Design of Drilled Shafts in Expansive Soils

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Question:

How do you convert the usual data from a Soils Lab report into information you can use to design a drilled shaft?
What kind of data is in the usual Soils Lab report?

Answer:

- Atterberg limits,
  - Liquid limit, LL
  - Plasticity index, PI

- Water content, $w$

- Dry unit weight (density) of the soil, $\gamma_d$

- Strength
  - Unconfined compressive strength, psi, tsf
  - Pocket penetrometer, tsf
  - Vane shear strength, tsf
What kind of information do you need to design a drilled shaft?

**Answer:**

- Volumetric water content, $\theta$
- Effective friction angle, $\phi'$
- Matric suction, pF
- Skin friction factor, $\alpha$

Some in the movement active zone
Some in the anchor zone
What conditions do you need to design for?

- Uplift (soil gets wetter)
- Bearing capacity (soil gets drier)
What other soils information will you need and where do you get it?

- Thornthwaite moisture index
  (for deep water tables)
  (map of TMI)

- Water content, Atterberg limits, dry unit weight, strength at or below the water table
  (for shallow water tables)

- Boring Log

- Natural resources conservation service county soil map
Thornthwaite Moisture Index (TMI, 1948)

\[
TMI = \frac{100R - 60\text{DEF}}{E_p}
\]

- \( R \) = runoff moisture depth
- \( \text{DEF} \) = deficit moisture depth
- \( E_p \) = evapotranspiration
Suction Distribution with Depth

(-) Suction Ground Surface

Wet Season Equilibrium

Dry Season
Soil Survey of Harris County, Texas

- Lake Charles series

The Lake Charles series consists of deep, neutral, nearly level to gently sloping, clayey soils on upland prairies. These soils are clayey throughout the profile and have wide deep cracks and intersecting slickensides (fig. 15). They formed in alkaline marine clay.

Undisturbed areas of these soils have gilgai microrelief, in which the microknolls are 6 to 12 inches higher than the microdepressions. When these soils are dry, deep, wide cracks form on the surface. Water enters the cracks rapidly, but when the soils are wet and the cracks are sealed, water enters very slowly. These soils are somewhat poorly drained. Surface runoff is very slow or medium. Internal drainage is very slow. Permeability is very slow, and the available water capacity is high.

These soils are used mainly for rice and pasture. Some are in urban uses.

Representative profile of Lake Charles clay, 0 to 1 percent slopes, at the center of a microdepression, in pasture, from the intersection of Cook Road and Alief Road in
Lake Charles series, cont.

Alief, 1.11 miles west along Alief Road, 1.37 miles north on Synott Road, and 75 feet west:

Ap—0 to 22 inches; black (10YR 2/1) clay, very dark gray (10YR 3/1) dry; moderate fine blocky structure; very hard, very firm, very sticky and plastic; many fine roots; few fine iron-manganese concretions; shiny pressure faces; neutral; diffuse wavy boundary.

A12—22 to 36 inches; very dark gray (10YR 3/1) clay, dark gray (10YR 4/1) dry; moderate fine blocky and subangular blocky structure in upper 12 inches and breaking to moderate fine and medium blocky in the lower part; the lower part contains common large wedge-shaped peds having long axes tilted 10 to 60 degrees from the horizontal and bordered by intersecting slickensides; extremely hard, very firm, very sticky and plastic; aggregates have shiny pressure faces; few fine iron-manganese and calcium carbonate concretions; mildly alkaline; diffuse wavy boundary.

AC1g—36 to 52 inches; dark gray (10YR 4/1) clay, gray (10YR 5/1) dry; common fine and medium distinct mottles of olive (5Y 4/3) and few fine distinct mottles of yellowish brown (10YR 5/4); common large wedge-shaped peds having long axes tilted 10 to 60 degrees from the horizontal and bordered by intersecting slickensides, peds break to moderate medium and coarse blocky structure; extremely hard, very firm, very sticky and plastic; few fine roots; aggregates have shiny pressure faces; few fine iron-manganese concretions; few calcium carbonate concretions as much as 1 centimeter in diameter; mildly alkaline; diffuse wavy boundary.

