DEEP EXCAVATION

GEOTECHNICAL SOFTWARE & ENGINEERING

# Enhancement of Deep Foundations Performance:

## Integrating CPT/CPTu, Case Histories & DeepFND Implementation

*Workshop*

Summary


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1. Background to Foundation Engineering Integrated with CPT & CPTu Data
2. CPT-Based Methods for Deep Foundations
3. Demo Examples
4. Cases: Histories & Studies

**Scope**

***Deep Foundations Performance through Integrating CPT/CPTu and Case Histories***

**Objectives**

- ***CPT & CPTu Records Significancy***
- ***SBC & Characterization***
- ***Installation Depth***
- ***Bearing Capacity***
- ***Resistance Distribution***
- ***Load – Displacement***

**Aim**

***Design Enhancement***

1. Background to Foundation Engineering Integrated with CPT & CPTu Data
2. CPT-Based Methods for Deep Foundations
3. Demo Examples
4. Cases: Histories & Studies

I. Foundation Engineering

II. Deep Foundations: Geotechnical Design

III. Foundation Engineering: Complementary Aspects

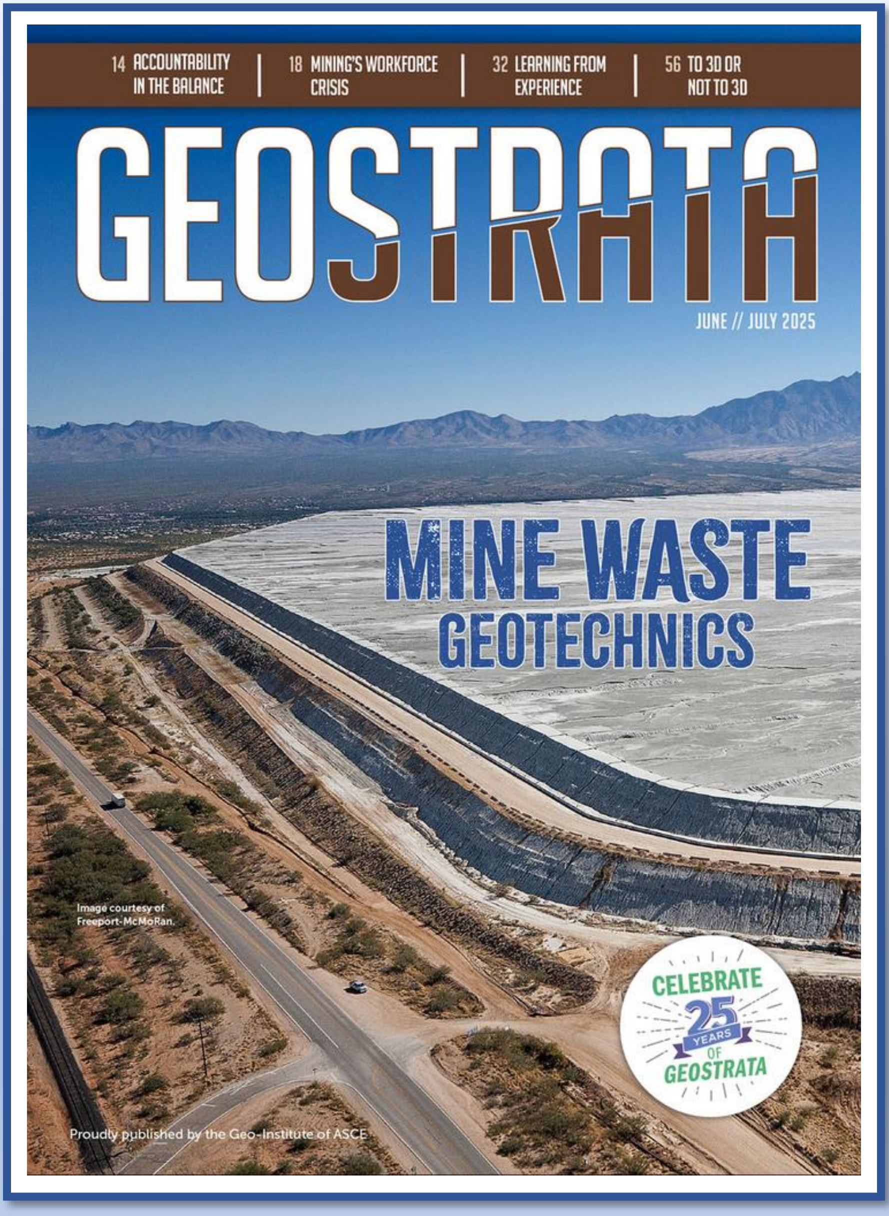
IV. Geotechnical Engineering & Site Investigations

V. Cone & Piezocone Penetration Tests (CPT & CPTu)

VI. Applications of CPT & CPTu in Geotechnical Engineering

VII. Cases Review

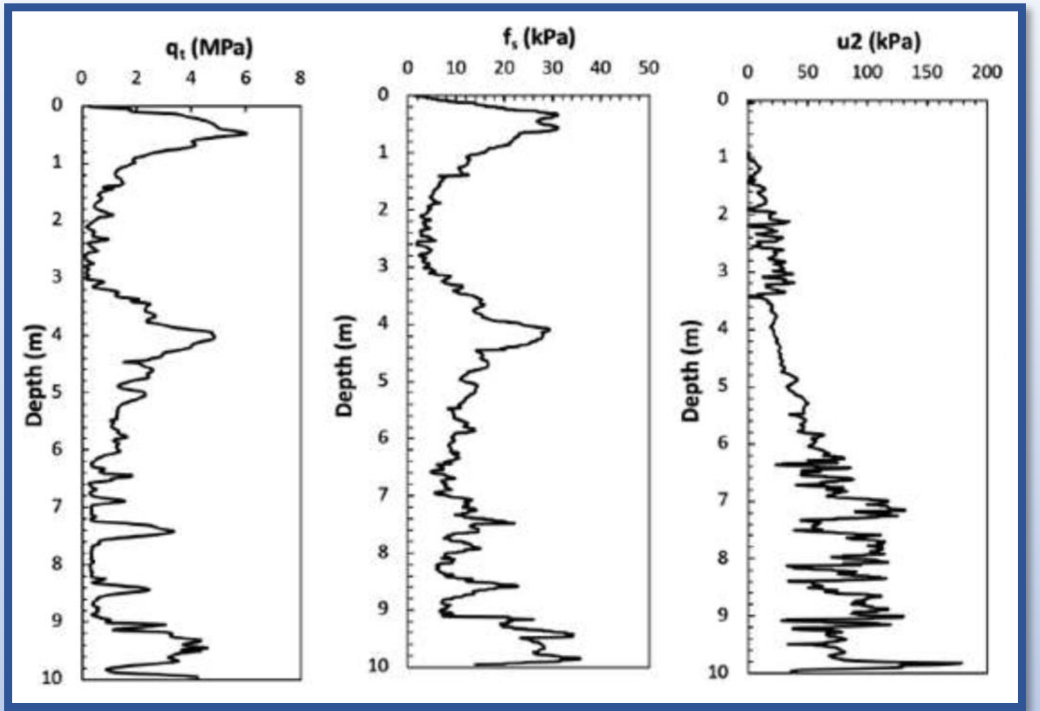
**Case No. 1:
Significancy of CPT/CPTu Records for Management of Mine Waste (GEOSTRATA-June/July 2025)**



