Site Exploration and In Situ Testing in Geotechnical Engineering Characterization

Presented by
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Three Day Training Programme on Best Practices in Civil Engg.

Introduction

Prakasham Barrage
Nagarjuna Sagar
Metro Rail
Outer Ring Road
Introduction

Contents

- Background on *in situ* characterization
- NDT testing in geotechnical engineering
- Compaction Q/C using LWD testing
- Conclusions
Why is Site Investigation required?

- To have information about the Ground

Goals of Site Investigation

- To have a “Picture” of the Ground
- Establish soil stratigraphy
- Establish water table
  - Piezometers
Factors Controlling Site Investigation

- Structure to be supported
  - Size and Importance
  - Depth of Influence of Foundations
- Type and Method of Construction
- Nature of soil (weak vs. strong, permeable vs. impermeable)
- Geology

Types of Site Investigation Methods

- Borings – cylindrical vertical holes made in the ground
- Pits
- Trenches
- In situ testing (CPT, SPT, etc.)
- Geophysical tests
How many Borings?

- Depends on the importance of the project
- Minimum 3
- 5 for a rectangular plot – Get “Profiles”
- More required for sites with highly variable profiles
- Experience often helps
- Decide as you proceed

Depth of Boring

- Borings should be extended to a depth at which stresses have diminished to ~10% of the stresses applied at the base of the foundation

- A few borings must extend to bedrock or to a competent (hard) layer
How are Boreholes Made?

- By Drilling (with Drill Bits or Continuous Flight Auger)
- Wash Boring

Drill Bits and Augers
Wash Boring

Boring with Continuous Flight Auger
Typical Boring Log

<table>
<thead>
<tr>
<th>Depth</th>
<th>Water</th>
<th>USCS</th>
<th>Description</th>
<th>SPT</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>in feet</td>
<td>climb</td>
<td></td>
<td>Rock, line, and fine-grained sand.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td>GROVEL: Dark brown and gray, moist, stiff, SANDY CLAY with trace to little gravel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>CL</td>
<td>Dark gray and brown, slightly moist, very stiff, SANDY CLAY with trace to little sand</td>
<td>1</td>
<td>11.6.6</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>CL</td>
<td>Dark brown, very moist to wet, loose CLAYEY SAND with trace to gravel and clay</td>
<td>2</td>
<td>12.18.12</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>CL</td>
<td>Dark brown, very moist to wet, loose CLAYEY SAND with trace to gravel and clay</td>
<td>3</td>
<td>12.10.10</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>CL</td>
<td>Dark brown, very moist to wet, loose CLAYEY SAND with trace to gravel and clay</td>
<td>4</td>
<td>9.11.10</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>SC</td>
<td>Dark brown, very moist to wet, loose CLAYEY SAND with trace to gravel and clay</td>
<td>5</td>
<td>5.5.5</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>SM</td>
<td>Dark brown, very moist to wet, loose CLAYEY SAND with trace to gravel and clay</td>
<td>6</td>
<td>4.4.4</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td>SC</td>
<td>Dark brown, wet, medium dense, CLAYEY SAND with little to some gravel and trace silt</td>
<td>7</td>
<td>3.3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Boring terminated at 30 feet</td>
<td>8</td>
<td>2.2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground water was not encountered during drilling or upon completion</td>
<td>9</td>
<td>2.2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>2.2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>6.6.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>4.4.4</td>
</tr>
</tbody>
</table>

In situ Tests

- Standard Penetration Test (SPT)
- Cone Penetration Test (CPT)
- Vane Shear Test
- Pressuremeter Test
- Dilatometer Test
- Others
Standard Penetration Test (SPT)

- Most widely used In situ Test
- Crude – Hammer a Sampler into the Ground, Record the Resistance
- Done Intermittently with Drilling of Bore Holes
SPT - Procedure

