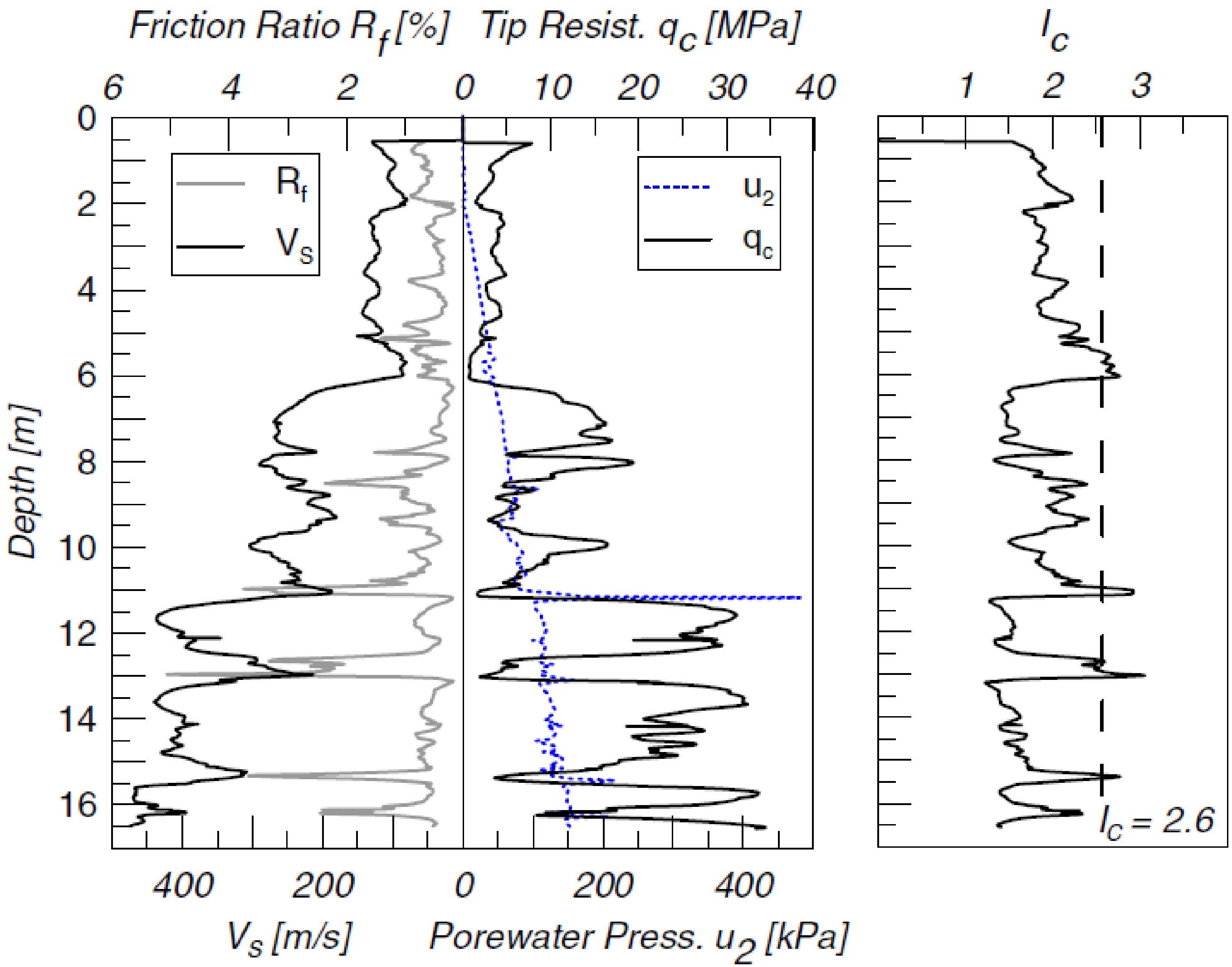
Determination of p-y Curves and Pile Lateral Capacity by Direct Use of CPT Data

Scott J. Brandenberg, Ph.D., P.E.
Professor, Civil and Environmental Engineering, UCLA
Shawn Ariannia, Ph.D., G.E.
President, Geo-Advantec, Inc.

Outline

- Background and Motivation
- Proposed Method for CPT-Based p-y Analysis
  - PySimple3 Material Model
  - Computing p-y Properties from CPT Data
  - Partially Drained "Intermediate Soils"
  - Layer Corrections
- Analysis of Case Histories
  - Saturated Clay Site in Oakland
  - Unsaturated Clay Site in Hawthorn
  - Sandy Site at LAX

Background and Motivation



Background and Motivation

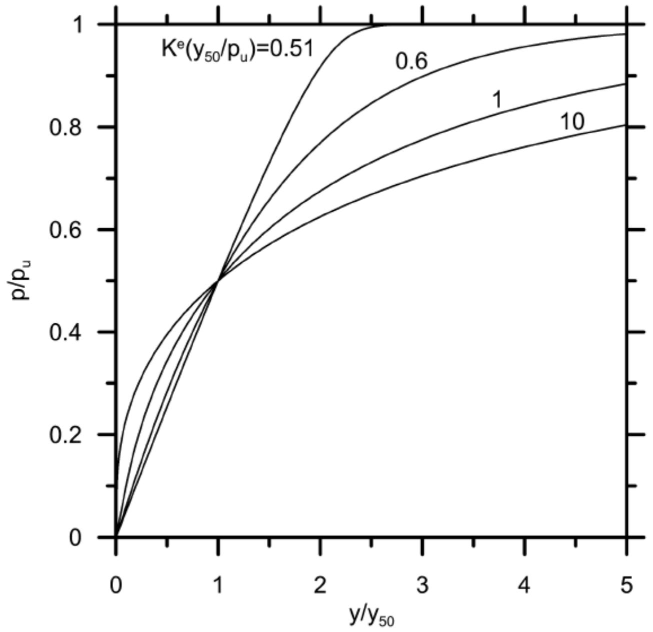
- Existing methods do not use the full CPT record, and rely on engineers to define layers.
- The CPT data contains nearly continuous information about the subsurface.
- Our objective is to develop a method to utilize the full CPT record to develop p-y elements for lateral pile analysis.

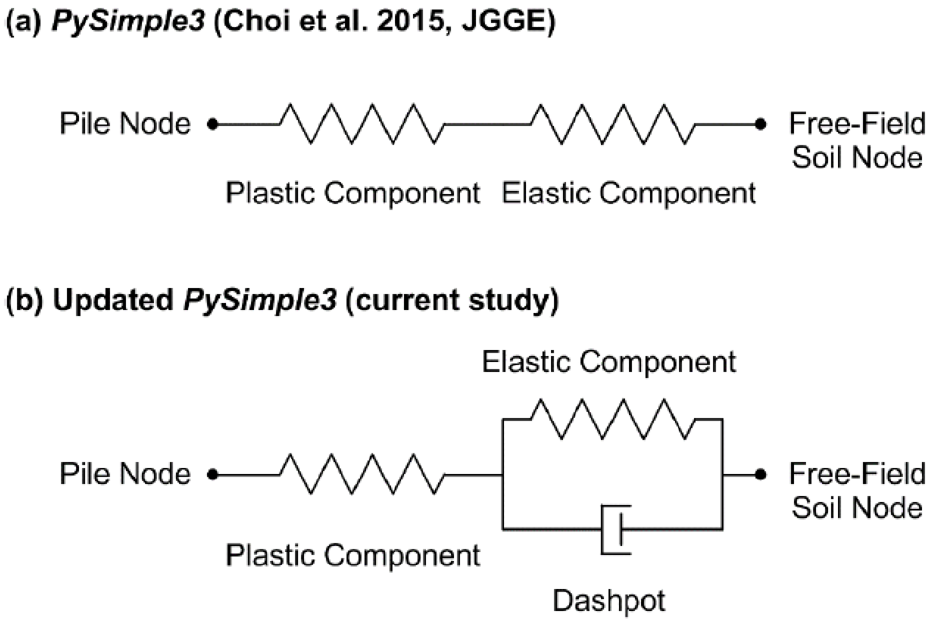
Background and Motivation

- Technical hurdles:
  - Develop a code to extract soil properties from CPT data (at every measurement point), and use these properties to compute p-y material properties.
  - Current p-y material models are either for sand or clay. What about intermediate soils (e.g., $2.3 < I_c < 2.7$)?
  - The CPT and laterally loaded piles are known to have layering effects. How do we handle those?
  - Implementing a huge number of user-specified p-y elements into LPile is not practical. How do we do the calculation?