**Case No. 1:
GEOSTRATA (June/July 2025)**

## a) Liquefaction & Tailings Storage Facility (TSF) Failure

***By: Jorge Macedo, Jonathan D. Bray, Scott M. Olson, Christina Winckler, Paul Ridlen, and Kimberly Finke Morrison***




### Insights from CPTu Records:

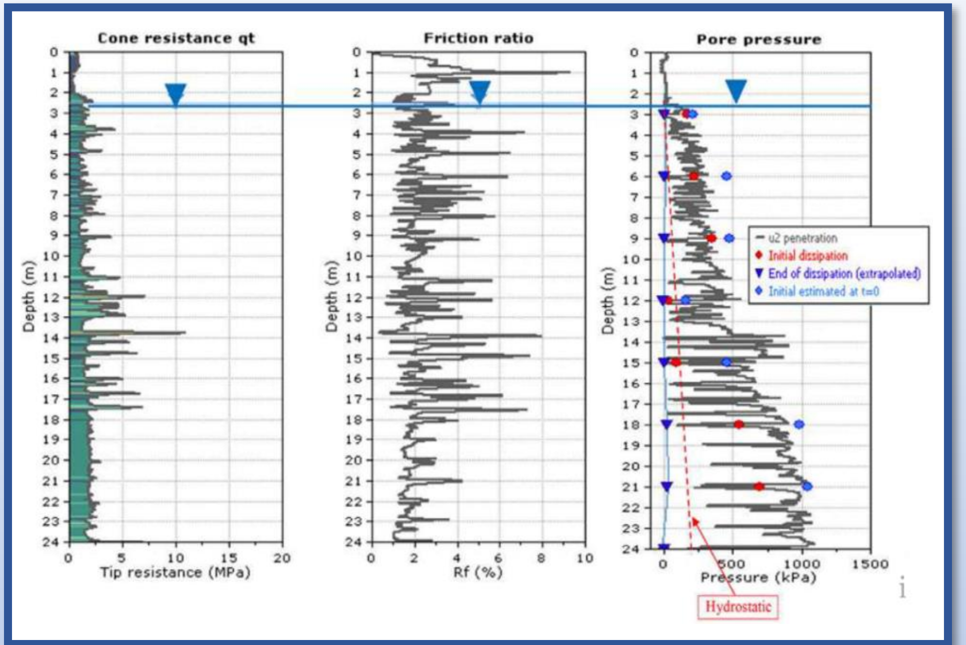
- $\mathbf{q_t}$ < 5 MPa: The tailings are loose and suspectable to liquefaction
- $\mathbf{f_s}$ < 30 kPa: The tailings could lose significant when sheared

**Case No. 1:**
**GEOSTRATA (June/July 2025)**

## b) Understanding the Piezometric Profile & Soil Behavior

***By: Peter K. Robertson & Kelly Cabal***

- **CPTu: The primary In-situ test for characterization of tailings**
- **Importance of suitable interpretation of CPTu records**
- **Depositional history:**
  - ❖ **Density**
  - ❖ **Mechanical properties**
  - ❖ **Stability**

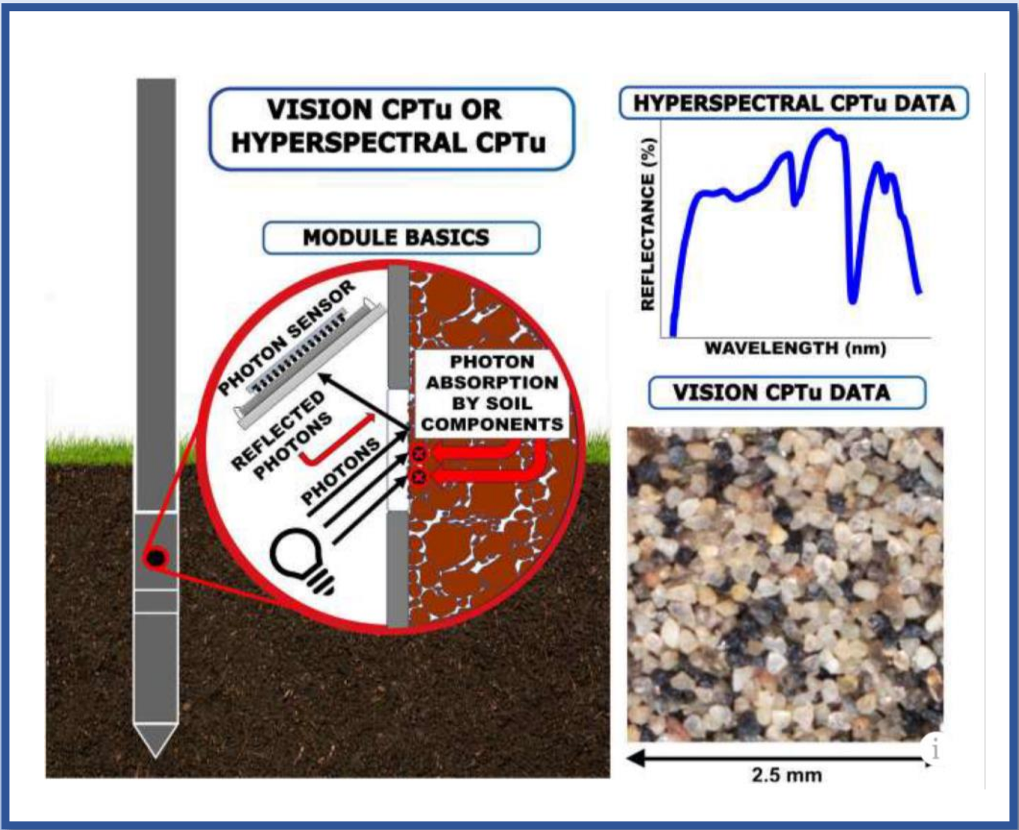



**Case No. 1:
GEOSTRATA (June/July 2025)**

## c) Optical Sensors for In-situ Measurements: Hyperspectral CPTu and Vision CPTu

***Study 1: Laboratory Hyperspectral Sensing for Gold Tailings***

***By: Joseph Bindner, Iman Entezari, Dallas McGowan, and Joseph Scalia***

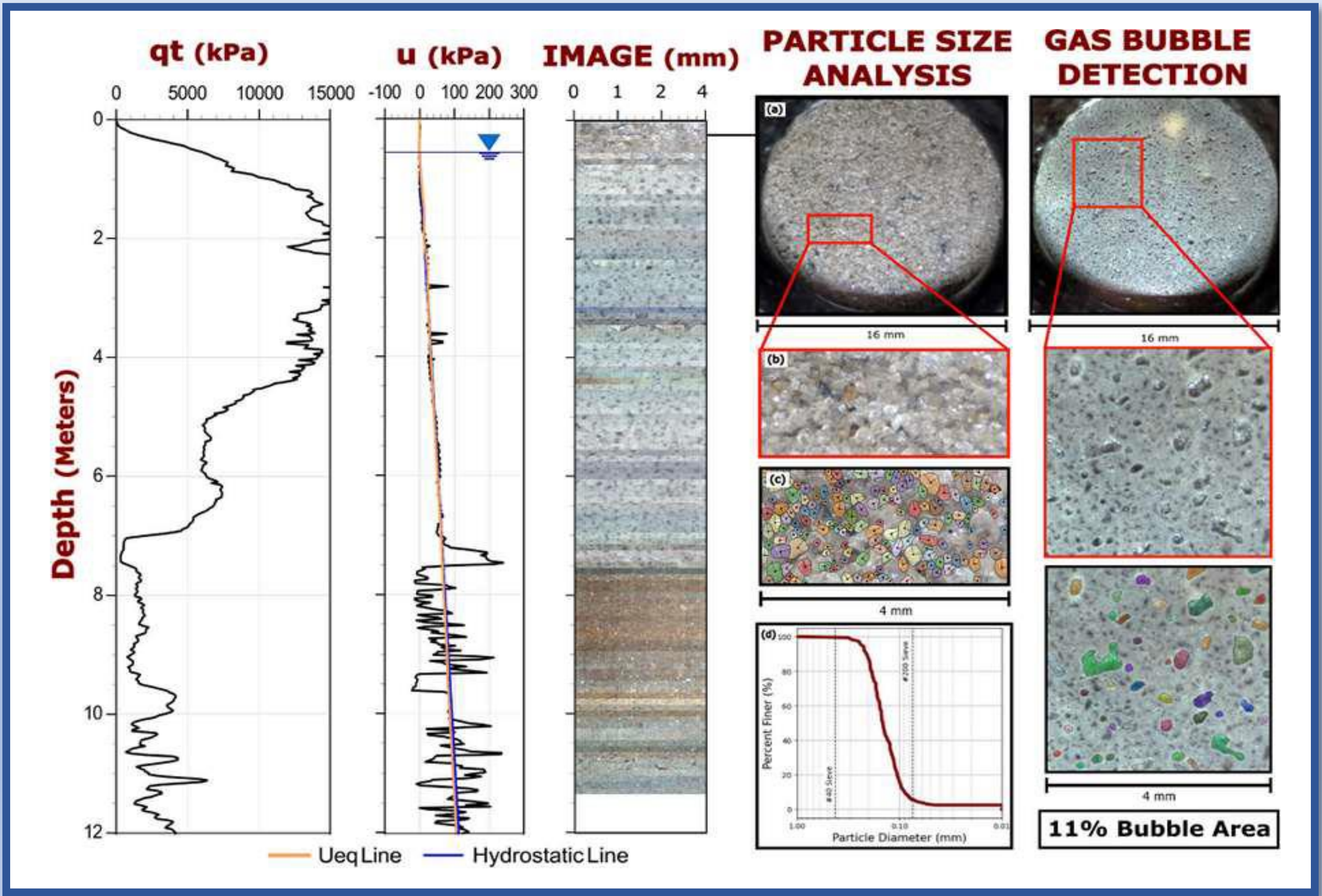


**Case No. 1:**
**GEOSTRATA (June/July 2025)**

## c) Optical Sensors for In-situ Measurements: Hyperspectral CPTu and Vision CPTu

*Study 2: High-resolution Imaging for CPTu*

*By: Joseph Bindner, Iman Entezari, Dallas McGowan, and Joseph Scalia*



1. Background to Foundation Engineering Integrated with CPT & CPTu Data
2. CPT-Based Methods for Deep Foundations
3. Demo Examples & Cases
4. Cases: Histories & Studies