- Drilling of bore hole is interrupted at regular intervals
- “Split-spoon” sampler is introduced into the bore hole
- Sampler is driven into the ground by dropping a hammer on top of the rods (over an anvil)
- Sampler is driven into the soil for an overall depth of 45 cm (18 inches) in intervals of 15 cm (6 inches)
- Operator counts the number of blows required for each 15 cm (6 inch) penetration of the sampler
- Sampler is then retrieved back to the ground surface (soil samples collected in the sampler is stored for subsequent transportation to the lab)
- Drilling of bore hole is resumed until the next SPT testing depth

SPT Blow Count N (or $N_{SPT}$)

- Number of blows per 15 cm of penetration
- $N = 12 + 11 = 23$
- $30 \text{ cm} = 12 \text{ in.} = 1 \text{ ft of penetration}$
### Split-spoon Sampler

![Diagram of Split-spoon Sampler](image)

- **Driving shoe**
- **Sampler head**
- **Split-barrel sampling tube**
- **Ball check valve**
- **Vent**

Optional “catcher” may be placed to improve the recovery of saturated cohesionless soils.

### Typical Boring Log with SPT Blow Count

<table>
<thead>
<tr>
<th>Depth in feet</th>
<th>Water levels:</th>
<th>Graphs:</th>
<th>Descriptions</th>
<th>Samples</th>
<th>SPT results</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□ During drilling</td>
<td>□ After completion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>11.66</td>
<td>12.18.12</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>Dark brown and gray, moist; stiff to very stiff; SANDY CLAY with trace to little gravel</td>
<td>12.10.10</td>
<td>9.11.10</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>Dark gray and brown, slightly moist, very stiff, SANDY CLAY with trace to little sand</td>
<td>5.5.7</td>
<td>3.3.3</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td>Dark, moist, stiff, SANDY CLAY with trace to small gravel</td>
<td>4.4.4</td>
<td>3.3.3</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>Dark brown, very moist to wet, loose CLAYEY SAND with trace to gravel and clay</td>
<td>2.2.3</td>
<td>2.2.2</td>
<td>Boring ceased to 21 feet upon auger removal</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td>Dark brown, wet, medium dense, CLAYEY SAND with little to some gravel and trace silt</td>
<td>2.2.4</td>
<td>6.6.6</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td>Boring terminated at 30 feet</td>
<td>4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ground water was not encountered during drilling or auger correlation.
SPT Specifications

- Sampler (ASTM - 1586):
  - Outer Diameter = 2 in (51mm)
  - Inner Diameter = 1.375in (35mm) with liner
- Hammer: 140lb (63.5kg)
- Fall height: 30in (76cm)
- Borehole Diameter – 66 to 115 mm

When should SPT be stopped?

- 50 blows required for any 15-cm interval
- 100 blows required for a 30-cm interval
- 10 successive blows produce no advance/penetration
Limitations of SPT

- Lack of Standardization
- Different hammers produce different driving energy
- Operator dependent (quality of operation, method of hammer release affects N)
- Conditions of rope, anvil, sampler, cathead affect N
- Sampler type also affects N
- Total string length, tightness of rod connections affect N
- Borehole diameter affects N

Hammer Types and Energy Imparted

- Ideally: \( E = m_{\text{hammer}}gh \)
- Pin-weight Hammer: \(~70\%\) Efficiency or Energy Ratio ER (i.e., energy imparted = 0.7 \( m_{\text{hammer}}gh \))
- Safety Hammer: \(~60\%\) ER
- Donut Hammer: \(~45\%\) ER
Sampler Types

- With and Without Liners

Bore Hole Diameter

\[ N_{SPT} \text{ of } B_1 > N_{SPT} \text{ of } B_2 \]
Elimination of Uncertainties: Blow Count Corrections

\[ N_{60} = C_h C_r C_s C_d N \]

- \( N_{60} \) is the corrected blow count
- \( C_h \) is hammer correction
- \( C_r \) is rod length correction
- \( C_s \) is sampler correction
- \( C_d \) is borehole diameter correction
- \( N \) is measured blow count value in field

Hammer Correction

\[ C_h = \frac{\text{ER}_{\text{hammer typ}}}{\text{ER}_{\text{safety hammer}}} = \frac{\text{ER}_{\text{hammer typ}}}{60\%} \]