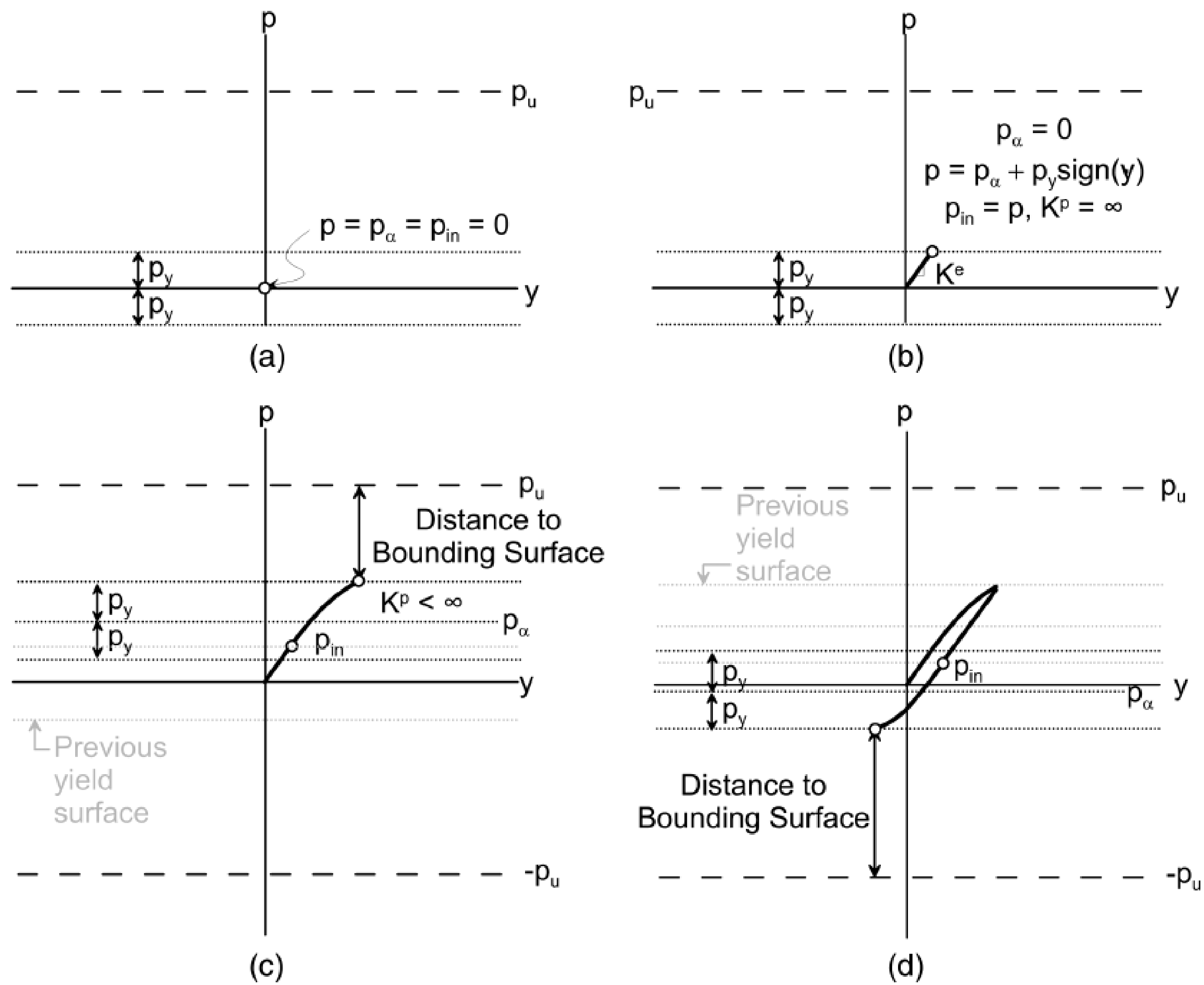
PySimple3 Material Model

- Choi et al. (2015) and Turner (2016)
  - PySimple3 material model implemented in OpenSees.





PySimple3 Material Model



PySimple3 Material Model

- User Inputs for PySimple3:
  - p_u (ultimate capacity).
  - p_y (yield force).
  - K^e (elastic stiffness).
  - C (backbone shape coefficient).

$$C = \frac{(p_u - p_y)[\ln(p_u - p_y) - \ln(p_u)] + p_u[\ln(2) - 0.5] + p_y[1 - \ln(2)]}{K^e y_{50} - 0.5 p_u}$$

Computing p-y Properties from CPT Data

- Sand ($I_c < 2.3$)
  - Compute peak friction angle, ϕ', using critical state soil mechanics framework by Robertson (2012).
  - Assume critical state friction angle, ϕ'_{cs}, based on soil type (e.g., 34 deg for quartz sand).

$$\phi' = \phi'_{cv} + 15.84 \, [\log Q_{tn,cs}] - 26.88$$

Computing p-y Properties from CPT Data

- Clay ($I_c > 2.7$)
  - Compute undrained shear strength using traditional equation $s_u = (q_t - \sigma_{vo})/N_{kt}$
  - Cone factor Nkt from site-specific laboratory tests (ideal approach).
  - In absence of site-specific tests, can assume $N_{kt} = 15$, or use Robertson (2012).

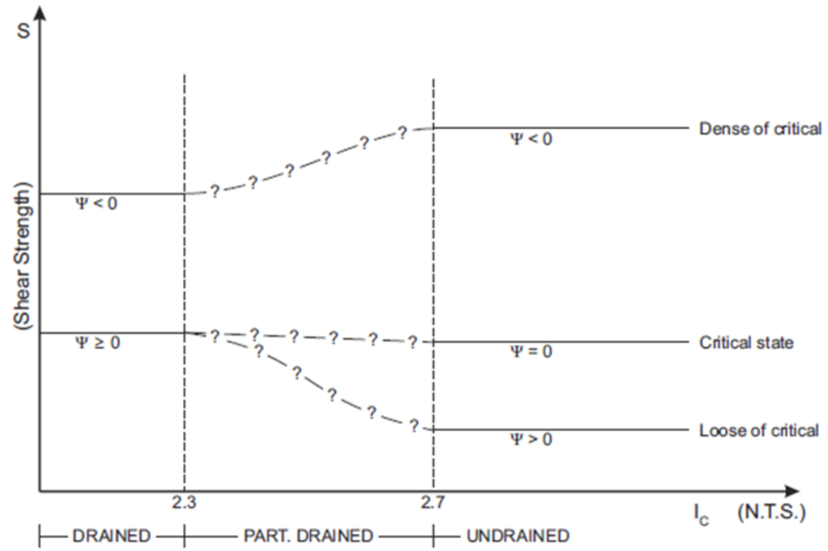
$$N_{kt} = 10.5 + 7 \log(F_r)$$

Computing p-y Properties from CPT Data

- Use API (1993) equations for sand
- Use Matlock (1970) for clay

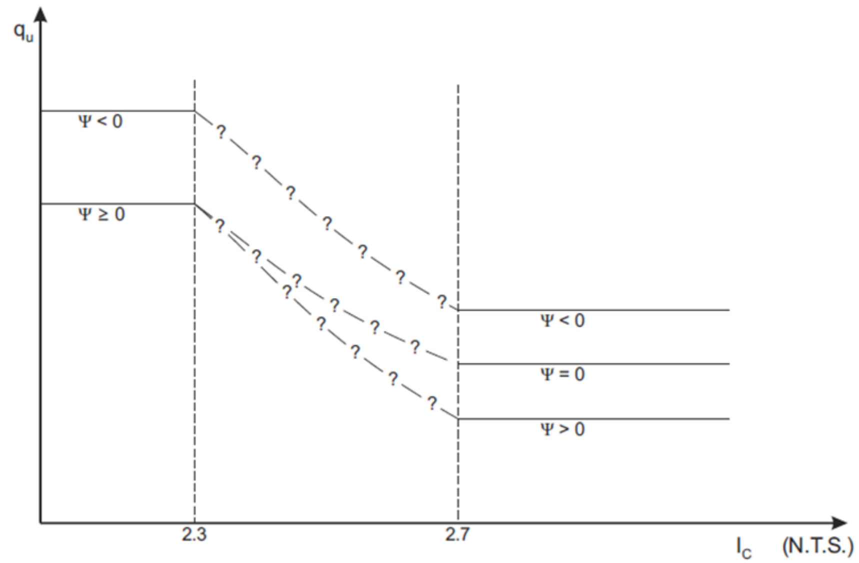
Computing p-y Properties from CPT Data

- Intermediate Soils ($2.3 < I_c < 2.7$)
  - Two issues: partially drained shear strength



Computing p-y Properties from CPT Data

- Intermediate Soils (2.3 < I_c < 2.7)
  - Two issues: partially drained shear strength
  - CPT bearing factor



Computing p-y Properties from CPT Data

- Intermediate Soils ($2.3 < I_c < 2.7$)
  - Adopted approach: Compute $p_{u,drained}$ as if soil is drained using API (1993).
  - Compute $p_{u,undrained}$ as if soil is undrained using Matlock (1970).
  - Linearly interpolate p_u based on I_c.
  - Note: This assumes drainage condition for p-y analysis is the same as during CPT.

$$p_u = p_{u,undrained} + \frac{p_{u,drained} - p_{u,undrained}}{2.7 - 2.3}\left(2.7 - I_c\right)$$

Computing p-y Properties from CPT Data

- Initial Stiffness
  - Measure V_S profile at site (ideal approach).
  - Correlate V_S with q_t (last resort due to uncertainty).

$$V_{s1} = (\alpha_{vs} Q_{tn})^{0.5} \quad \alpha_{vs} = 10^{(0.55 Ic + 1.68)}$$ Robertson (2012)