# Subjects

I. Indirect Application of CPT & CPTu Records

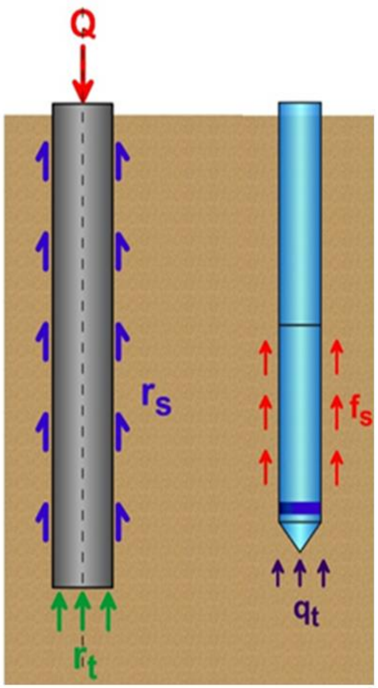
II. Direct Application for Shallow Foundations

III. CPT & Pile: Scale Effects

IV. CPT- & CPTu-Based Methods

V. Cases Review

## Direct & Indirect Approach




**Indirect Approach** $\left\{ \begin{array}{l} \mathbf{q_c} \\ \mathbf{f_s} \\ \mathbf{u_2} \end{array} \right.$ $\Rightarrow$ C, $\boldsymbol{\varphi}$ $\Rightarrow$ $r_t$, $r_s$

**Direct Approach** $\left\{ \begin{array}{l} q_c \Rightarrow r_t\ (\mathbf{q_b}) \\ f_s \Rightarrow r_s\ (\mathbf{q_s}) \end{array} \right.$

## CPT-Based Methods

- ***Meyerhof Method (1956, 1976, 1983)***
- ***LCPC Method, (Bustamante and Gianeselli, 1982)***
- ***UniCone Method, Eslami & Fellenius (1997)***
- ***German Method, Kempfert & Becker (2010)***
- ***Enhanced UniCone Method, Niazi & Mayne (2016)***

# Case No. 5: Urmia Lake Causeway: Long Piles & Super Soft Deposits (Eslami et al., 2011, 2019 & 2024)

- Decreasing the proposed route from 300 km to 120 km,
- Total length of 1260 m
- 19 spans
- 100 m in length for the main span

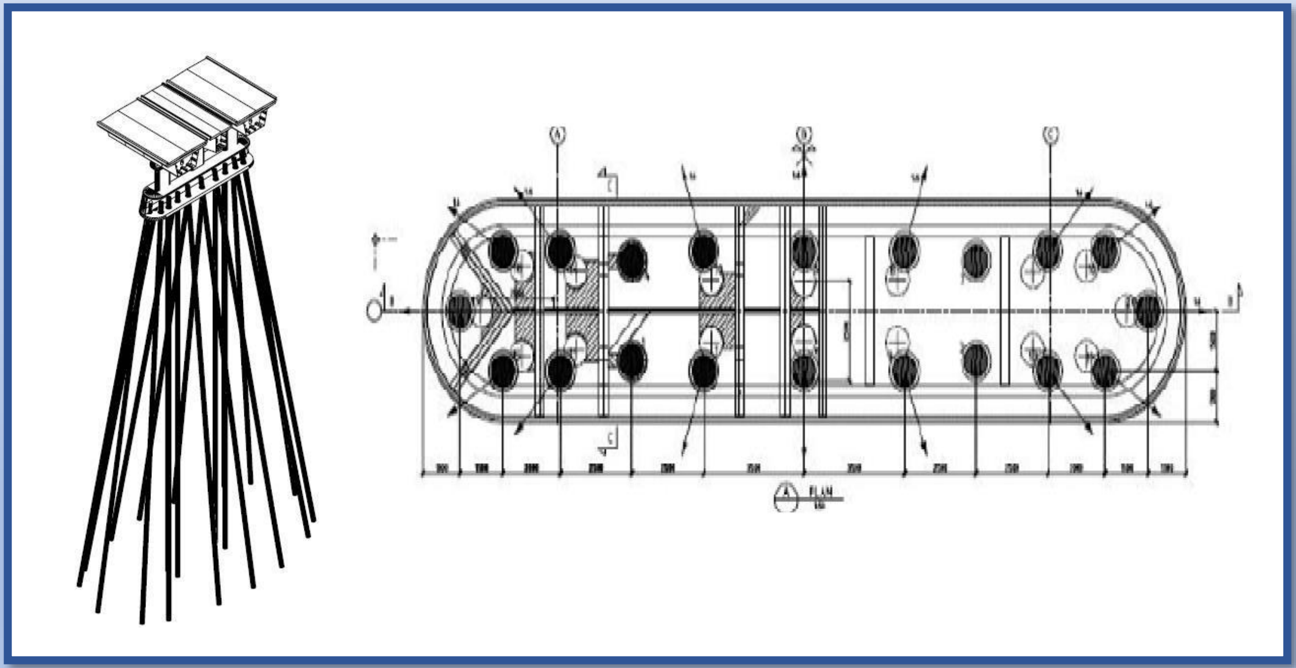
(a)

(b)