<table>
<thead>
<tr>
<th>Hammer</th>
<th>Approximate energy ratio (%)</th>
<th>( C_h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>Donut</td>
<td>45</td>
<td>0.75</td>
</tr>
<tr>
<td>Automatic trip</td>
<td>80</td>
<td>1.33</td>
</tr>
<tr>
<td>Pin weight</td>
<td>72</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Sampler Correction

- Sampler that cannot accommodate liner: $C_s = 1.0$
- Sampler that can accommodate liner and with the liner in space: $C_s = 1.0$
- Sampler that can accommodate liner but does not have a liner in place: $C_s = 1.2$

Why?
Soil can expand and occupy the space where the liner could be placed resulting in less frictional resistance

Borehole Diameter Correction

- $C_d = 1.0$ for borehole diameter = 65-115 mm
- $C_d = 1.05$ for borehole diameter = 150 mm
- $C_d = 1.15$ for borehole diameter = 200 mm
Rod Length Correction

- \( C_r = 0.75 \) if rod length < 4 m
- \( C_r = 0.85 \) if rod length 4-<6 m
- \( C_r = 0.95 \) if rod length 6-<10 m
- \( C_r = 1.0 \) if rod length >= 10 m

Elimination of Uncertainties: Blow Count Corrections

\[
N_{60} = C_h C_r C_s C_d N
\]

- \( N_{60} \) is the corrected blow count
- \( C_h \) is hammer correction
- \( C_r \) is rod length correction
- \( C_s \) is sampler correction
- \( C_d \) is borehole diameter correction
- \( N \) is measured blow count value in field
Stress Normalization of N

- Intuitively N depends on density and confining stress

\[ N_1 = N \sqrt[\frac{p_A K_{0,NC}}{\sigma'_v K_0}} \]

- Some correlations are related to stress-normalized N i.e., \( N_1 \)

- We can separate the effect of confinement and density

Four Types of N

\( N, N_{60}, N_1 \) and \( (N_1)_{60} \)

Which one to use?

- Depends on the Correlations Available
IS Code 2131: Method for SPT for soils

3.6 Corrections

3.6.1 Due to Overburden — The \( N \) value for cohesionless soil shall be corrected for overburden as per Fig. 1 (\( N' \)).

3.6.2 Due to Dilatancy — The value obtained in 3.6.1 shall be corrected for dilatancy if the stratum consists of fine sand and silt below water table for values of \( N' \) greater than 15, as under (\( N'' \)):

\[
N'' = 15 + \frac{1}{2} (N' - 15)
\]

Interpretations of SPT Blow Count

- Two Approaches: Direct and Indirect

- Direct Interpretation: \( N \) is related directly to foundation capacity (bearing capacity)

- Indirect Interpretation: \( N \) is related to soil variables like \( \phi, D_r \) etc. which, in turn, is related to foundation capacity
Correlations with N - Sand

- $N_{60}$ with $\phi_{\text{peak}}$
- Use caution when using Correlations
- De Mello (1971)

\[ A = 27-46 \]
\[ B = 27 \]
\[ C = (1 + 2K_0)/(1 + 2K_{0, NC}) \]
Correlations with N - Sand

\[
\phi'(\text{deg}) = 27.1 + 0.3N_{60} - 0.00054(N_{60})^2
\]

Peck, Hanson and Thornburn (1974)

\[
\phi' = \tan^{-1}\left[\frac{N_{60}}{12.2 + 20.3\left(\frac{\gamma_{w}}{p_{o}}\right)}\right]^{0.34}
\]

Schmertmann (1975)

\[
\phi' = \sqrt{20(N_{1})_{60} + 20}
\]

Hatanaka and Uchida (1996)