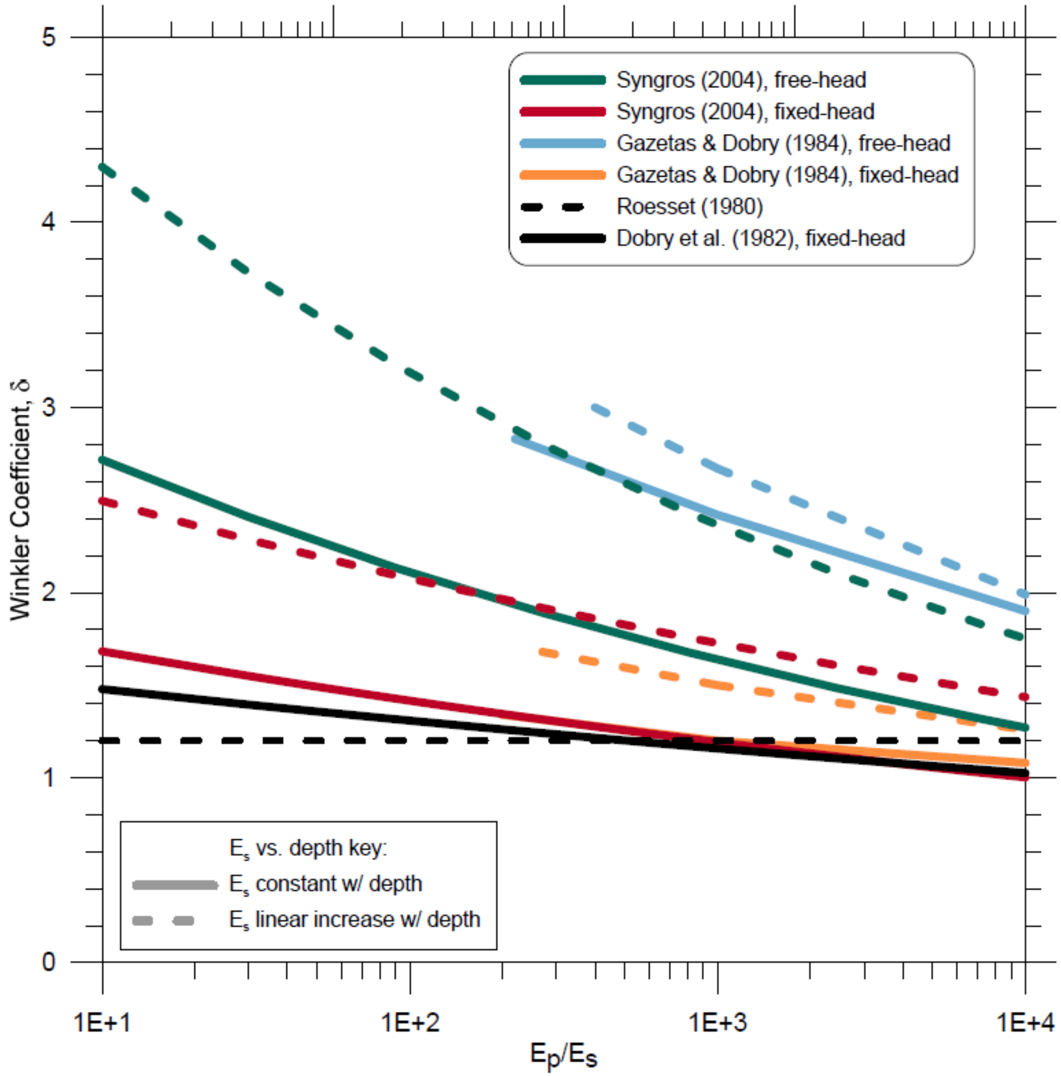
$$V_S = a \cdot q_t^{\,b} \cdot f_s^{\,c} \cdot \sigma'_v{}^{d}$$ Wair et al. (2012)

  - Compute K^e

$$K^e = \delta E_s$$

$$E_s = 2(1+\nu)\rho V_s^{\,2}$$

Computing p-y Properties from CPT Data



Computing p-y Properties from CPT Data

- Yield Force
  - We know soil becomes nonlinear at small strains (e.g., 0.001%).
  - Average shear strain in soil around pile (Kagawa and Kraft 1980):

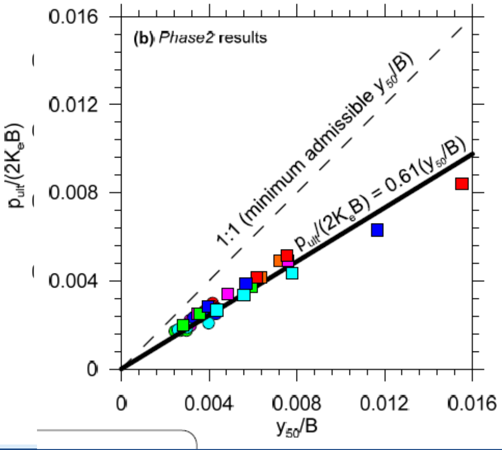
$$\gamma_{ave} = \frac{(1+\nu)y}{2.5B}$$

$$p_y = y_{yield} \cdot K^e = \frac{2.5B(0.001\%)}{(1+\nu)} K^e$$

Computing p-y Properties from CPT Data

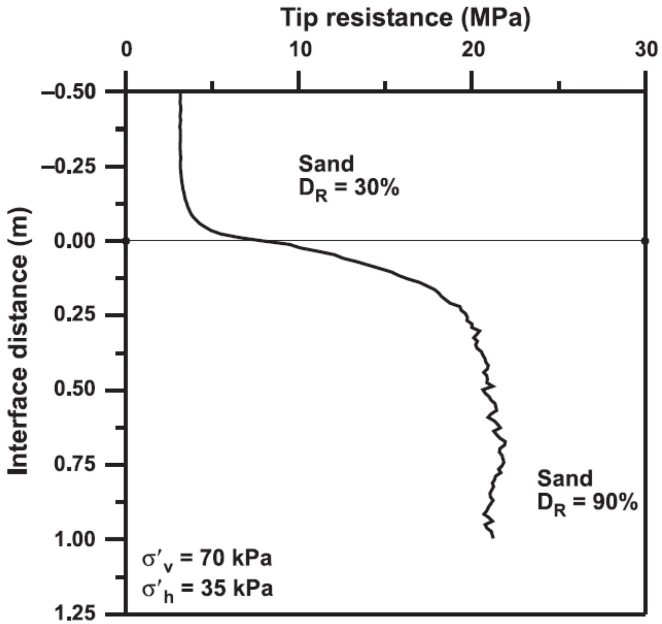
- Shape Parameter, C
  - Compute y_{50}
  - API (1993) and Matlock (1970) equations can be used, but should ideally be related to p_u and K^e.
  - Turner (2016) used 2-D continuum finite element analyses to develop the following:

$$y_{50} = \frac{0.82 p_{ult}}{K_e}$$



Layer Correction

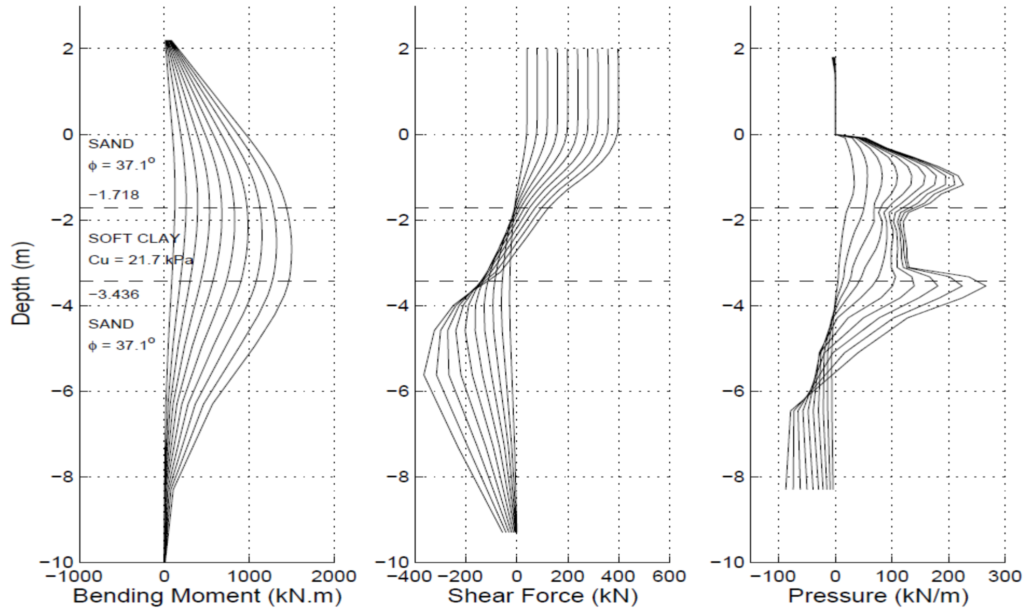
- CPT tip resistance represents average soil properties in zone of influence (10 to 20 cone diameters)



Ahmadi and Robertson (2011)

Layer Correction

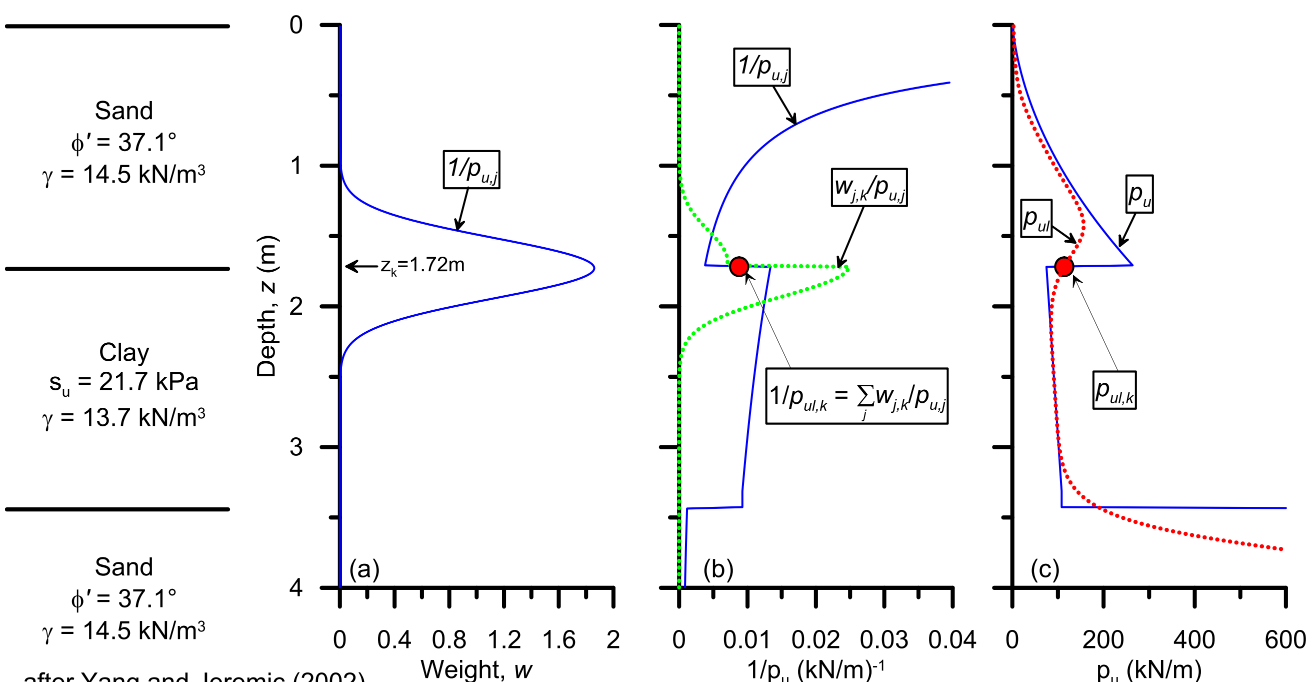
- Lateral pile loading also exhibits a layering effect in zone of influence (about 1 pile diameter).