a) Location, b) longitudinal view of the causeway

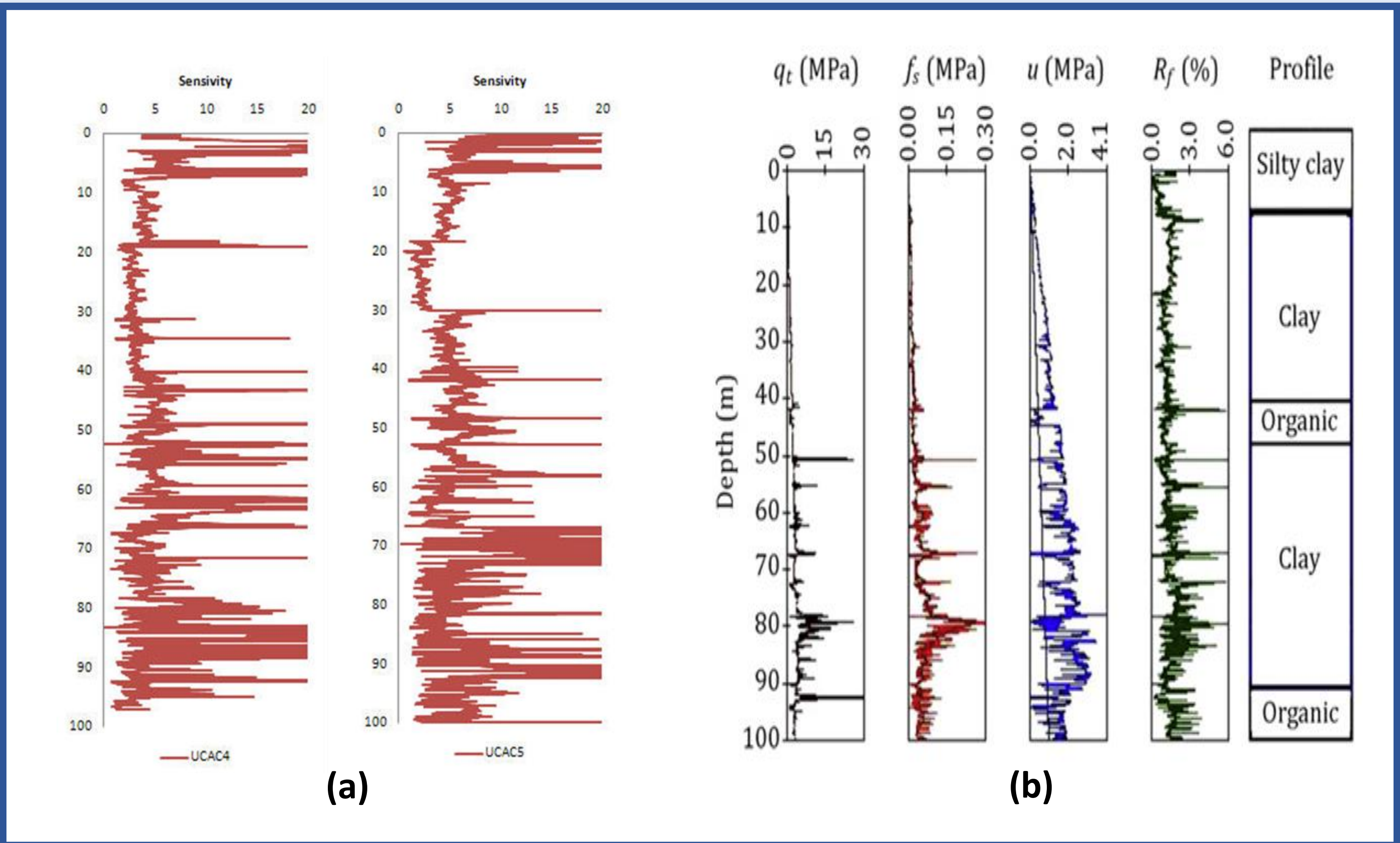
## Case No. 5: Continued

- More than 400 pipe piles
- Total installed length of 32 km
- Piles 813 mm in diameter and 66 to 75 m in depth
- Total 800 m piles applied for static & dynamic tests