Correlations with N - Sand

<table>
<thead>
<tr>
<th>Description</th>
<th>Very loose</th>
<th>Loose</th>
<th>Medium</th>
<th>Dense</th>
<th>Very dense</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative density (D_r)</td>
<td>0</td>
<td>0.15</td>
<td>0.35</td>
<td>0.65</td>
<td>0.85</td>
</tr>
<tr>
<td>SPT (N_{60}): fine</td>
<td>1–2</td>
<td>3–6</td>
<td>7–15</td>
<td>16–30</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>2–3</td>
<td>4–7</td>
<td>8–20</td>
<td>21–40</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>3–6</td>
<td>5–9</td>
<td>10–25</td>
<td>26–45</td>
</tr>
<tr>
<td>(\phi): fine</td>
<td>26–28</td>
<td>28–30</td>
<td>30–34</td>
<td>33–38</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>28–30</td>
<td>30–34</td>
<td>33–40</td>
<td>40–50</td>
</tr>
<tr>
<td>(\gamma_{w}), kN/m(^3)</td>
<td>11–16*</td>
<td>14–18</td>
<td>17–20</td>
<td>17–22</td>
<td>20–23</td>
</tr>
</tbody>
</table>
**Correlations with N - Clay**

<table>
<thead>
<tr>
<th>Standard penetration number, ( N_{60} )</th>
<th>Consistency</th>
<th>C1</th>
<th>Uncorrelated compression strength, ( q_u ) (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2</td>
<td>Very soft</td>
<td>&lt;0.5</td>
<td>&lt;25</td>
</tr>
<tr>
<td>2–8</td>
<td>Soft to medium</td>
<td>0.5–0.75</td>
<td>25–80</td>
</tr>
<tr>
<td>8–15</td>
<td>Stiff</td>
<td>0.75–1.0</td>
<td>80–150</td>
</tr>
<tr>
<td>15–30</td>
<td>Very stiff</td>
<td>1.0</td>
<td>150–400</td>
</tr>
<tr>
<td>&gt;30</td>
<td>Hard</td>
<td>&gt;1.5</td>
<td>&gt;400</td>
</tr>
</tbody>
</table>

\[ c_u = K N_{60} \]  
Stroud (1974)

\( K = 3.5 - 6.5 \) kPa

---

**Correlations with N - Clay**

<table>
<thead>
<tr>
<th>Consistency</th>
<th>( N_{60} )</th>
<th>( q_u ), kPa</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very soft</td>
<td>0–2</td>
<td>&lt;25</td>
<td>Squishes between fingers when squeezed</td>
</tr>
<tr>
<td>Soft</td>
<td>3–5</td>
<td>25–50</td>
<td>Very easily deformed by squeezing</td>
</tr>
<tr>
<td>Medium</td>
<td>6–9</td>
<td>50–100</td>
<td>??</td>
</tr>
<tr>
<td>Stiff</td>
<td>10–16</td>
<td>100–200</td>
<td>Hard to deform by hand squeezing</td>
</tr>
<tr>
<td>Very stiff</td>
<td>17–30</td>
<td>200–400</td>
<td>Very hard to deform by hand squeezing</td>
</tr>
<tr>
<td>Hard</td>
<td>&gt;30</td>
<td>&gt;400</td>
<td>Nearly impossible to deform by hand</td>
</tr>
</tbody>
</table>

Increasing OCR  
Aged  
concentrated

A correlation for \( N \) versus \( q_u \) is in the general form of

\[ q_u = kN \]

where the value of \( k \) tends to be site-dependent; however, a value of \( k = 12 \)
Correlations with $N$ - Clay

- $N$ depends on many factors like clay sensitivity, loading rate etc. – correlations less reliable

$$\frac{s_u}{p_A} = f_1 N$$

$$m_v p_A = \frac{1}{f_2 N}$$

---

Correlations of $N$ with $E_s$ for sand

$$\frac{E_s}{p_A} = \alpha N_{60}$$

(Kulhawy and Mayne (1990))

where

- $p_A$ = atmospheric pressure (same unit as $E_s$)
- $\alpha = \begin{cases} 
5 & \text{for sands with fines} \\
10 & \text{for clean normally consolidated sand} \\
15 & \text{for clean overconsolidated sand}
\end{cases}$
Correlations of N with Es for clay

<table>
<thead>
<tr>
<th>Clay and silt</th>
<th>IP &gt; 30 or organic</th>
<th>E_s = (100 to 500)s_u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty or sandy clay</td>
<td>IP &lt; 30 or stiff</td>
<td>E_s = (500 to 1500)s_u</td>
</tr>
</tbody>
</table>

Again, E_{OCR} = E_{sec} × OCR

If general application in clays is

\[ E_s = K s_u \]  \hspace{1cm} \text{(units of } s_u) \]

where \( K \) is defined as

\[ K = 4200 - 142.54I_p + 1.73I_p^2 - 0.0071I_p^3 \]

and \( I_p \) = plasticity index in percent. Use 20% ≤ \( I_p \) ≤ 100% and round \( K \) to the nearest multiple of 10.