AC2g—52 to 74 inches; gray (5Y 5/1) clay, gray (5Y 6/1) dry; common fine and medium distinct mottles of light olive brown (2.5Y 5/4) and few fine distinct mottles of yellowish brown (10YR 5/6); weak fine angular blocky structure; extremely hard, very firm, very sticky and plastic; few fine iron-manganese concretions; few intersecting slickensides; few irregularly shaped pitted calcium carbonate concretions generally less than 3 centimeters in size; mildly alkaline.

In undisturbed areas, gilgai microknoolls are 6 to 12 inches higher than microdepressions. The center of the microknoolls is about 4 to 16 feet from the center of the microdepressions. When the soils are dry, cracks 1 to 2 inches wide form on the surface and extend into the ACg horizon. Intersecting slickensides begin at a depth of about 20 to 30 inches. The A horizon is black or very dark gray. It ranges from slightly acid through mildly alkaline. The ACg horizon is very dark gray, dark gray, or gray. Mottles in the ACg horizon are olive, yellowish brown, light olive brown, strong brown, yellow, or red. The ACg horizon is clay or silty clay. It ranges from neutral through moderately alkaline. In some places it is calcareous in the lower part.
### Soil Survey of Harris County, Texas

- **Engineering properties and classifications**

<table>
<thead>
<tr>
<th>Soil name and map symbol</th>
<th>Depth</th>
<th>USDA texture</th>
<th>Classification</th>
<th>Percentage passing sieve number</th>
<th>Liquid limit</th>
<th>Plasticity index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unified</td>
<td>AASHTO</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Lake Charles:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LcA, LcB-----------------</td>
<td>0-22</td>
<td>Clay---------</td>
<td>CH</td>
<td>A-7</td>
<td>100</td>
<td>99-100</td>
</tr>
<tr>
<td></td>
<td>22-74</td>
<td>Clay---------</td>
<td>CH</td>
<td>A-7</td>
<td>98-100</td>
<td>98-100</td>
</tr>
<tr>
<td>Lu::</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lake Charles part</td>
<td>0-22</td>
<td>Clay---------</td>
<td>CH</td>
<td>A-7</td>
<td>100</td>
<td>99-100</td>
</tr>
<tr>
<td></td>
<td>22-74</td>
<td>Clay---------</td>
<td>CH</td>
<td>A-7</td>
<td>98-100</td>
<td>98-100</td>
</tr>
</tbody>
</table>
Soil Survey of Harris County, Texas

- **Engineering test data**

### TABLE 19.—ENGINEERING TEST DATA—Continued

<table>
<thead>
<tr>
<th>Soil name and location</th>
<th>Depth from surface</th>
<th>Shrinkage</th>
<th>Mechanical analysis$^1$</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Linear</td>
<td>Ratio</td>
<td>Volumetric</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenney loamy fine sand:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From Spring, 3.75 miles west on Spring-Stuebner Road to Rothwood Road, 1.8 miles north on Rothwood Road and 40 feet west in timber (modal). Texas report no. 1271L-347, 348.</td>
<td>9-56</td>
<td>1.7</td>
<td>18.3</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>56-80</td>
<td>3.5</td>
<td>18.6</td>
<td>1.71</td>
</tr>
<tr>
<td>Lake Charles clay:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From Alief, 1.11 miles west on Alief Road to Synott Road, then 1.37 miles north on Synott Road and 75 feet west in pasture (modal). Texas report no. 1271L-198, 199, 200.</td>
<td>0-22</td>
<td>26.2</td>
<td>12.5</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>36-52</td>
<td>29.9</td>
<td>6.0</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>52-74</td>
<td>29.0</td>
<td>6.3</td>
<td>2.14</td>
</tr>
</tbody>
</table>
Soil Survey of Harris County, Texas