Yang and Jeremic (2002)

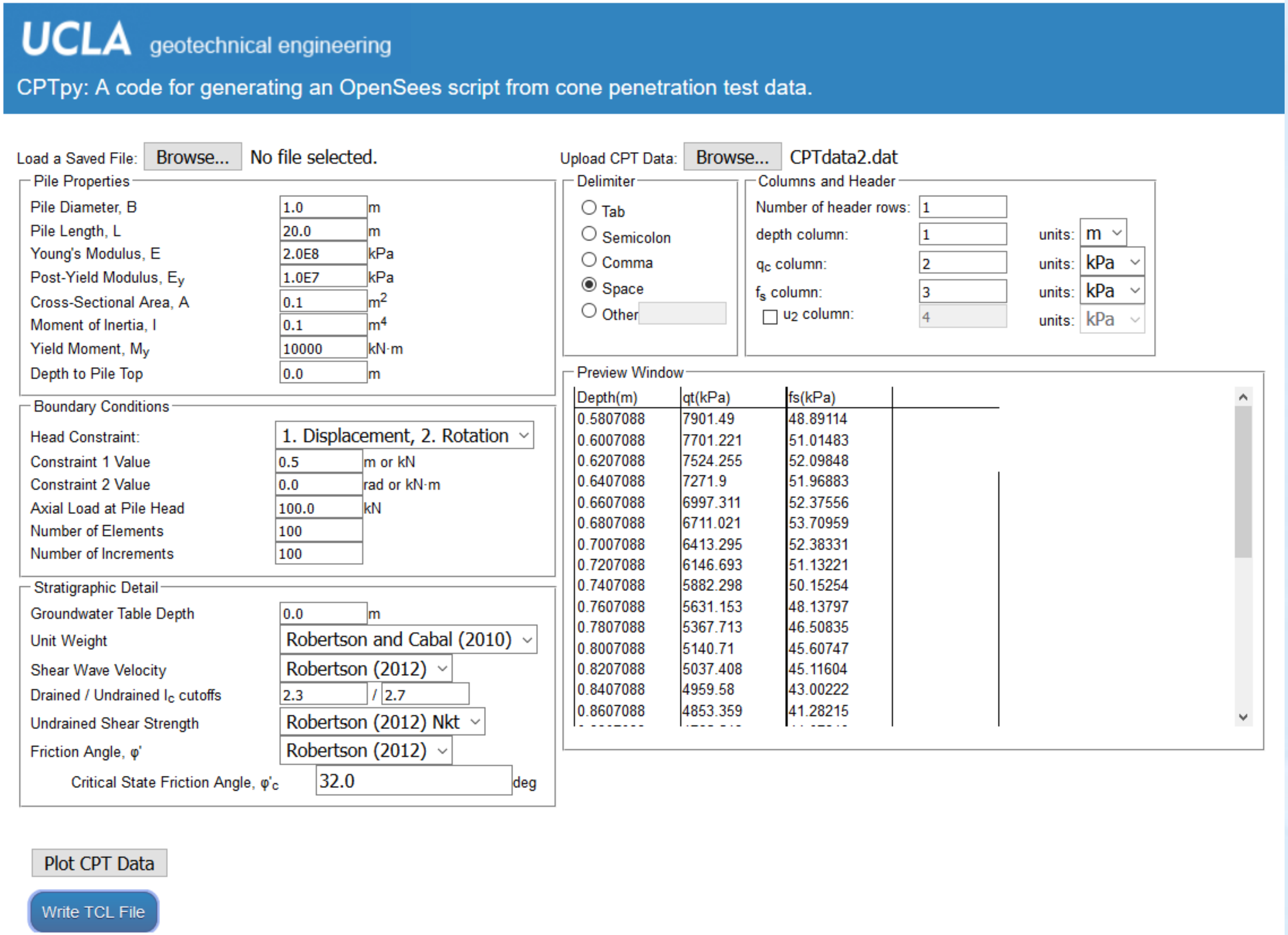
Layer Correction

- Adopt Gaussian window weighting scheme

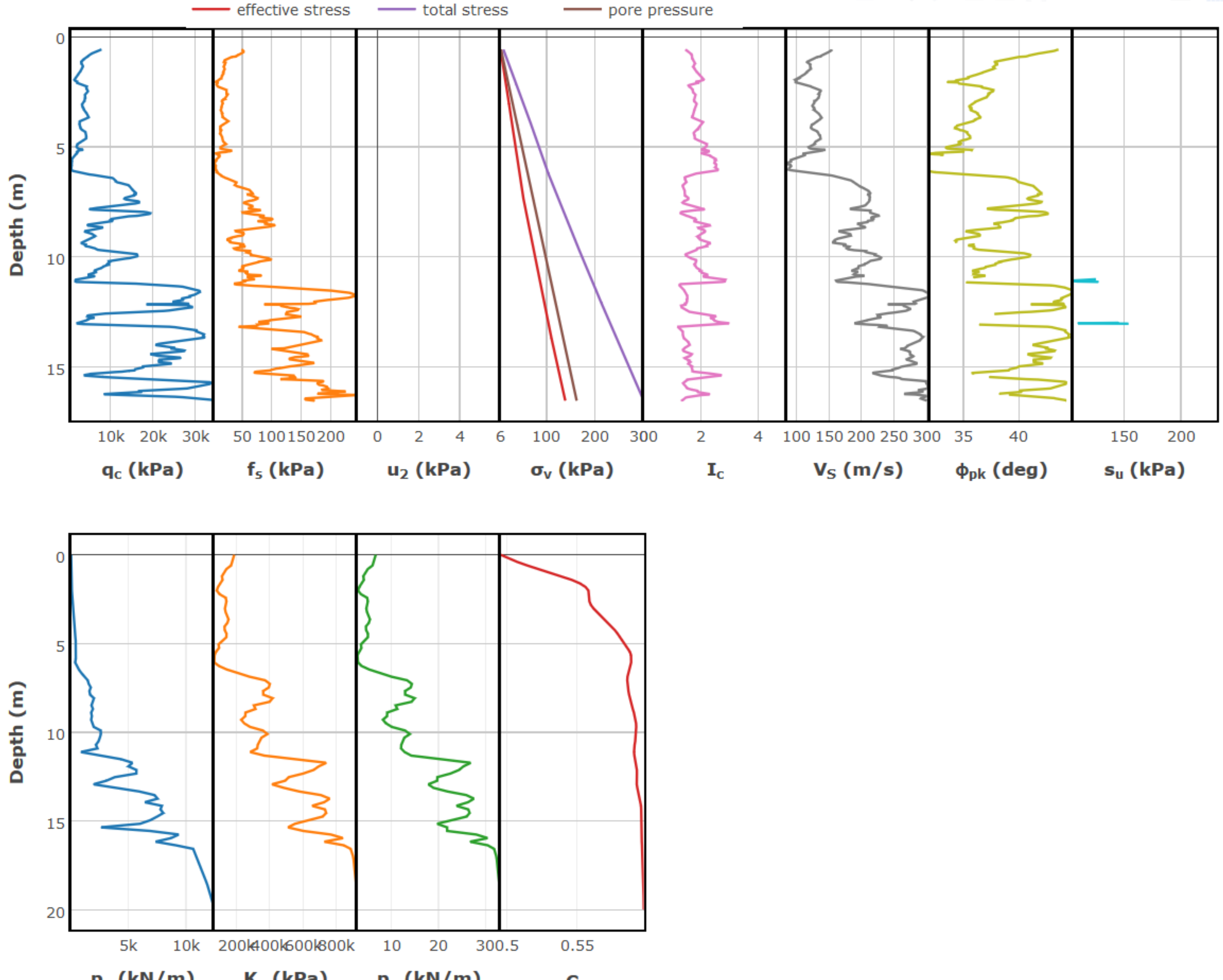


after Yang and Jeremic (2002)