Cone Penetration Test

- A “cone” penetrometer is pushed in the ground at a constant penetration rate of 2 cm/s
- Resistance is recorded
- Advantages
  - Speed of performance
  - Simplicity
  - Continuous profiling
  - Reliability
Cone Specifications

• Cone diameter = 3.57cm
• Cone projected area = 10cm²
• Cone sleeve area = 150cm²
• Cone apex angle = 60°
CPT Rigs

- Three types
  - Truck-mounted
  - Crawler-mounted
  - Trailer-mounted

Quantities Measured

- Cone tip resistance \( q_c \) = Force acting on Cone/Projected Cone Area
- Sleeve Resistance \( f_s \) = Shear Force on Cylindrical Sleeve/Sleeve Area
- Pore pressure (piezocone)
- Shear Wave (seismic cone)
- Temperature
- Chemical Analysis (Envirocone)
Interpretation of CPT Data

- Friction Ratio $f_s/q_c$ indicates soil type
- Better to rely on soil boring for soil type
- $q_c$ related to Relative Density and Lateral Stress for Sands
- $q_c$ related to Undrained Shear Strength for Clays

Robertson (1990)
CPT Results For Sands

- \( q_c = f(D_R, \sigma'') \) (Cavity Expansion Analysis)

\[
\frac{q_c}{p_A} = 1.64 \exp(0.1041 \phi_v + (0.0264 - 0.0302 \phi_v) D_R) \left( \frac{\sigma''}{p_A} \right)^{0.841 - 0.047 D_R}
\]

CPT Results for Clays

- \( q_c = f(s_u, \text{drainage or penetration rate}) \)
- \( q_c = N_k s_u + \sigma_v \)
- \( N_k = 10-12 \)
Correlation between CPT and SPT

Vane Shear Test

- Used in Clayey Soils
- Undrained Shear Strength $s_u$ is estimated by rotating the vane with a Torque
Vane Shear Test (VST)

Vane Shear Test (VST) per ASTM D 2573:
- Unrestrained Shear Strength: $s_u = 6 T/(\pi D)$
- In-Situ Sensitivity: $S_i = s_u/\lambda$

Vane Shear Test

$$T = 2\pi B^2 \frac{B}{2} + n \int_0^{B/2} (s_u)(2\pi r) r dr$$

$$(s_u)_{FV} = \frac{12T}{(12 + n)\pi B^3}$$

Bjerrum 1972, 1973

$$s_u = \lambda (s_u)_{FV}$$

$$\lambda = 1.18 - 0.0107(PI) + 0.0000513(PI)^2 \leq 1$$
Pressuremeter Test

- Louis Menard (1956)
- Pressure meter lowered into pre-existing borehole
- It is forced to expand (like a balloon) and soil resistance is measured
Pile Loading Test

Interpretation

Plate Bearing Test - Interpretation
Field Plate Load Test

For tests in clay,

\[ q_{u(r)} - q_{u(r)} \]

where

- \( q_{u(r)} \) = ultimate bearing capacity of the proposed foundation
- \( q_{u(r)} \) = ultimate bearing capacity of the test plate

For tests in sandy soils,

\[ q_{u(r)} = q_{u(r)} \frac{R_t}{B_p} \]

where

- \( B_p \) = width of the foundation
- \( B_p \) = width of the test plate

Field Plate Load Test

The allowable bearing capacity of a foundation, based on settlement considerations and for a given intensity of load, \( q_{sr} \), is

\[ S_{fr} = S_p \frac{B_p}{B_p} \]

for clayey soil

\[ S_t = S_p \frac{B_p (B_p + 0.3)}{B_p (B + 0.3)} \]

for sandy soil

where

- \( B \) = the size of footing in m,
- \( B_p \) = size of test plate in m,
- \( S_p \) = settlement of test plate in m, and
- \( S_t \) = settlement of footing in m.