- Profile of Lake Charles clay

Figure 15.—Profile of Lake Charles clay, 0 to 1 percent slopes. Wide, deep cracks are in the upper layers, and intersecting slickensides are in the lower layers.
Geotechnical Study Report No. 11-700E

- Plan of Borings
Log of Boring No. B-1
Log of Boring No. B-2
Steps in Design Calculations

- Strength and suction
- Depth of the movement active zone
- Depth of the anchor zone
- Size of the bell
  - Short term loading
  - Long term loading
- Reinforcing steel and size of shaft
Strength and Suction

- **Input (in movement active and anchor zones)**
  - Atterberg limits
  - Water content
  - Dry unit weight
  - Unconfined compressive strength in psi, tsf, or psf
  - Skin friction stress coefficient

- **Output (in movement active and anchor zones)**
  - Effective friction angle
  - Volumetric water content
  - Total unit weight
  - Present matric suction
  - Future matric suction
  - Skin friction stress
### Design Parameters for Drilled Piers in Clay

<table>
<thead>
<tr>
<th>Parameter (1)</th>
<th>Design category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A.1 (2)</td>
</tr>
<tr>
<td>$a_{avg}$ Limit on side shear, in tons per square foot</td>
<td>0.5</td>
</tr>
<tr>
<td>$N_a$</td>
<td>9</td>
</tr>
</tbody>
</table>

* May be increased to Category A.1 value for segments of pier drilled dry.
* Limiting side shear is 0.9 t/sf for segments of pier drilled dry.
* May be increased to Category B.1 value for segments of pier drilled dry.
* Limiting side shear is 0.4 t/sf for segments of pier drilled dry.

Note: 1 t/sf = 95.8 kN/m².

\[
(Q_x)_\text{limit} = (Q_x)_\text{nom} + \frac{(Q_n)_\text{nom}}{3} \cdot \frac{1}{(Q_T)_\text{ult}/2}
\]

**Category A.** Straight-sided shafts in either homogeneous or layered soil with no soil of exceptional stiffness below the base.

**Category A.1.** Piers in Category A installed dry or by advancing the borehole with light weight drilling slurry and displacing the slurry directly with fluid concrete.

**Category A.2.** Piers in Category A installed with drilling mud along some portion of the hole such that the entrapment of drilling mud between the sides of the pier and the natural soil is possible.

**Category B.** Belled piers in either homogeneous or layered clays with no soil of exceptional stiffness below the base.

**Category B.1.** Piers in Category B installed dry.

**Category B.2.** Piers in Category B installed with drilling mud along some portion of the hole such that the entrapment of drilling mud between the sides of the pier and the natural soil is possible.

**Category C.** Straight-sided piers with base resting on soil significantly stiffer than the soil around the stem.

**Category D.** Belled piers with base resting on soils significantly stiffer than the soil around the stem.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>A.1</th>
<th>A.2</th>
<th>B.1</th>
<th>B.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Side Shear limit, tsf</td>
<td>0.9</td>
<td>0.4</td>
<td>0.4</td>
<td>0.25</td>
</tr>
<tr>
<td>A: straight-sided shafts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: belled piers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* From Reese, Touma, and O’Neill
Correlation between $\phi'$ and PI

Fig. 12A: Empirical correlation between $\phi'$ and PI from triaxial compression tests on normally consolidated undisturbed clays (after U.S. Navy, 1971, and Ladd, et al., 1977).

