY
Seismic Electric Piezocone (SCPTu)
Electric Piezocone

Fig. 1. Various Penetrometers (bottom to top): Miniature 4 cm² Electric Cone; 10 cm² Type 2 Piezocone (shoulder element); Type 1 (midface) piezocones; Type 2 Seismic, Hogentogler Dual Type 1 & 2 Seismic; 15 cm² Fugro Triple-Element Cone.
Electric Piezocone Results

IBC requires exploration to 100 feet for seismic site class.
Local Data

Note increase in pore pressure while advancing in clay

SBT – Soil Behavior Type
Dissipation Tests

![Graph showing dissipation tests with Head (feet) on the y-axis and Time (minutes) on the x-axis.]
Groundwater Level Discrepancy

Pore pressure is measured in the piezocene in sand layers where excess pressure from the advancement of the cone dissipates rapidly. The pore pressure measured in feet is the weight of water above the free water pressure.
CPT Correlations

Mayne & Kulhawy

\[ D_r := \left( \frac{1}{305 Q_c \cdot OCR^{1.8}} \right) \left[ \frac{q_c}{p_a} \right] \left[ \frac{\sigma_0}{p_a} \right]^{0.5} \]

Q_c = 0.91 to 1.09 depending on compressibility of sand

Robertson et al.

\[ \phi' := \tan \left( 0.1 + 0.38 \log \left( \frac{q_c}{\sigma_0} \right) \right) \]

Mayne & Kemper

\[ S_u := \frac{q_c - \sigma_0}{N_k} \]

\[ \sigma_c := 0.243 \cdot (q_c)^{0.96} \]

\[ OCR := 0.37 \left( \frac{q_c - \sigma_0}{\sigma_0} \right)^{1.01} \]

Note total and effective stress

Pay attention to units

Q_c = 0.91 to 1.09 depending on compressibility of sand

Q_c = 0.91 to 1.09 depending on compressibility of sand

Note total and effective stress
Corrected $q_c$

The effects of pore pressure on the cone and sleeve affects the total stress measured by the cone and friction sleeve.

For this reason, we correct the point resistance $q_c$ to account for this. This correction is:

$$q_t = q_c + u_2(1-a)$$

where:
- $q_t = \text{corrected point resistance}$
- $u_2 = \text{pore pressure behind the cone}$
- $a = \text{cone area ratio} = A_n/A_c$
- $A_n = \text{cross-sectional area of the load cell or shaft}$
- $A_c = \text{projected area of the cone (0.8 is typical)}$
Typical Data from Correlations

1. Undrained Shear Strength (Su) vs. Elevation
2. Shear Wave Velocity vs. Depth
3. Friction Angle vs. Elevation
4. Preconsolidation Pressure (P’c) vs. Elevation
5. Constrained Modulus (M) vs. Elevation
6. Relative Density (Dr) vs. Elevation

Graphs show data from CPT-1 and CPT-2 for different soil types and conditions.
Data from All Methods

- CPT-1 (Nkt)
- CPT-2 (Nkt)
- CPT-3 (Nkt)
- DMT-1
- DMT-2
- Consolidation Tests
- UU Triaxial Tests
- Atterberg Limits
- Atterberg Limits (Mayne)
- SPT-1
- SPT-2
- SPT-3

- $\frac{S_u}{P_{(oc)}} = 0.45$
- $\frac{S_u}{P_{(oc)}} = 0.63$
- $\frac{S_u}{P_{(oc)}} = 0.80$
- $\frac{S_u}{P_{(oc)}} = 0.96$
- $\frac{S_u}{P_{(oc)}} = 1.21$
- $\frac{S_u}{P_{(oc)}} = 1.35$
Variation of $q_c$ with $\sigma'_0$ and $\phi'$ in normally consolidated quartz sand

(after Robertson and Campanella, 1983)
Relative Density and $q_t$
Correlation between $q_c$, $F_r$, and the type of soil

Robertson and Campanellas (1983)
Soil Behavior Type (SBT)

After Robertson & Campanella

Figure 1  Non-Normalized Behavior Type Classification Chart
And Yes – Even SPT
General range of variation of $q_c/N_{60}$ for various types of soil

(after Robertson and Campanella, 1983)
### Simplified SPT to qc Ratio

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>$q_t^{(tsf)}/N$ Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>1</td>
</tr>
<tr>
<td>Fine Silt</td>
<td>1.5</td>
</tr>
<tr>
<td>Medium Silt</td>
<td>2</td>
</tr>
<tr>
<td>Coarse Silt</td>
<td>3</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>3.5</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>4.5</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>5</td>
</tr>
<tr>
<td>Fine Gravel</td>
<td>6</td>
</tr>
</tbody>
</table>