IS 1882: Method of load tests on soils
Non-destructive Testing

Geophysical Exploration

- Largely based on principles of geophysical properties of the soil, for e.g., wave velocity, electrical properties, magnetic properties, etc.

- Soil stratigraphy, buried objects etc. can be identified

Seismic Refraction

ASTM D 5777

Note: $V_{p1} < V_{p2}$

Determine depth to rock layer, $z_R$

Source (Plate)

Vertical Geophones

Rock: $V_{p2}$

Soil: $V_{p1}$
Mechanical Waves (Shear)

Ground Penetrating Radar (GPR)

- GPR surveys conducted on gridded areas
- Pair of transmitting and receiver antennae
- Short impulses of high-freq EM wave
- Relative changes in dielectric properties reflect differences in subsurface.
- Depth of exploration is soil dependent (up to 30 m in dry sands; only 3 m in wet saturated clay)
Ground Penetrating Radar (GPR)

Illustrative Results from Ground Penetrating Radar (GPR)

Crossing an underground utility corridor
Illustrative Results from Ground Penetrating Radar (GPR)

Illustrative Results of Ground Penetrating Radar (GPR)

Geostratigraphy
Examples of Ground Penetrating Radar (GPR)

Useful in Locating Underground Utilities

Results from Ground Penetrating Radar (GPR)

GPR Survey to Locate Underground Storage Tanks
Electrical Resistivity Measurements

Electrical Resistivity (ER) Surveys

- Resistivity $\rho_R$ (ohm-m) is an electrical property. It is the reciprocal of conductivity.
- Arrays of electrodes used to measure changes in potential.
- Evaluate changes in soil types and variations in pore fluids.
- Used to map faults, karst features (caves, sinkholes), stratigraphy, contaminant plumes.
Electrical Resistivity Measurements

\[ \rho_a = \frac{2\pi a \Delta V}{i} \]

\[ \rho_s = \frac{\pi (s^2 - a^2/4) \Delta V}{a} \]

Electrical Resistivity Measurements

Legend

Entrance to Cave

Existing Sinkhole

Possible Sinkhole

Estimated Bedrock Surface

Potential Bedrock Fractures
Electrical Resistivity Measurements

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity (ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (dry)</td>
<td>10^1 - 10^2</td>
</tr>
<tr>
<td>Sand (saturated)</td>
<td>10^2 - 10^3</td>
</tr>
<tr>
<td>Silt</td>
<td>10^3</td>
</tr>
<tr>
<td>Slate</td>
<td>10^3 - 10^4</td>
</tr>
<tr>
<td>Lime</td>
<td>10^5</td>
</tr>
<tr>
<td>Humid soil</td>
<td>10^5 - 10^6</td>
</tr>
<tr>
<td>Cultivated soil</td>
<td>10^6</td>
</tr>
<tr>
<td>Rocky soil</td>
<td>10^7</td>
</tr>
<tr>
<td>Sandy soil (dry)</td>
<td>10^7</td>
</tr>
<tr>
<td>Sandy soil (saturated)</td>
<td>10^8</td>
</tr>
<tr>
<td>Loamy soil (dry)</td>
<td>10^9</td>
</tr>
<tr>
<td>Loamy soil (saturated)</td>
<td>10^9</td>
</tr>
<tr>
<td>Clayey soil (dry)</td>
<td>10^10</td>
</tr>
<tr>
<td>Clayey soil (saturated)</td>
<td>10^11</td>
</tr>
<tr>
<td>Sandstone (saturated)</td>
<td>10^12</td>
</tr>
<tr>
<td>Limestone (dry)</td>
<td>10^12</td>
</tr>
<tr>
<td>Limestone (saturated)</td>
<td>10^13</td>
</tr>
<tr>
<td>Basalt</td>
<td>10^13</td>
</tr>
<tr>
<td>Granite</td>
<td>10^14</td>
</tr>
<tr>
<td>Coal</td>
<td>10^15</td>
</tr>
<tr>
<td>Fresh water</td>
<td>10^14</td>
</tr>
<tr>
<td>Permafrost</td>
<td>10^12</td>
</tr>
<tr>
<td>Dry snow</td>
<td>10^15</td>
</tr>
<tr>
<td>Ice</td>
<td>10^15</td>
</tr>
</tbody>
</table>