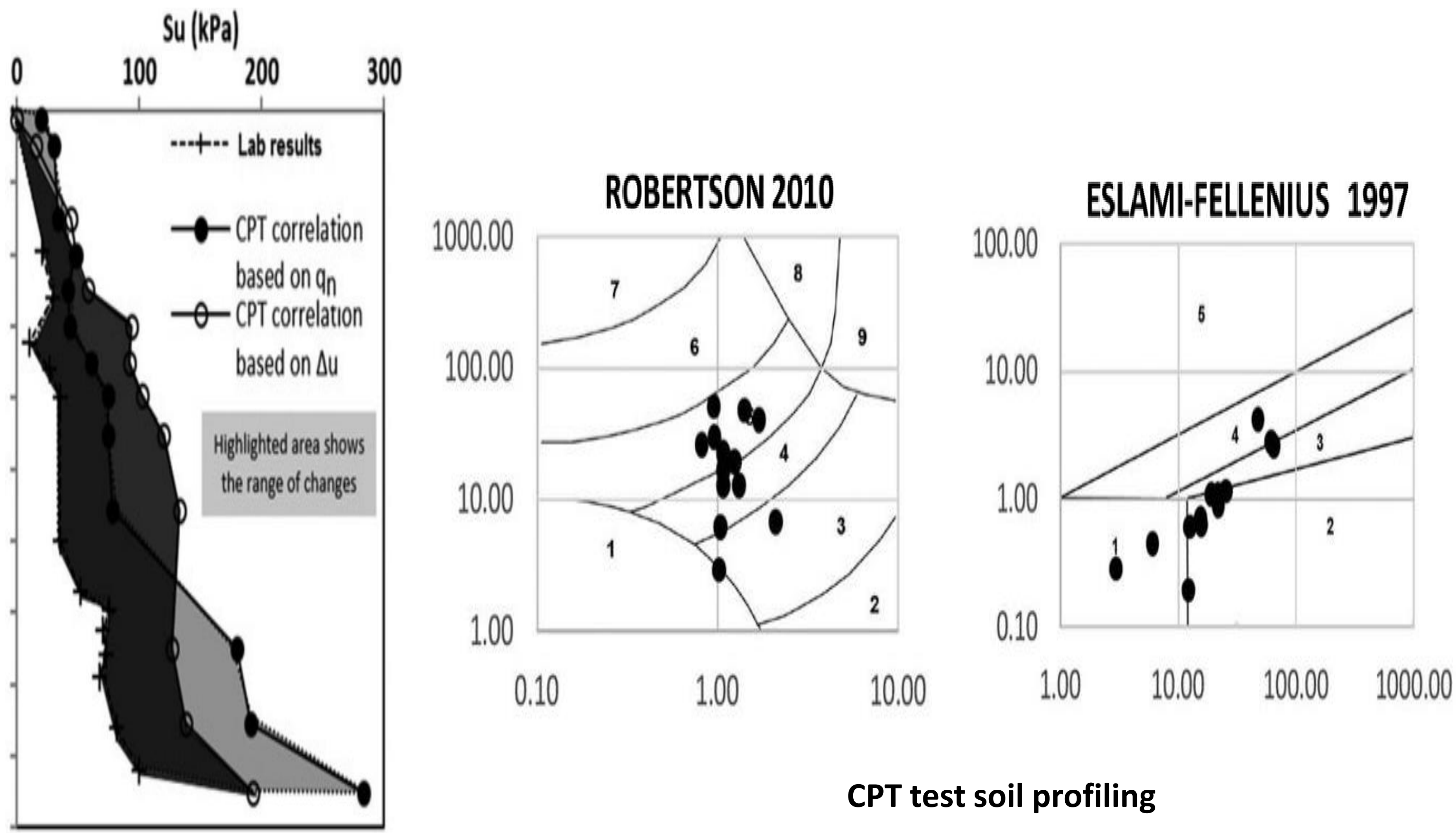
Configuration of installed piles

**Case No. 5: Continued**



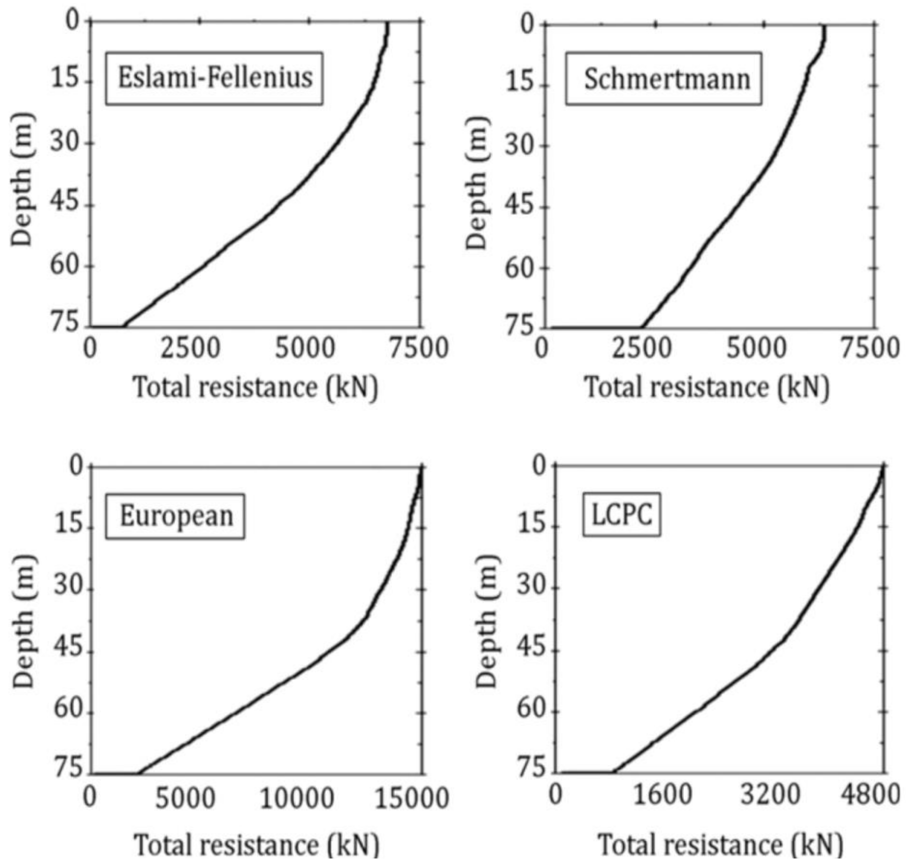

a) Sensitivity log, b) Typical CPT logs

## Case No. 5: Continued



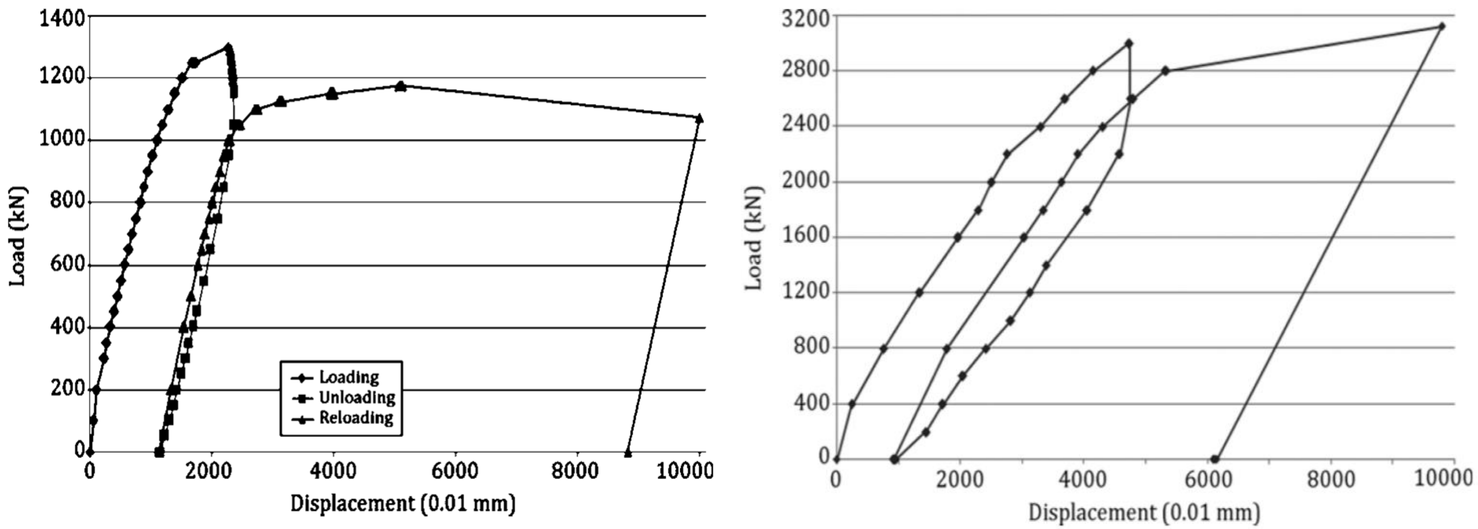

CPT test soil profiling

## Case No. 5: Continued




**Pile total capacity distribution (length of 75 m, diameter of 813 mm & wall thickness of 38.1 mm) (Eslami et al., 2011)**

# Case No. 5: Continued – Tested Piles




(a) (b)

**Static load test result; a) Compressive (length of 30 m, diameter of 356 mm & wall thickness of 12 mm), b) Tension (length of 70 m, diameter of 305 mm & wall thickness of 16 mm (Eslami et al., 2011)**

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2. CPT-Based Methods for Deep Foundations
3. **Worked Examples**
4. Cases: Histories & Studies

## I. Worked Examples

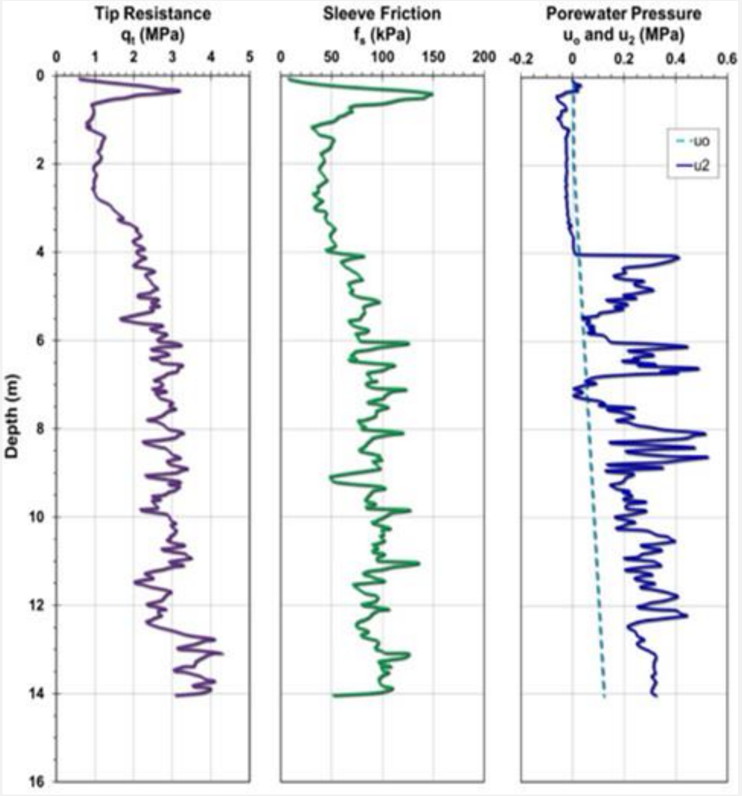
1. Driven Pile Bearing Capacity via Static Analyses
2. Pile Bearing Capacity via Direct CPT-Based Methods
3. Ten CPT-Based Methods Referenced to Load-Displacement
4. In-Situ Based Methods Vs. Static Load Test (SLT)
5. CPT & SPT Based Methods Vs. Load Test; Single Pile
6. Static Analysis, CPT & SPT Methods and SLT; Drilled Shaft

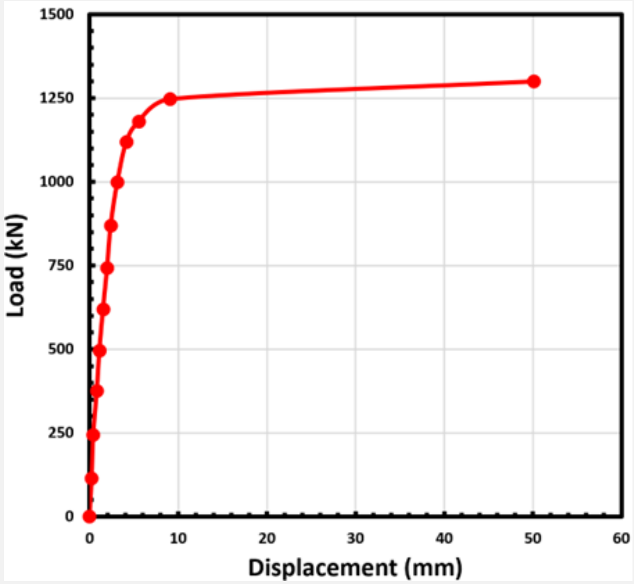
## II. Cases Review

7. Probabilistic Comparison of Methods (Heidari et al., 2020)
8. Capacity Loss Under Dynamic Conditions (Eslami et al., 2025)

## Example No. 6:
## Static Analysis, CPT & SPT Based Methods and SLT; Drilled Shaft

***The embedment depth and diameter of the shaft are 12 m and 500 mm, respectively. The surrounding deposit is composed of 4m of silt underlain by stiff homogeneous clay.***



## Example No. 6: Solution – Static Analysis

$\gamma_{avg} = 20\ \mathrm{kN}/m^3$, **Fully saturated**
**Unified method:** $\beta = 0.32, N_t = 10$

**Shaft Resistance**
$q_s = \beta \times \sigma'_v = 0.32 \times \left(6 \times (20 - 10)\right) = 38.4\ \mathrm{kPa}$
$A_s = \pi \times 0.5 \times 12 = 18.85\ \ m^2$
$Q_s = q_s \times A_s = 38.4 \times 18.85 = 723.84\ \mathrm{kPa}$

**Toe Resistance**
$q_t = N_t \times \sigma'_v = 10 \times \left(12 \times (20 - 10)\right) = 1200\ \mathrm{kPa}$
$A_t = \left(\frac{\pi}{4}\right) \times 0.5^2 = 0.196\ m^2$
$Q_t = q_t \times A_t = 1200 \times 0.196 = 235.2\ \mathrm{kN}$