**Average Grain Size (mm) = 0.00043+0.664\(q_c/N\)**
Flat Plate Dilatometer

Advantages
• Measures soil properties in-situ
• Provides data more frequently thru subsurface
• Can conduct dissipation tests
• More dependable settlement estimates

Disadvantages
• Does not provide a soil sample for visual classification or lab testing
• Can be difficult to penetrate very dense sands and gravels
• Unknown to some clients
Flat Plate Dilatometer
Flat Plate Dilatometer
Local DMT Data
Local DMT Data Correlations
Local DMT Data Modulus

Ground Surface Elev.: Water Depth: ~1.8 m
Primary DMT Equations

1. Material Index – $I_D$ (Soil Type)
2. Horizontal Stress Index – $K_D$
3. Dilatometer Modulus – $E_D$

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_D = \frac{(p_1 - p_0)}{(p_0 - u_0)}$</td>
<td>Material Index</td>
<td>Unitless</td>
</tr>
<tr>
<td>$K_D = \frac{(p_0 - u_0)}{\sigma'_o}$</td>
<td>Horizontal Stress Index</td>
<td>Unitless</td>
</tr>
<tr>
<td>$E_D = 34.7 \cdot (p_1 - p_0)$</td>
<td>Dilatometer Modulus</td>
<td>$p_1$ &amp; $p_0$ in kN/m²</td>
</tr>
<tr>
<td>$E_D = 34.7 \cdot (p_1 - p_0) \cdot 0.01044227$</td>
<td></td>
<td>$p_1$ &amp; $p_0$ in kN/m², in ksf</td>
</tr>
</tbody>
</table>

Pay attention to units
DMT Correlations

All correlations from Marchetti

\[ K_o = \left( \frac{K_D}{1.5} \right)^{0.47} - 0.6 \]

\[ S_u = 0.35 \cdot \sigma'_o \cdot (0.47 \cdot K_D)^{1.14} \]

\[ OCR = (0.5 \cdot K_D)^{1.56} \]

\[ \phi' = 31 + \left( \frac{K_D}{0.236 + 0.066 \cdot K_D} \right) \]

\[ \left( \frac{S_u}{\sigma'_o} \right)_{oc} = \left( \frac{S_u}{\sigma'_o} \right)_{nc} \cdot (0.5 \cdot K_D)^{1.25} \]

\[ \phi'_{ult} = 28 + 14.6 \cdot \log(K_D) - 2.1 \log(K_D)^2 \]

\[ E_s = (1 - \mu^2) \cdot E_D \]
Chart for determination of soil description and unit weight

(after Schmertmann, 1986)

Note: 1 t/m³ = 9.18 kN/m³
Data Set Comparison

SPT, CPT or DMT value

Depth (feet)
How Thick is the Clay Layer?

SPT Soil Boring – Sample Every 5 Feet

<table>
<thead>
<tr>
<th>Sample Depth</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 to 10 feet</td>
<td>SAND</td>
</tr>
<tr>
<td>13 to 15 feet</td>
<td>CLAY</td>
</tr>
<tr>
<td>18 to 20 feet</td>
<td>SAND</td>
</tr>
</tbody>
</table>

2 feet? 5 feet? 8 feet?

With CPT – Measuring Every 1 to 2 Inches
With DMT – Measuring Every 1 Foot
Why it Matters – One Example

\[ S = \frac{C \cdot H_c}{1 + e_0} \cdot \log \left[ \frac{\sigma'_0 + \Delta \sigma}{\sigma'_0} \right] \]

Thickness of Clay Layer
Another Example – Time Rate

\[ t = T_v \cdot \frac{H^2}{C_v} \]

Thickness of Clay Layer
Vane Shear Test

Now automatic readers are available.
Undrained Strength From VST

Derivation of $s_{uv}$ for Rectangular Vane

At both ends:
$$T_v = 2 \int_0^{D/2} (2\pi r^2 \tau) \, dr$$
For uniform distribution of shear stresses, $\tau$:
$$T_v = 2 \left( \frac{2}{3} \pi r^3 \right)_{r=D/2}^{D/2} = \left( \frac{\pi}{6} \right) D^3$$
Along the vertical side shear:
$$T_w = F \cdot r = \tau D \frac{H}{D/2} = \tau D^2 H/2$$
Total measured torque (moment):
$$T = T_v + T_w = \left( \frac{\pi}{6} \right) D^3 + \tau D^2 H/2$$
Assume undrained conditions, such that $\tau_{\text{uv}} = \tau_{\text{uv}}$:
$$s_{uv} = \frac{6T}{\pi D^3 (D + 3H)}$$
For standard vane ($H/D = 2$):
$$s_{uv} = \frac{6T}{7\pi D^3}$$