Compaction Quality Control of Pavement Layers using NDT Methods
Nuclear Gauge Method

- Several Advantages
- Both in situ field density and moisture content
- Ease of use
- Reliability of test results
- Drawbacks: Safety concerns – Harmful radiations

QC in terms of Stiffness

- Success rate in locating construction defects using density-based measurements is as low as 25%
- Modulus-based QC tests possess a high success rate of 64-86% - Quintus et al. (2009)
QC in terms of Stiffness

Light Weight Deflectometer

Dynamic Cone Penetrometer

Schematic of LWD

1. Grip
2. Top fix and release mechanism
3. Guide rod
4. Round grip
5. Falling weight (10 kg)
6. Set of Steel springs (buffer)
7. Measuring element that contains the sensor
8. Loading plate (diameter = 30 cm)
9. Carry Grip

Image Source: Jet Materials
Deformation Modulus

\[ E_{LWD} = \frac{qr(1 - \nu^2)}{w} f_R \]

- \( E_{LWD} \) = modulus of deformation of pavement layer (MPa);
- \( f_R \) = plate rigidity factor (taken as \( \pi = 2 \) for a rigid plate);
- \( q \) = maximum contact pressure (MPa);
- \( r \) = radius of bearing plate (mm);
- \( \nu \) = Poisson’s ratio of soil; and
- \( w \) = settlement of bearing plate measured at its center (mm).
## Properties of Various LWD’s

<table>
<thead>
<tr>
<th>Properties</th>
<th>Zorn</th>
<th>Prima</th>
<th>TFT</th>
<th>Dynatest</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plate style</strong></td>
<td>Solid</td>
<td>Annulus</td>
<td>Annulus</td>
<td>Solid</td>
</tr>
<tr>
<td><strong>Plate diameter (mm)</strong></td>
<td>150, 200, 300</td>
<td>100, 200, 300</td>
<td>100, 150, 200, 300</td>
<td>100, 150, 200, 300</td>
</tr>
<tr>
<td><strong>Drop mass (kg)</strong></td>
<td>10</td>
<td>10, 15, 20</td>
<td>10, 15, 20</td>
<td>10, 15, 20</td>
</tr>
<tr>
<td><strong>Drop height (m)</strong></td>
<td>0.72</td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>Damper</strong></td>
<td>Steel spring</td>
<td>Rubber</td>
<td>Rubber</td>
<td>Urethane</td>
</tr>
</tbody>
</table>

## Testing

- LWD testing was done at 95 test locations (54 tests on base layers and 41 tests on surface layers) located on 6 test pads of expressways.
- Case study considered to demonstrate procedure to establish relationship between \( E_{LWD} \) and the compacted density of the base layer of a low-
**Grain-size distribution curves**

WMM layer

DBM layer

**Compaction Curve**

Compaction curve of base layer material (WMM)
Typical cross section of pavement layers of an expressway

Test Pad - 1
Test Pad - 6

Calculations

\[ \bar{w} = \frac{1}{m} \sum_{i=1}^{m} w_i \]  
\[ \sigma_w = \sqrt{\frac{\sum_{i=1}^{m} (w_i - \bar{w})^2}{m - 1}} \]  
\[ \text{COV}_w = \frac{\sigma_w}{\bar{w}} \]