uclageo.com/CPTpy/



uclageo.com/CPTpy/



cptPyOutput.tcl - Notepad

File Edit Format View Help

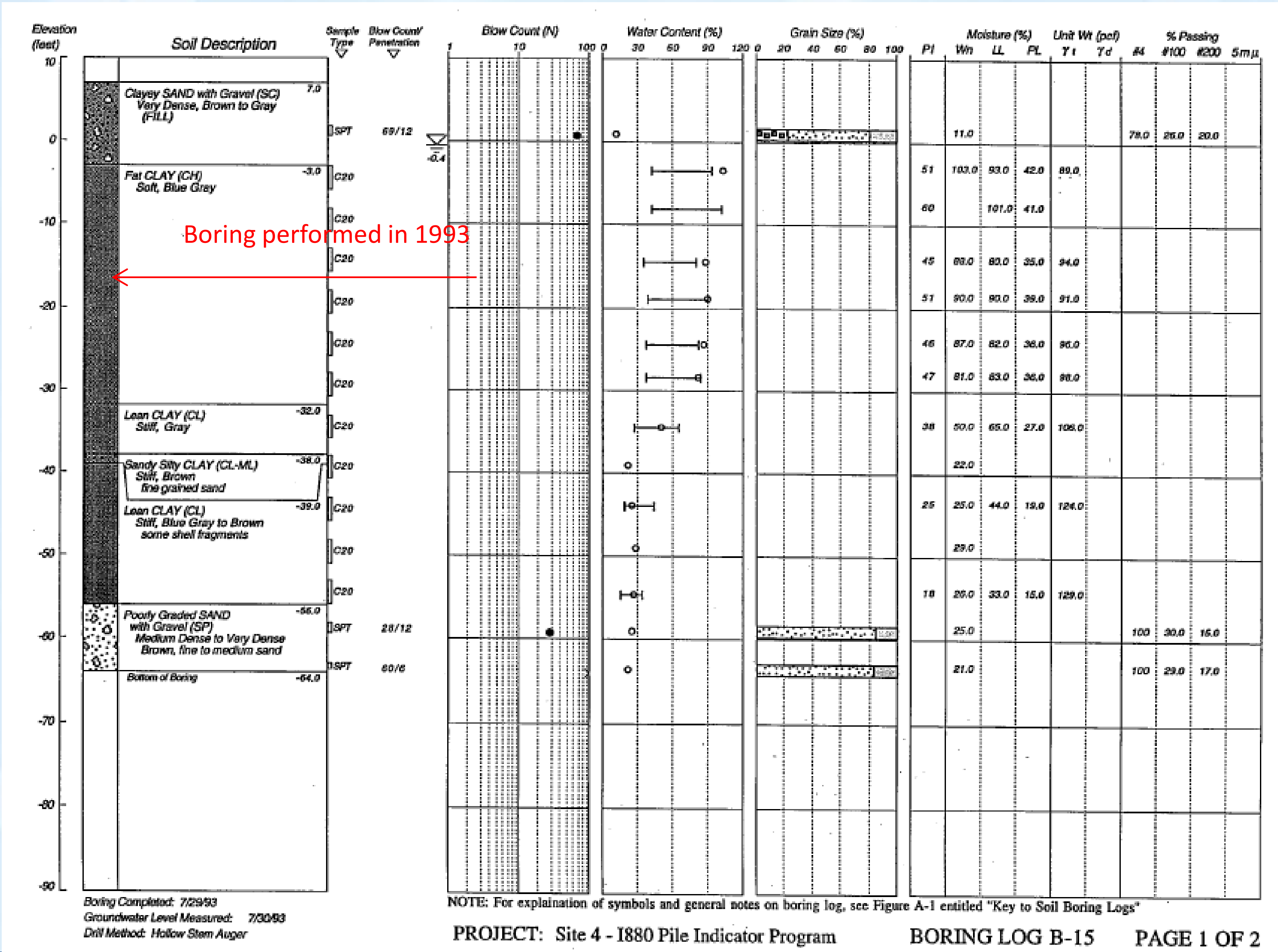
```
#########################################################################################
# Script for performing lateral loading of a single pile with p-y springs along pile.
# material properties are based on CPT data using the file website www.uclageo.com/cptpy/
#
# Created by Scott Brandenberg (sjbrandenberg@g.ucla.edu).
#########################################################################################

wipe
model basic -ndm 2 -ndf 3
set numNodes 100
set dz 0.2

#Define Pile Nodes:
node 1 0.0 0
node 2 0.0 -0.20202020202020202
node 3 0.0 -0.40404040404040403
node 4 0.0 -0.6060606060606061
node 5 0.0 -0.8080808080808081
node 6 0.0 -1.0101010101010102
node 7 0.0 -1.2121212121212122
node 8 0.0 -1.4141414141414141
node 9 0.0 -1.6161616161616161
node 10 0.0 -1.8181818181818181
node 11 0.0 -2.0202020202020203
node 12 0.0 -2.2222222222222223
node 13 0.0 -2.4242424242424243
node 14 0.0 -2.6262626262626263
node 15 0.0 -2.8282828282828283
node 16 0.0 -3.0303030303030303
node 17 0.0 -3.2323232323232323
node 18 0.0 -3.4343434343434343
node 19 0.0 -3.6363636363636362
node 20 0.0 -3.8383838383838382
```

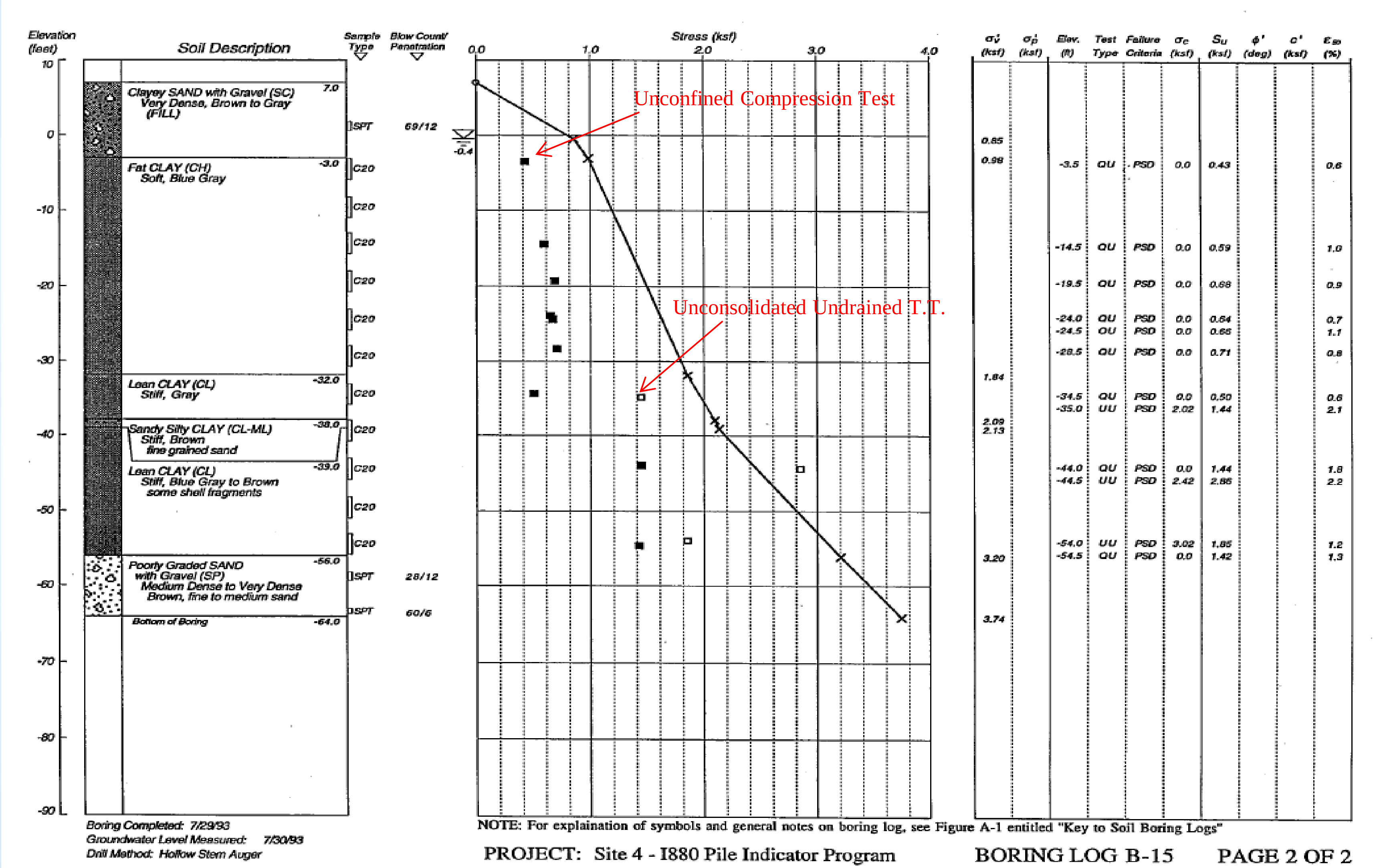
Case Histories

SITE	PREDOMINANT SOIL TYPE	LOAD TEST MEASUREMENTS	REFERENCES
Oakland California	Soft Saturated Clay, San Francisco Bay Mud	Load-Displacement at pile head, pile slope, and back-calculated p-y relations	Lemke (1997)
Hawthorne California	Stiff Partially Saturated Sandy Clay	Load-Displacement at pile head, bending moment along pile, inferred p-y relations	Lemnitzer et al (2010) Khalili Tehrani (2014)
Los Angeles International Airport	Sandy Fill	Load-Displacement at pile head	Diaz Yourman Associates, personal communications (2015)