**Total Resistance**

$Q_u = Q_s + Q_t = 723.84\ + 235.2 = 959.04\ \mathrm{kN}$

# Example No. 6: Solution – SPT-based Methods

**Equivalent SPT below number ($N_{60}$) have been incorporated in calculations.**

***Shioi and Fukui (1982)***

**Shaft Resistance**

$\mathbf{N_{ave-shaft} = 9.2, B = 5}$

$\mathbf{r_s = BN_{ave} = 5 \times 9.2 = 46\ kPa, A_s = \pi \times 0.5 \times 12 = 18.85\ m^2, R_s = r_s A_s = 18.85 \times 46 = 867.1\ kN}$

**Toe Resistance**

$\mathbf{A = 0.15, N_{ave-base} = 10.65}$

$\mathbf{r_t = AN_{base} = 0.15 \times 10.65 = 1.6\ MP, A_t = \left(\frac{\pi}{4}\right) \times 0.5^2 = 0.196\ m^2, R_t = r_t A_t = 1600 \times 0.196 = 313.6\ kN}$

**Total Resistance**

$\mathbf{R_u = R_t + R_s = 867.1 + 313.6 = 1180.7\ kN}$

***Decourt (1982)***

**Shaft Resistance**

$\mathbf{N_{ave-shaft} = 9.2, B = 3.3}$

$\mathbf{r_s = BN_{ave} = 3.3 \times 9.2 = 30.4\ kPa, A_s = \pi \times 0.5 \times 12 = 18.85\ m^2, R_s = r_s A_s = 30.4 \times 18.85 = 573.04\ kN}$

**Toe Resistance**

$\mathbf{A = 0.15, N_{ave-base} = 10.65}$

$\mathbf{r_t = AN_{base} = 0.15 \times 10.65 = 1.6\ MPa, A_t = \left(\frac{\pi}{4}\right) \times 0.5^2 = 0.196\ m^2, R_t = r_t A_t = 317.2 \times 0.196 = 313.6\ kN}$

**Total Resistance**

$\mathbf{R_u = R_t + R_s = 573.04 + 313.6 = 886.64\ kN}$

## Example No. 6: Solution – CPT-Based Methods

***Meyerhof (1976)***

**Shaft Resistance**

$\mathbf{r_s = Kf_s\ (K = 1), f_{s_{avg}} = 0.077\ Mpa}$

$\mathbf{r_s = Kf_s = 1 \times 0.077 = 0.077\ MPa = 77\ kPa, A_s = \pi \times 0.5 \times 12 = 18.85\ \ m^2}$

$\mathbf{Q_s = r_s \times A_s = 77 \times 18.85 = 1451.45\ kN}$

**Toe Resistance**

$\mathbf{q_{c.a} = 2.84\ \mathit{MPa}, c_1 = \left(\frac{B + 0.5}{2B}\right)^n :\ B = 0.5\ \rightarrow\ c_1 = 1, c_2 = \frac{D_b}{10B} :\ D_b = 8m\ >\ 10B = 5m\ \ \rightarrow\ c_2 = 1}$

$\mathbf{r_t = q_{c.a}c_1c_2}$**=2.84 MPa = 2840 kPa,** $\mathbf{A_t = \left(\frac{\pi}{4}\right) \times 0.5^2 = 0.196\ m^2, Q_t = r_t \times A_t = 2840 \times 0.196 = 556.64\ kN}$

**Total Resistance**

$\mathbf{Q_u = 0.5Q_s + 0.7Q_t = 0.5 \times 1451.45\ + 0.7 \times 556.64 = 1115.37\ kN}$

***Eslami & Fellenius (1997)***

**Shaft Resistance**

$\mathbf{r_s = C_s q_E\ , q_{E_{avg}} = 2.04\ Mpa, Silt\ \rightarrow C_s = 1.5\% = 0.015}$

$\mathbf{r_s = C_s q_E\ \ = 0.015 \times 2.04 = 0.031\ MPa = 31\ kPa, A_s = \pi \times 0.5 \times 12 = 18.85\ \ m^2, Q_s = r_s \times A_s}$
$\mathbf{= 31 \times 18.85 = 584.35\ kN}$

**Toe Resistance**

$\mathbf{r_t = C_t q_{Eg}, C_t = 1, q_{Eg(z=10-14)} = 2.8\ MPa}$

$\mathbf{r_t = q_{Eg} = 2.8\ MPa = 2800\ kPa, A_t = \left(\frac{\pi}{4}\right) \times 0.5^2 = 0.196\ m^2, Q_t = r_t \times A_t = 2800 \times 0.196 = 548.8\ kN}$

**Total Resistance**

$\mathbf{Q_u = Q_s + Q_t = 584.35\ + 548.8 = 1133.15\ kN}$

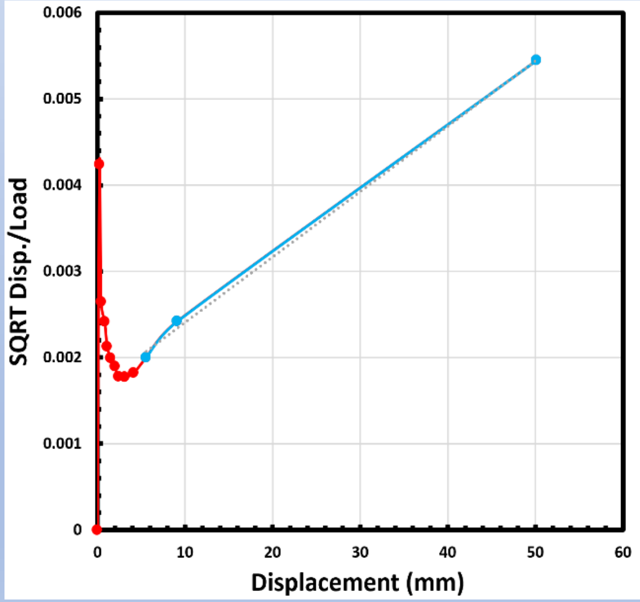
# Example No. 6: Solution – Load-Displacement Analysis

## Brinch Hansen (1963)

$$C_1 = 0.00008\,,\, C_2 = 0.0016$$

$$Q_u = \frac{1}{2\sqrt{C_1 C_2}} = \frac{1}{2\sqrt{0.00008 \times 0.0016}} = 1397.54\ \text{kN}$$

$$\delta_u = \frac{C_2}{C_1} = \frac{0.0016}{0.00008} = 20\ \text{mm}$$




**Ultimate load based on Brinch-Hansen 80% method**

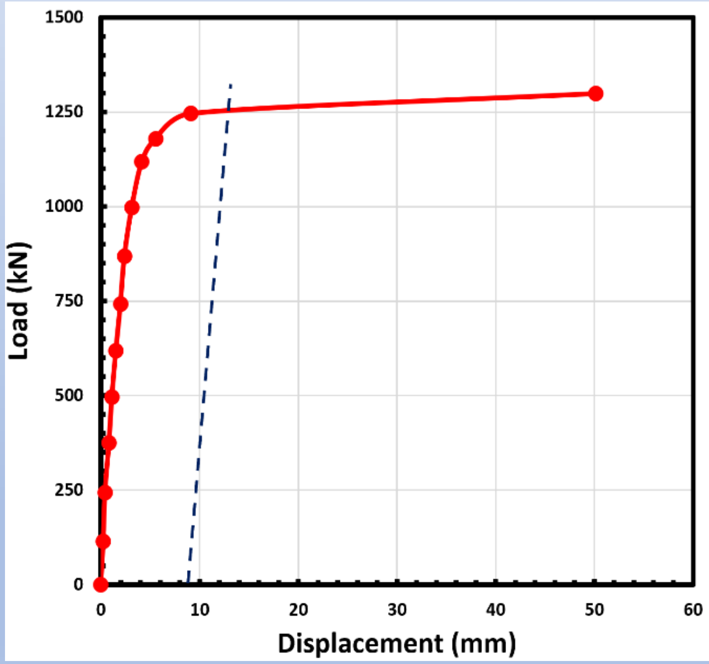
# Example No. 6: Solution – Load-Displacement Analysis