\( m = \text{Total number of hammer blows} = 3 \) for all test points
Calculations

\[ \bar{E}_{\text{LWD}} = \frac{1}{n} \sum_{i=1}^{n} E_{\text{LWD}(i)} \]

\[ \sigma_{E-\text{LWD}} = \sqrt{\frac{\sum_{i=1}^{n} (E_{\text{LWD}(i)} - \bar{E}_{\text{LWD}})^2}{n - 1}} \]

\[ \text{COV}_{E-\text{LWD}} = \frac{\sigma_{E-\text{LWD}}}{E_{\text{LWD}}} \]

\[ n = \text{Total number of test points for a given test pad} \]

Summary of Results

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>Test pad number</th>
<th>Number of tests</th>
<th>(E_{\text{LWD}}) (MPa)</th>
<th>(\sigma_{\text{LWD}}) (MPa)</th>
<th>COV (E_{-\text{LWD}}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base layer (WMM)</td>
<td>1</td>
<td>12</td>
<td>48.1</td>
<td>5.72</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>18</td>
<td>45.5</td>
<td>3.92</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>24</td>
<td>54.6</td>
<td>4.53</td>
<td>8.3</td>
</tr>
<tr>
<td>Surface layer (DBM)</td>
<td>4</td>
<td>16</td>
<td>105.4</td>
<td>8.91</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>07</td>
<td>114.2</td>
<td>5.06</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>18</td>
<td>113.5</td>
<td>8.23</td>
<td>7.3</td>
</tr>
</tbody>
</table>
### Summary of test results on low-volume road

<table>
<thead>
<tr>
<th>Description</th>
<th>Field density (g/cc)</th>
<th>Relative compaction (%)</th>
<th>$E_{LWD}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without passes</td>
<td>2.10</td>
<td>93.3</td>
<td>28.0</td>
</tr>
<tr>
<td>One plain pass</td>
<td>2.15</td>
<td>95.6</td>
<td>30.5</td>
</tr>
<tr>
<td>Two plain passes</td>
<td>2.20</td>
<td>97.8</td>
<td>32.0</td>
</tr>
<tr>
<td>Two low vibratory passes</td>
<td>2.25</td>
<td>100.0</td>
<td>34.5</td>
</tr>
<tr>
<td>Two high vibratory passes</td>
<td>2.28</td>
<td>101.3</td>
<td>35.0</td>
</tr>
</tbody>
</table>

*Maximum dry density = 2.25 g/cc and Optimum moisture content = 4.5%*

---

**Relative compaction $\text{vs. } E_{LWD}$ modulus of base layer of a low-volume road**
Conclusions

• Site exploration and in situ testing important components of any project. Due attention to be paid in major projects
• Soil characterization based on in situ testing more reliable
• QC using LWD device found to provide quick test results and the frequency of QC tests can be increased
• NDT to be encouraged for soil characterization to determine relevant properties for the project.

Assignment

• Raft of a escape regulator to be designed. One representative bore log on the plan of this structure is provided. Estimate the safe bearing capacity of the raft.
• RL of existing ground level is at +24.171 and raft bottom is proposed at +10.560.
• The proposed size of raft is 15.5m x 40.5 m (in plan).
<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Depth</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00 AM</td>
<td>Laid out</td>
<td>6-6 cm</td>
<td>Clay &amp; Fine Sand</td>
</tr>
<tr>
<td>9:00 AM</td>
<td>Laid out</td>
<td>6-6 cm</td>
<td>Clay &amp; Fine Sand</td>
</tr>
<tr>
<td>10:00 AM</td>
<td>Laid out</td>
<td>6-6 cm</td>
<td>Clay &amp; Fine Sand</td>
</tr>
<tr>
<td>11:00 AM</td>
<td>Laid out</td>
<td>6-6 cm</td>
<td>Clay &amp; Fine Sand</td>
</tr>
<tr>
<td>12:00 PM</td>
<td>Laid out</td>
<td>6-6 cm</td>
<td>Clay &amp; Fine Sand</td>
</tr>
</tbody>
</table>

**Notes:**
- Time in AM/PM format.
- Depths in centimeters.
- Materials listed as per written description.
Reference Material

- Principles of Foundation Engineering by B. M. Das
- Foundation Analysis and Design by J. E. Bowles
- The Engineering of Foundations by R. Salgado
- Relevant IS Codes
THANK YOU
Email: buma@iith.ac.in

Questions ?