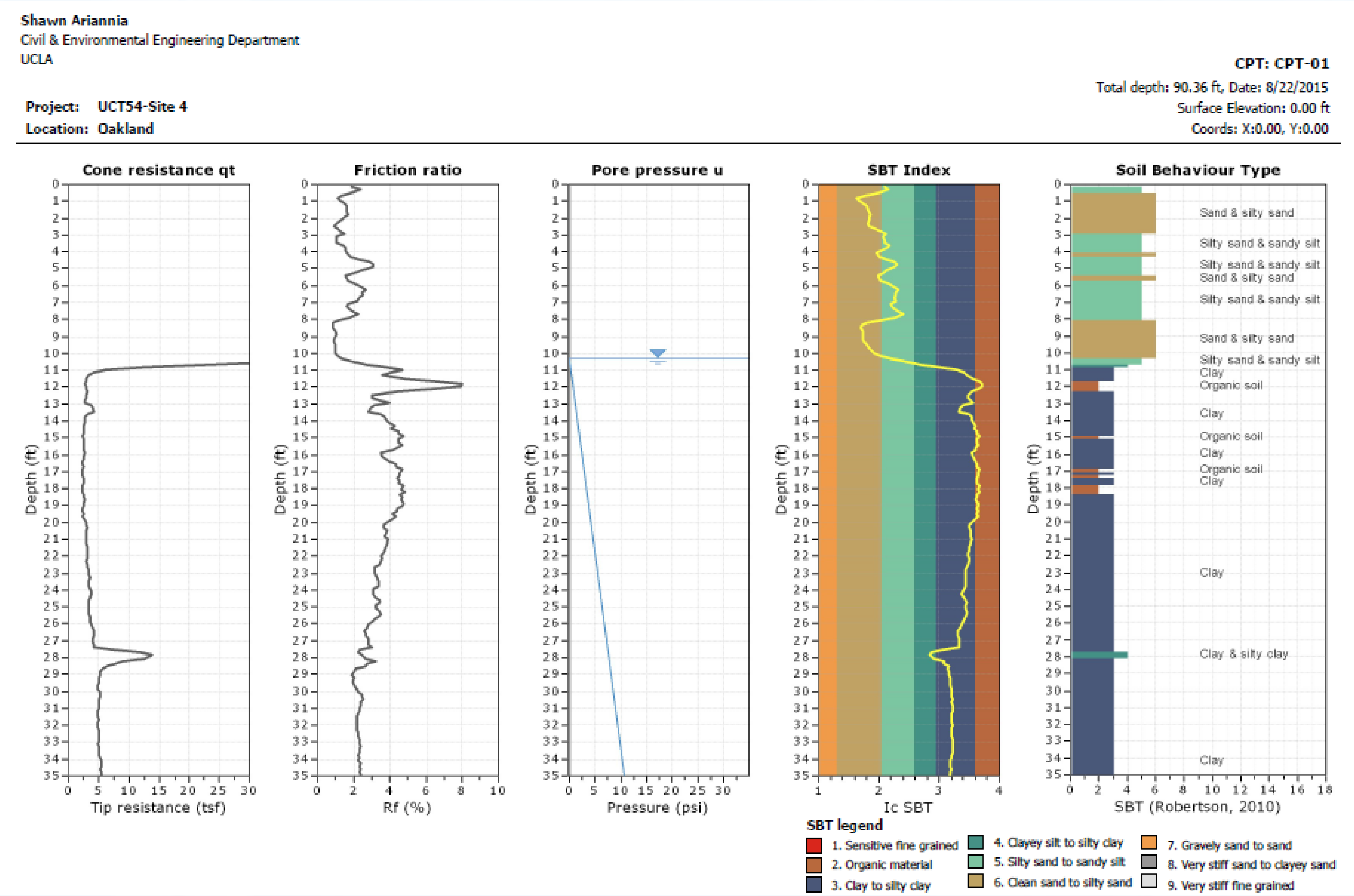
Caltrans Test Site 4 - Oakland

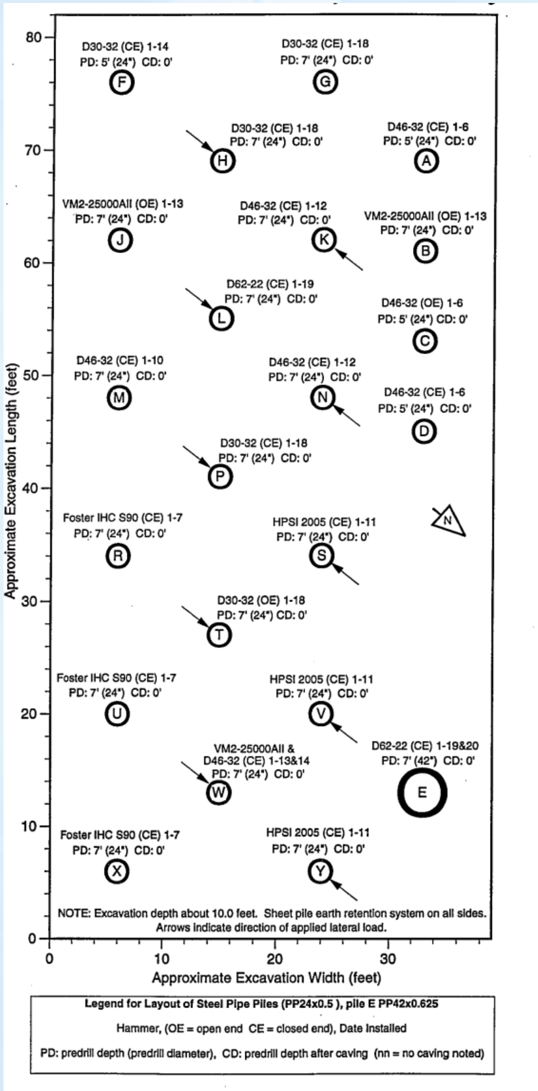
Caltrans Test Site 4 - Oakland

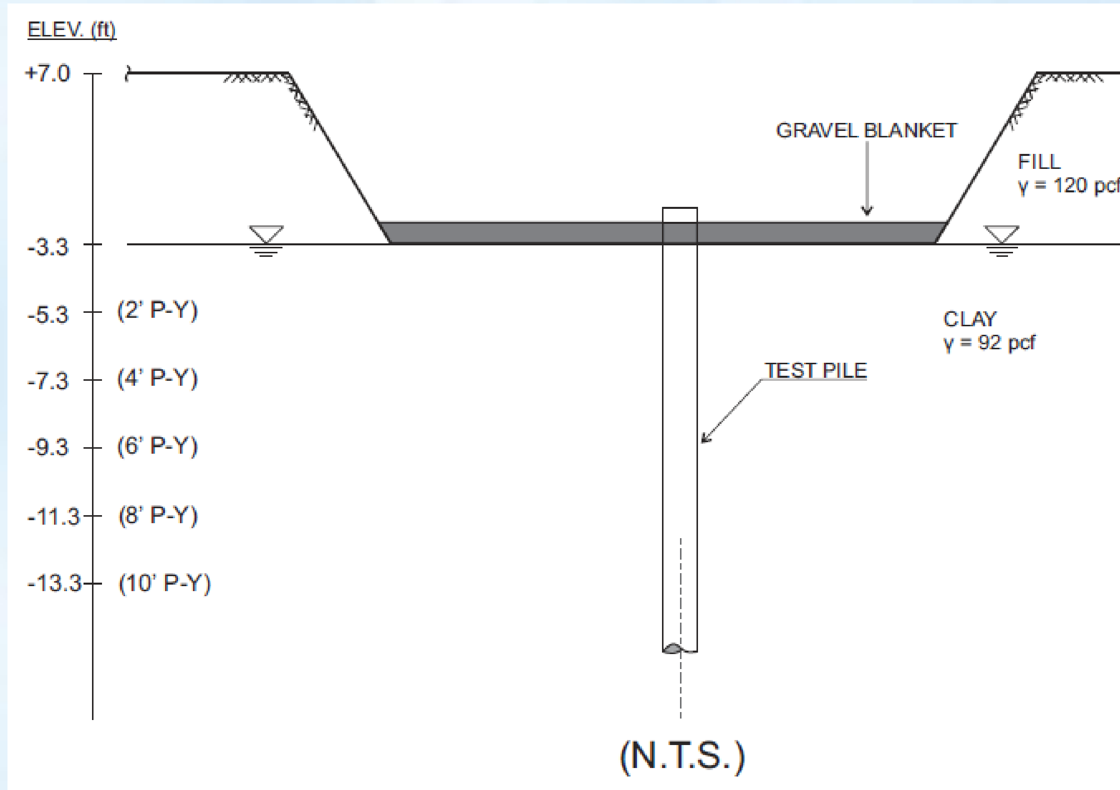



Elevation (feet)
Soil Description
Sample Type
Blow Count/ Penetration
Stress (ksf)
Clayey SAND with Gravel (SC) Very Dense, Brown to Gray (FILL)
Fat CLAY (CH) Soft, Blue Gray
Lean CLAY (CL) Stiff, Gray
Sandy Silty CLAY (CL-ML) Stiff, Brown fine grained sand
Lean CLAY (CL) Stiff, Blue Gray to Brown some shell fragments
Poorly Graded SAND with Gravel (SP) Medium Dense to Very Dense Brown, fine to medium sand
Bottom of Boring
Unconfined Compression Test
Unconsolidated Undrained T.T.
Elev. (ft)
Test Type
Failure Criteria
-3.5 QU PSD 0.0 0.43 0.6
-14.5 QU PSD 0.0 0.59 1.0
-19.5 QU PSD 0.0 0.68 0.9
-24.0 QU PSD 0.0 0.64 0.7
-24.5 QU PSD 0.0 0.66 1.1
-28.5 QU PSD 0.0 0.71 0.8
-34.5 QU PSD 0.0 0.50 0.6
-35.0 UU PSD 2.02 1.44 2.1
-44.0 QU PSD 0.0 1.44 1.8
-44.5 UU PSD 2.42 2.86 2.2
-54.0 UU PSD 3.02 1.85 1.2
-54.5 QU PSD 0.0 1.42 1.3
Boring Completed: 7/29/93
Groundwater Level Measured: 7/30/93
Drill Method: Hollow Stem Auger
NOTE: For explaination of symbols and general notes on boring log, see Figure A-1 entitled "Key to Soil Boring Logs"
PROJECT: Site 4 - I880 Pile Indicator Program
BORING LOG B-15
PAGE 2 OF 2