**Davisson Offset Limit (1972)**

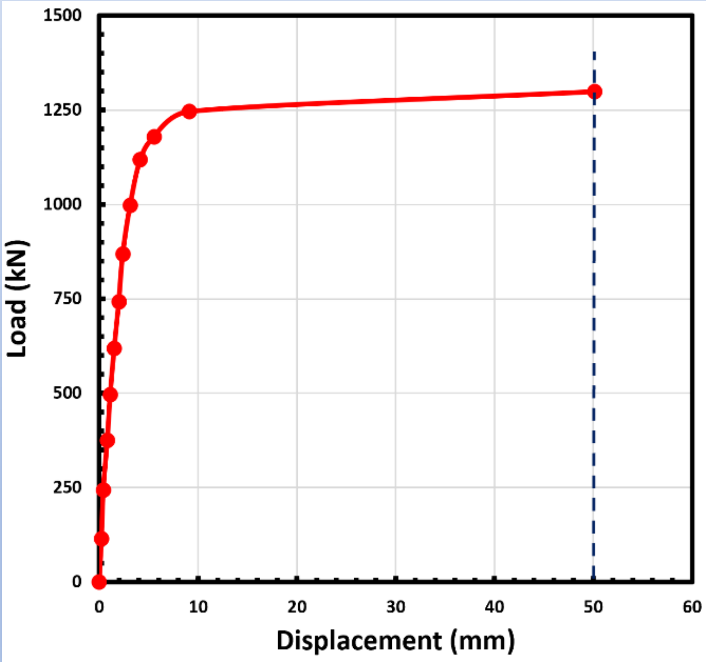
$$\text{Offset} = 4 + \frac{500}{120} = 8.2 \text{ mm}$$
$$R_u = 1254.35 \text{ kN}$$

***10% B***

$$R_u = 1320.15 \text{ kN}$$




**Ultimate load based on Davisson offset limit method**




**Ultimate load based on 10%B criteria**

## Example No. 6: Solution

| Capacity | Static Analysis | CPT-Based Methods | | SPT-Based Methods | | Load-Displacement | | |
|---|---|---|---|---|---|---|---|---|
| | | Eslami & Fellenius (1997) | Meyerhof (1976) | Shioi & Fukui (1982) | Decourt (1992) | Davisson Offset Limit (1972) | Hansen (1963) | w/d=10 % |
| $R_t$ (kN) | 235.2 | 548.8 | 1451.5 | 313.6 | 313.6 | - | | - |
| $R_s$ (kN) | 723.8 | 584.4 | 556.6 | 867.1 | 573 | - | | - |
| $R_u$ (kN) | 959 | 1133.2 | 1115.4 | 1180.7 | 886.6 | 1254.4 | 1397.5 | 1320.2 |

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## I. Supplementary Cases



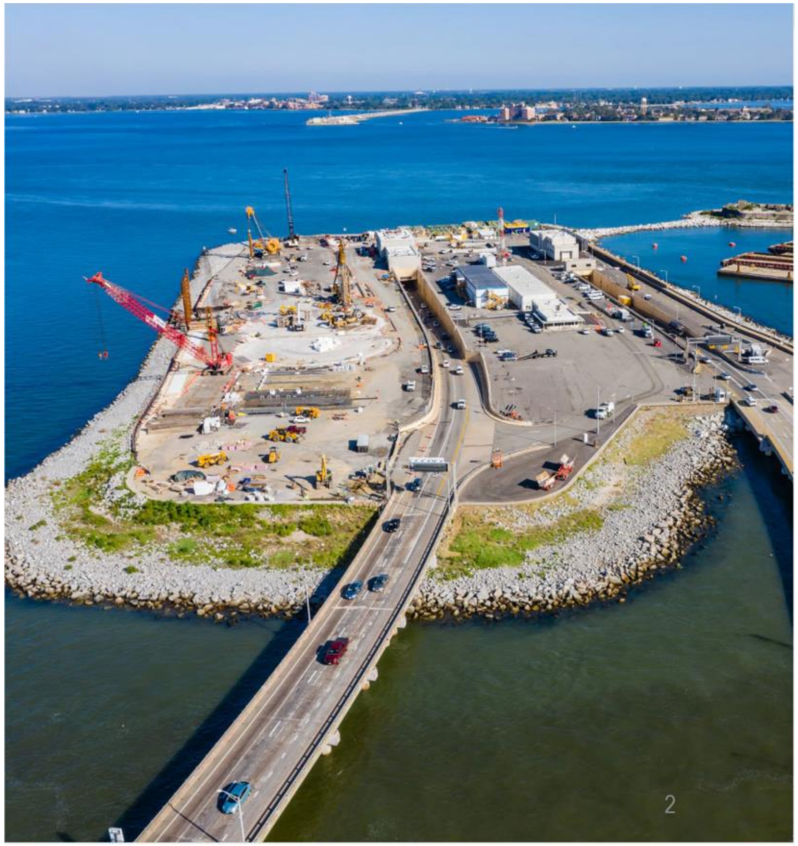
## II. Summary

## Case History No. 13: James River bridge, Virginia (Batten & Keaney, 2021)

### Optimization Large Diameter Concrete Piles for Marine Bridges

**Project Overview**

- **$3.8 Billion Design-Build awarded by VDOT to HRCP Construction Joint Venture in 2019**
- **Design Joint Venture of HDR and Mott MacDonald**
- **2.7 miles marine trestle bridges over the James River on 1-64**
- **Connect Hampton to Norfolk, VA**
- **North and South Trestles connect shoreline to man made island expansions**



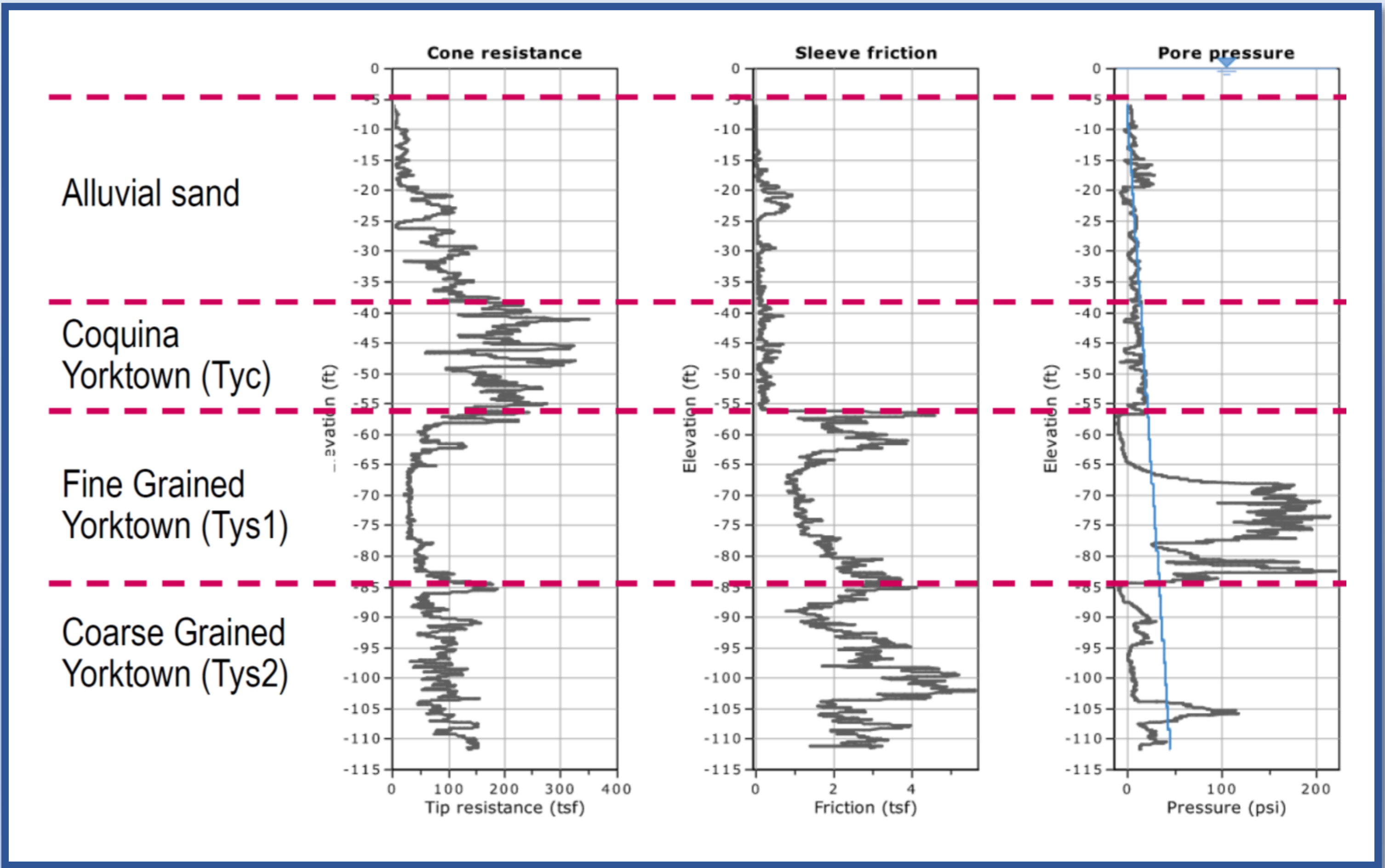
## Case History No. 13: Continued

### Subsurface Exploration

- **Historic VDOT Marine Trestle Data: 17 SPT and 35 CPTu**
- **Supplemental Marine Trestle Data: 135 SPT and 149 CPTu**
  - ***Jack up barges for deep water***
  - ***Spud barges for shallow water***