Effective Friction Angle, $\phi'$

$$\phi' = 0.0016(PI, \%)^2 - 0.3021(PI, \%) + 36.208$$
Total Unit Weight, lb/ft³

\[ \gamma_t = dry\ unit\ weight \times (1 + w) \]

Volumetric Water Content

\[ \theta = w \times \frac{dry\ unit\ weight,\ lb/ft^3}{unit\ weight\ of\ water\ (62.4\ lb/ft^3)} \]
Matric Suction, stress units

Matric suction \( \approx -\frac{\text{unconfined compressive strength}}{2} \cdot \frac{1 - \sin \phi'}{f \theta \sin \phi'} \)
“Skin Friction” or Side Shear Stress

"Skin friction" = \( \alpha(-\theta f h_m) \frac{\sin \phi' \cos \phi'}{1 - \sin \phi'} \)

(compare with limiting side shear)
Calculation – Strength and Suction
Depth of the Movement Active Zone

- **Input**
  - Initial pF
  - Total unit weight (from “strength and suction” tab)
  - Final suction (from Thornthwaite Moisture Index)
  - Estimated percent fine clay (USDA NRCS county soil map)

- **Output**
  - Depth of movement active zone
Calculation – Depth of the Movement Active Zone
Formation of Suction vs. Pressure vs. Volume Surface
Equation of a Horizontal Path on the Surface

\[
\frac{\Delta V}{V} = -\gamma_h \log \left( \frac{h_f}{h_i} \right) - \gamma_\sigma \log \left( \frac{\sigma_f}{\sigma_i} \right)
\]

At the depth of the movement active zone

\[
\frac{\Delta V}{V} = 0
\]
Below this depth, pressure reduces volume change. 

\[ z_i \approx 80 \, \text{cm} \]
\[ z_i \approx 2.63 \, \text{ft} \]
Depth of the Movement Active Zone, $z_A$

$$z_{A, ft} = z_i \left( \frac{h_i}{h_f} \right) \left( \frac{\gamma_h}{\gamma_\sigma} \right)$$
Ratio of Volume Change Coefficients

\[
\left( \frac{\gamma_h}{\gamma_\sigma} \right) = 1 + \frac{0.4343}{S_w}
\]

S: slope of the suction vs. water content curve
w: water content
Estimate of $Sw$

$$Sw = pF - 5.622 - 0.0041(\% \text{ fine clay})$$
Design Procedure for Pavements on Expansive Soils
Report 0-4518-1
Depth of the Anchor Zone

- **Input**
  - Depth of the movement active zone
  - Skin friction stress (from “strength and suction” tab)
  - Trial diameter of pier shaft

- **Output**
  - Depth of the anchor zone
  - Depth of pier
  - Maximum tensile force in pier shaft
  - Required area of reinforcing steel
Reinforcing Steel

The smaller the bars
The smaller the debonding length
The smaller the crack width
Minimum size of pier shaft

- Minimum spacing
- Minimum cover
- Minimum size bars
Required Percent Steel

\[ P(\% \text{ steel}) = \left( \frac{4 S_u^M}{d f_y} - \frac{\gamma_c}{f_y} \right) - \frac{P}{A f_y} \]

d = diameter of shaft, in
\( S_u^M = \) side shear in the movement active zone, lb/in²
\( f_y = \) yield strength of the reinforcing steel, ksi
A = cross sectional area of the shaft, in²
P = minimum load at the top of the pier, kips
Reinforcing Steel

- **Input**
  - Required area of steel
  - Steel cover
  - Steel spacing

- **Select**
  - Reinforcing bar size

- **Output**
  - Number of reinforcing bars
  - Minimum pier shaft diameter
Calculation – Reinforcing Steel
Size of the Bell

- **Input**
  - Maximum load on pier
  - Depth of movement active zone
  - Depth of anchor zone
  - Skin fiction stress in the anchor zone
  - Long term bearing capacity factor of safety
  - Short term bearing capacity factor of safety

- **Output**
  - Diameter of bell
    - Short term loading
    - Long term loading
  - Minimum diameter of pier shaft
Calculation – Size of the Bell
Steps in Design Calculations

- Strength and suction
- Depth of the movement active zone
- Depth of the anchor zone
- Size of the bell
  - Short term loading
  - Long term loading
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