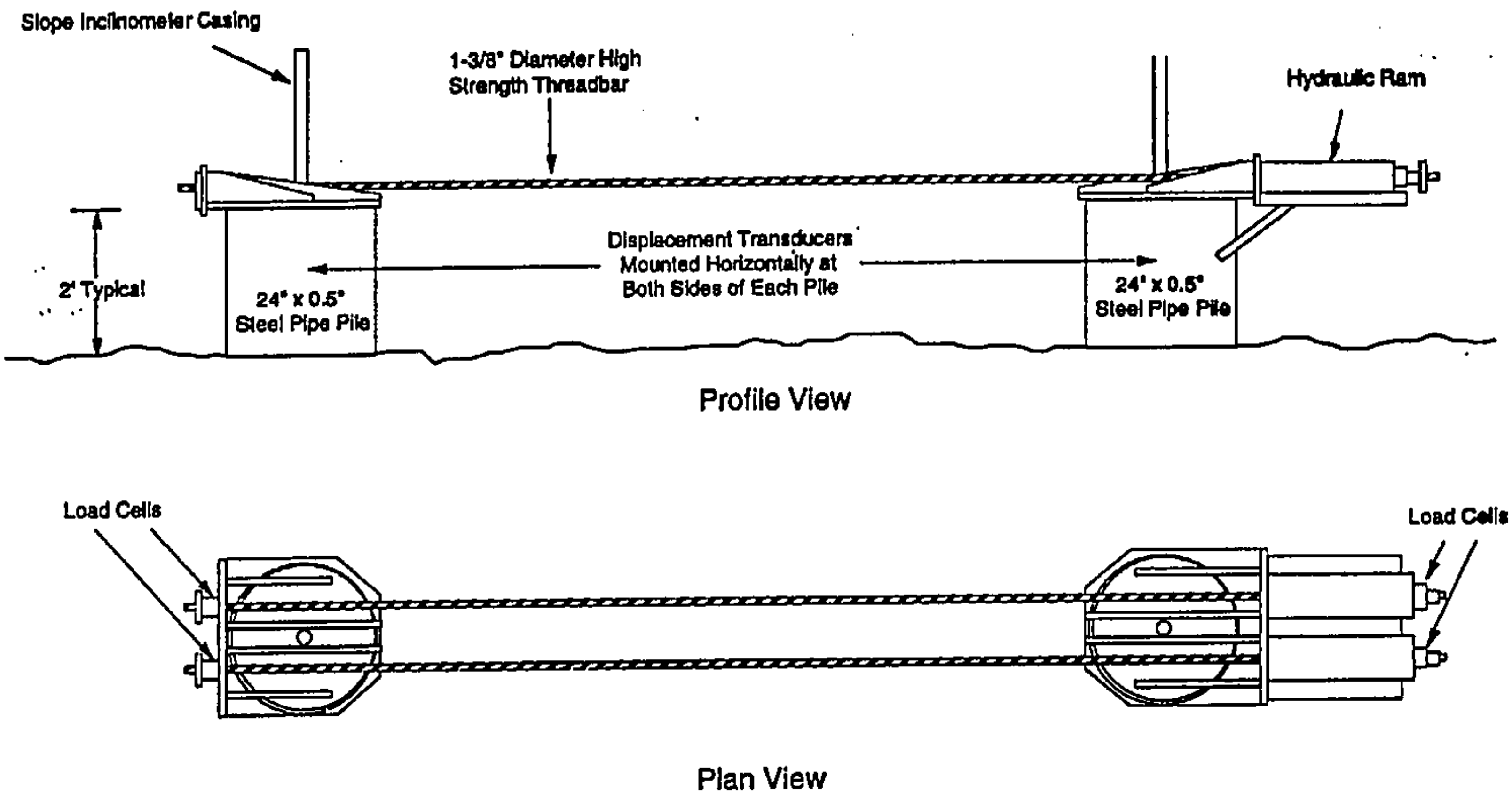
Caltrans Test Site 4 - Oakland



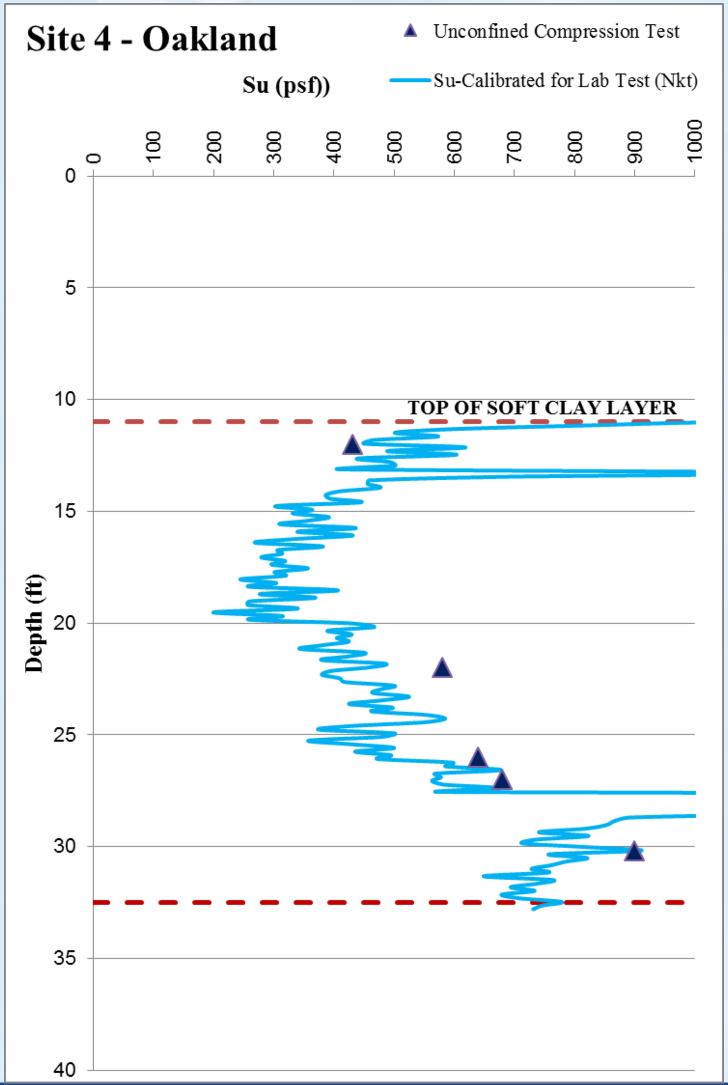

D30-32 (CE) 1-14
PD: 5' (24") CD: 0'
F
D30-32 (CE) 1-18
PD: 7' (24") CD: 0'
G
D30-32 (CE) 1-18
PD: 7' (24") CD: 0'
H
D46-32 (CE) 1-6
PD: 5' (24") CD: 0'
A
VM2-25000AII (OE) 1-13
PD: 7' (24") CD: 0'
J
D46-32 (CE) 1-12
PD: 7' (24") CD: 0'
K
VM2-25000AII (OE) 1-13
PD: 7' (24") CD: 0'
B
D62-22 (CE) 1-19
PD: 7' (24") CD: 0'
L
D46-32 (OE) 1-6
PD: 5' (24") CD: 0'
C
D46-32 (CE) 1-10
PD: 7' (24") CD: 0'
M
D46-32 (CE) 1-12
PD: 7' (24") CD: 0'
N
D46-32 (CE) 1-6
PD: 5' (24") CD: 0'
D
D30-32 (CE) 1-18
PD: 7' (24") CD: 0'
P
Foster IHC S90 (CE) 1-7
PD: 7' (24") CD: 0'
R
HPSI 2005 (CE) 1-11
PD: 7' (24") CD: 0'
S
N
D30-32 (OE) 1-18
PD: 7' (24") CD: 0'
T
Foster IHC S90 (CE) 1-7
PD: 7' (24") CD: 0'
U
HPSI 2005 (CE) 1-11
PD: 7' (24") CD: 0'
V
VM2-25000AII &
D46-32 (CE) 1-13&14
PD: 7' (24") CD: 0'
W
D62-22 (CE) 1-19&20
PD: 7' (42") CD: 0'
E
Foster IHC S90 (CE) 1-7
PD: 7' (24") CD: 0'
X
HPSI 2005 (CE) 1-11
PD: 7' (24") CD: 0'
Y
NOTE: Excavation depth about 10.0 feet. Sheet pile earth retention system on all sides.
Arrows indicate direction of applied lateral load.
Approximate Excavation Length (feet)
0
10
20
30
40
50
60
70
80
Approximate Excavation Width (feet)
Legend for Layout of Steel Pipe Piles (PP24x0.5), pile E PP42x0.625
Hammer, (OE = open end CE = closed end), Date Installed
PD: predrill depth (predrill diameter), CD: predrill depth after caving (nn = no caving noted)

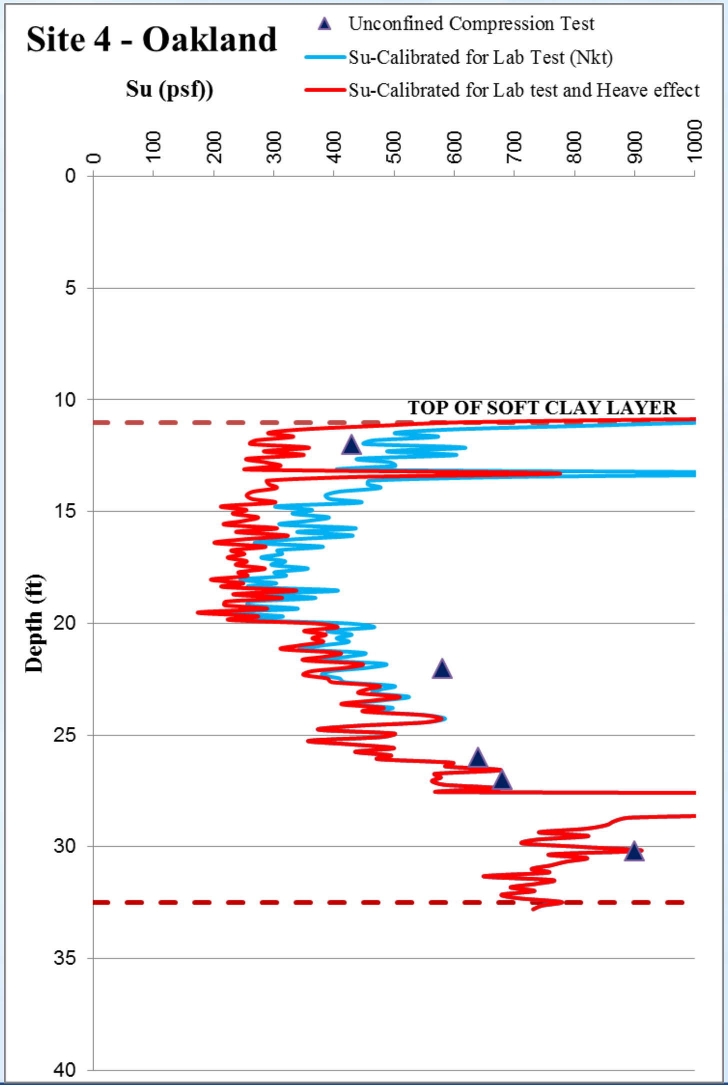

ELEV. (ft)
+7.0
-3.3
-5.3
(2' P-Y)
-7.3
(4' P-Y)
-9.3
(6' P-Y)
-11.3
(8' P-Y)
-13.3
(10' P-Y)
GRAVEL BLANKET
FILL
γ = 120 pcf
CLAY
γ = 92 pcf
TEST PILE
(N.T.S.)