# Case History No. 13: Continued

## Typical CPT Sounding



## Case History No. 13: Continued

### Pile Types

- **North & South Trestles:**

*54-inch precast prestressed concrete cylinder piles, 6.75-inch wall thickness, bed cast, NOT spun cast*

- **Willoughby Bay Trestle:**

*24-inch precast prestressed concrete square piles*

## Case History No. 13: Continued

## Pile Load Tests

- **North Trestle**

  *2 Dynamic Load Test Piles*

  *1 Static Load Test Pile*

- **South Trestle**

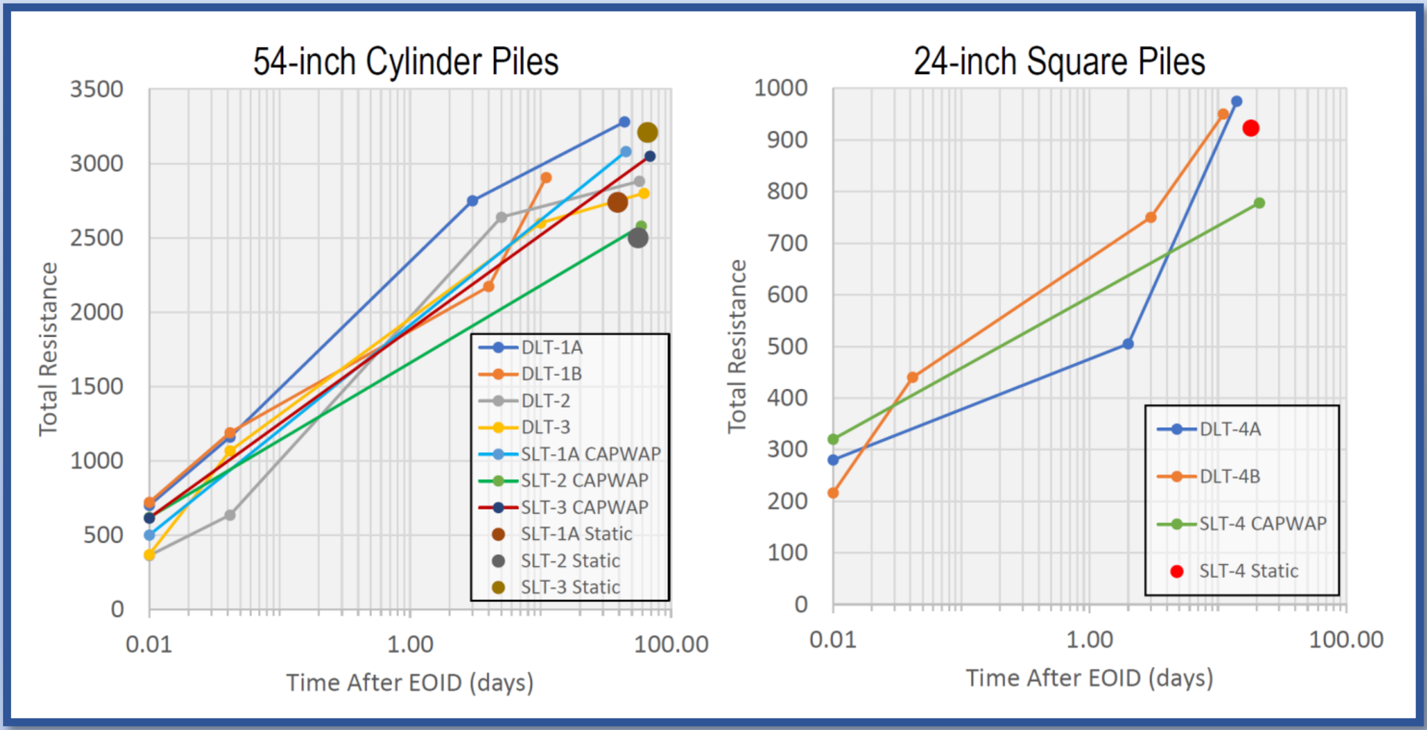
  *2 Dynamic Load Test Piles*

  *2 Static Load Test Piles*

- **Willoughby Bay Bridge.**

  *2 Dynamic Load Test Piles*

  *1 Static Load Test Pile*



## Project-Based Calibration of Parameters

**Case History No. 13: Continued**

| Soil Type | Soil Description | Original $C_s$ (Fellenius 2021) | Calibrated Against HRBT Static Load Tests | |
|---|---|---|---|---|
| | | | $C_s$ | Limiting $q_{skin}$ (ksf) |
| 1 | Soft sensitive soils | 0.08 | 0.150 | None |
| 2 | Clay | 0.05 | 0.066 | 1.5 |
| 3 | Silty clay, stiff clay and silt | 0.025 | 0.066 | 3.0 |
| 4a | Sandy silt and silt | 0.015 | 0.030 | 3.0 |
| 4b | Fine sand or silty sand | 0.010 | 0.017 | 3.0 |
| 5 | Sand to sandy gravel | 0.004 | 0.015 | 2.1 |

| Pile ID | Calculated Axial Compression Total Resistance[1] | | | | Max Static Axial Test Load | | |
|---|---|---|---|---|---|---|---|
| | Nordlund (1963; 1979) / Tomlinson (1987) | Martin et al (1987)[2] | Original Eslami and Fellenius (1997)[3] | Calibrated Eslami and Fellenius (1997) | Total Load (kips) | Skin Friction (kips) | Toe Resistance (kips) |
| SLT-1 | 2,954 | 1,895 | 2,495 | 2,642 | 2,738 | 2,117 | 621 |
| SLT-2 | 3,025 | 1,624 | 2,113 | 2,495 | 2,491 | 2,097 | 394 |
| SLT-3 | 2,961 | 2,650 | 2,276 | 2,954 | 3,209 | 2,607 | 602 |
| SLT-4 | 1,445 | 834 | 962 | 884 | 875 | 663 | 212 |

1 All axial resistance methods assumed an unplugged toe area for the open ended 54-inch cylinder piles.
2 The Martin et al (1987) method was only applied to pile embedment within the Yorktown strata. Conventional effective stress beta analysis was used to calculate unit skin friction for the Quaternary soils above the Yorktown.
3 The Original Eslami and Fellenius (1997) method calculations used a $C_t$ coefficient of 1.0 for both pile sizes.

- **Cone & Piezocone Penetration Tests (CPT & CPTu) in GE:**
    - ❖ **In-Situ Tests: Supplementary of Laboratory Tests**
    - ❖ **Major Records: $\mathbf{q_t}$, $\mathbf{f_s}$, $\mathbf{u_2}$; Efficient & Continuous**
    - ❖ **Providing Tons of Data; Towards Uncertainty Reduction**
    - ❖ **Specific Site Identification**
    - ❖ **Soil Behavior Classification (SBC)**

- **CPT & Deep Foundation: Optimum Design**
    - ❖ **Analogy of Cone Penetrometers & Pile**
    - ❖ **Geotechnical Design Targets:**
        - ✓ **Installation Depth**
        - ✓ **Bearing Capacity**
        - ✓ **Settlement**
        - ✓ **Resistance Distribution**
        - ✓ **Load-Displacement**
    - ❖ **Rely on Experienced & Data-based Methods**

- **Enhanced Deep Foundations Design**
    - ❖ **Meticulous Site Characterization & Accurate Data Acquisition**
    - ❖ **Integrating Site-Specific & Data-centric Solutions**
    - ❖ **Incorporating Fundamental Approaches, Recent Trends, and AI …**
    - ❖ **Value Foundation Engineering: Less Load Testing, More Modeling**

# Major References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