$S_{uv} = \frac{6T_{\text{max}}}{7\pi D^3}$
Modified Vane

\[ S_{mv} = \frac{12T}{\pi D^2 \left[ \left( D / \cos i_T \right) + \left( D / \cos i_B \right) + 6H \right]} \]

T = measured torque

Calculation of Undrained Shear Strength \( (s_{uv}) \) from Vane Shear Test from Limit Equilibrium

Width D

Height H

\( i_T \)

\( i_B \)
Vane Geometry

Interpretation of $s_{uv}$ from Vanes with $H/D = 2$ Geometries

- **Rectangular**
  \[ s_{uv} = \frac{6T}{7\pi D^3} = 0.273 \frac{T}{D^3} \]

- **Nilcon**
  \[ s_{uv} = 0.265 \frac{T}{D^3} \]

- **Geonor**
  \[ s_{uv} = 0.257 \frac{T}{D^3} \]
Results Similar To Lab Tests

Remote VST at Snorre, North Sea
(Lunne, Snorrasen, and Hauge, 1987)
Sensitivity

Sensitivity = Su(max)/Su(rem)

<table>
<thead>
<tr>
<th>Category</th>
<th>Sensitivity, $S_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insensitive</td>
<td>~ 1</td>
</tr>
<tr>
<td>Slightly sensitive</td>
<td>1 - 2</td>
</tr>
<tr>
<td>Medium sensitive</td>
<td>2 - 4</td>
</tr>
<tr>
<td>Very sensitive</td>
<td>4 - 8</td>
</tr>
<tr>
<td>Slightly quick</td>
<td>8 - 16</td>
</tr>
<tr>
<td>Medium quick</td>
<td>16 - 32</td>
</tr>
<tr>
<td>Very quick clay</td>
<td>32 - 64</td>
</tr>
<tr>
<td>Extra quick</td>
<td>&gt; 64</td>
</tr>
</tbody>
</table>
VST Correction

Bjerrum (1972), Larsson 1980; Azzouz, et al. (JGE, 1983); Aas, et al. (1986, ASCE GSP No. 6)
Field Tests With No Equipment

When you have no SPT, CPT or DMT data, what can you do?
Very very very crude.

<table>
<thead>
<tr>
<th>Term</th>
<th>Kips/Sq.Ft.</th>
<th>kN/Sq.M.</th>
<th>Field Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very soft</td>
<td>0 to 0.5</td>
<td>0 to 25</td>
<td>Squeezes between fingers when fist is closed</td>
</tr>
<tr>
<td>Soft</td>
<td>0.5 to 1</td>
<td>25 to 50</td>
<td>Easily molded by fingers</td>
</tr>
<tr>
<td>Firm</td>
<td>1 to 2</td>
<td>50 to 100</td>
<td>Molded by strong pressure of fingers</td>
</tr>
<tr>
<td>Stiff</td>
<td>2 to 3</td>
<td>100 to 150</td>
<td>Dented by strong pressure of fingers</td>
</tr>
<tr>
<td>Very stiff</td>
<td>3 to 4</td>
<td>150 to 250</td>
<td>Dented only slightly by finger pressure</td>
</tr>
<tr>
<td>Hard</td>
<td>4+</td>
<td>200+</td>
<td>Dented only slightly by pencil point</td>
</tr>
</tbody>
</table>

Unconfined Compressive Strength

(After Terzaghi & Peck)

Field Test

(After Cooling, Skampton, and Glossop)
Geotechnical Report

Executive Summary
Purpose of Exploration
Project Information
• Planned Major Structure
• Ancillary Structures
• Structural Loads
Subsurface Exploration
• Field Testing Program
• Borings
• CPT
• DMT
• Other Testing
Subsurface Conditions
• Number of Strata
• Individual Stratum Descriptions
• Lab Testing Program & Summary
• Groundwater
• Other Issues
Discussion of Subsurface Conditions & Foundations
Foundation Recommendations
• Types
• Capacities
• Settlement
Construction Recommendations
Special Recommendations

Drawings
• Site Location Plan
• Site Aerial Photo
• Historical Photos of Topo Maps
• Site Ground Photos
• Boring, CPT, DMT Testing Location Plan
• Subsurface Profile
• Charts of Field Data Summaries
• Charts of Field Data Correlations
• Charts of Lab Data Summaries
• Charts of Lab Data Correlations

Field Data
• Explanation Legends
• Boring Logs
• CPT Logs
• DMT Logs
• Other Field Test Logs

Lab Data
• Lab Summary Sheet
• Grain Size Charts
• Consolidation Data & Charts
• Strength Test Data & Charts
• Other Test Data & Charts

Procedures
Homework

From Chapter 2

CE 430

☐ 2.2 & 2.3
☐ 2.6
☐ 2.17
☐ 2.19
☐ + Problem--→

Read Chapter 3

CE 530

Same as CE430

Calculate total and effective stress at points A, B & C