Caltrans Test Site 4 - Oakland
Lateral Load Test Set-Up

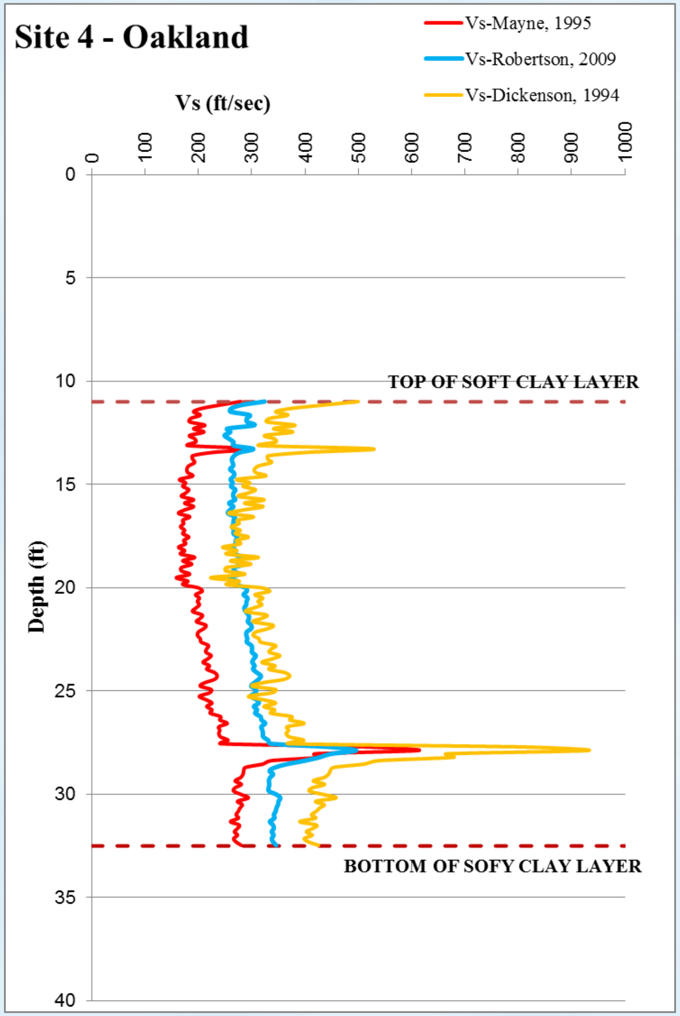


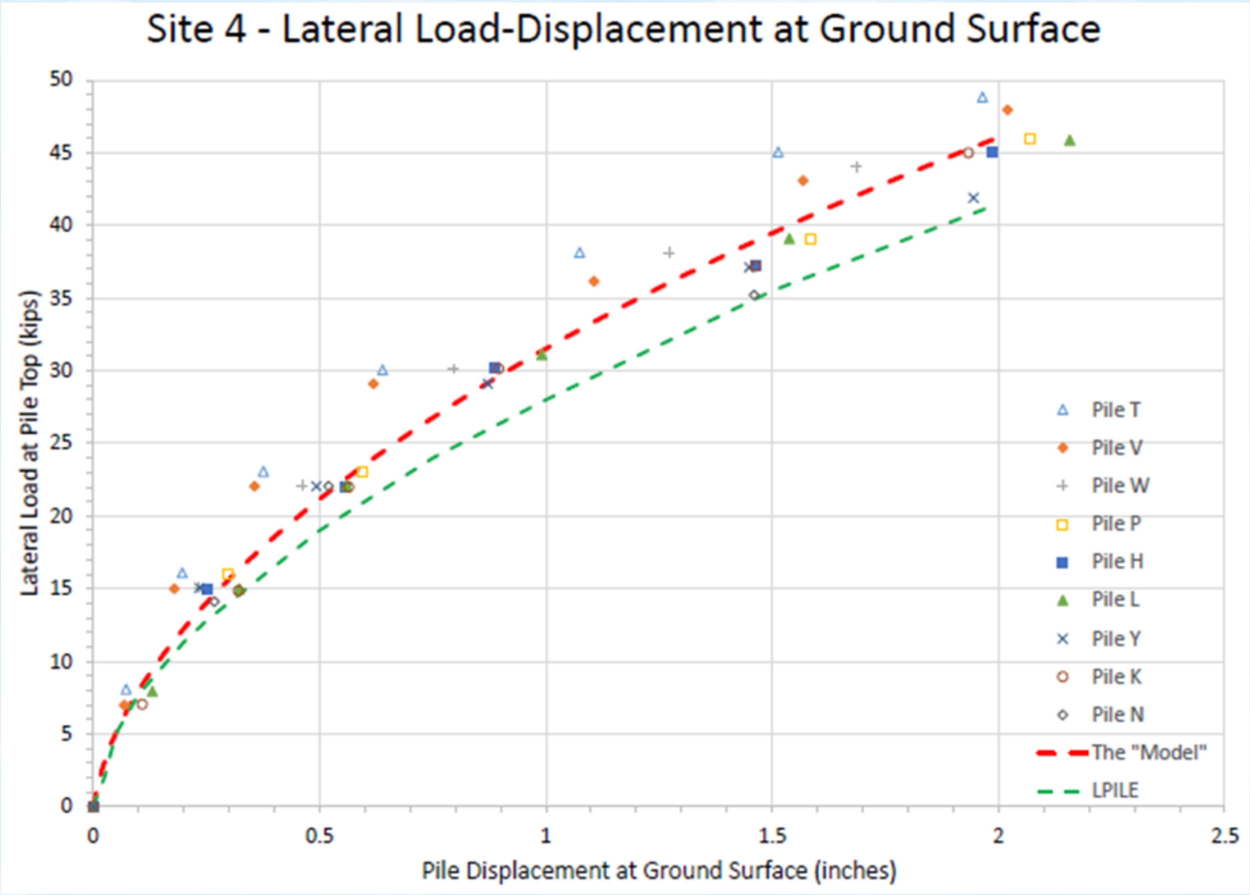
Caltrans Test Site 4 - Oakland
Site Specific Calibration of CPT



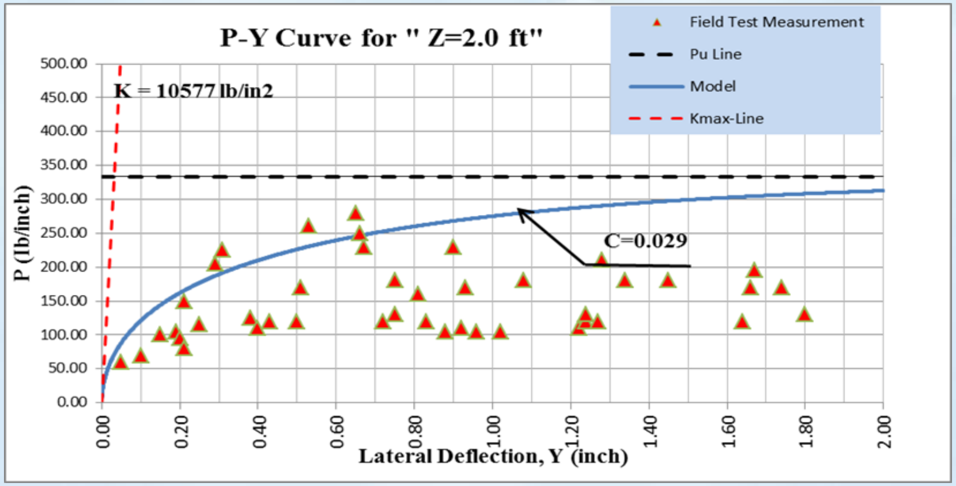


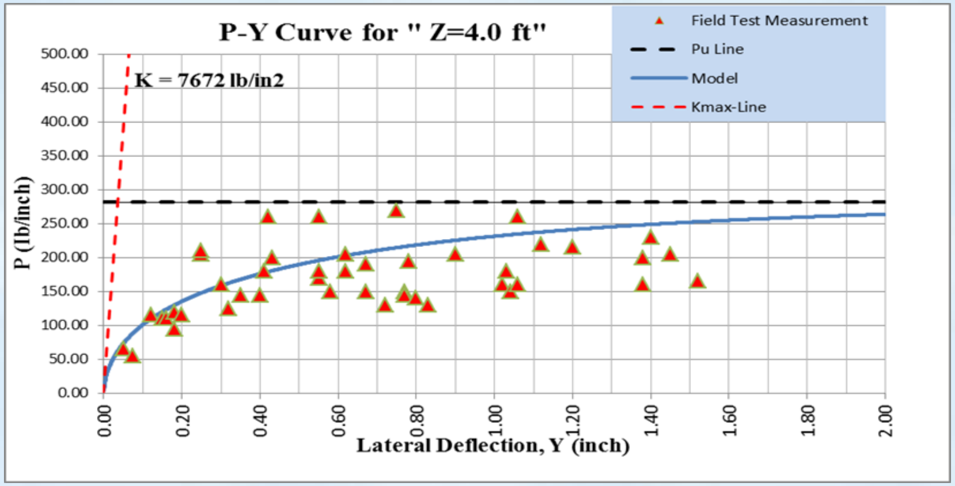
Caltrans Test Site 4 – Oakland
Shear Wave Velocity



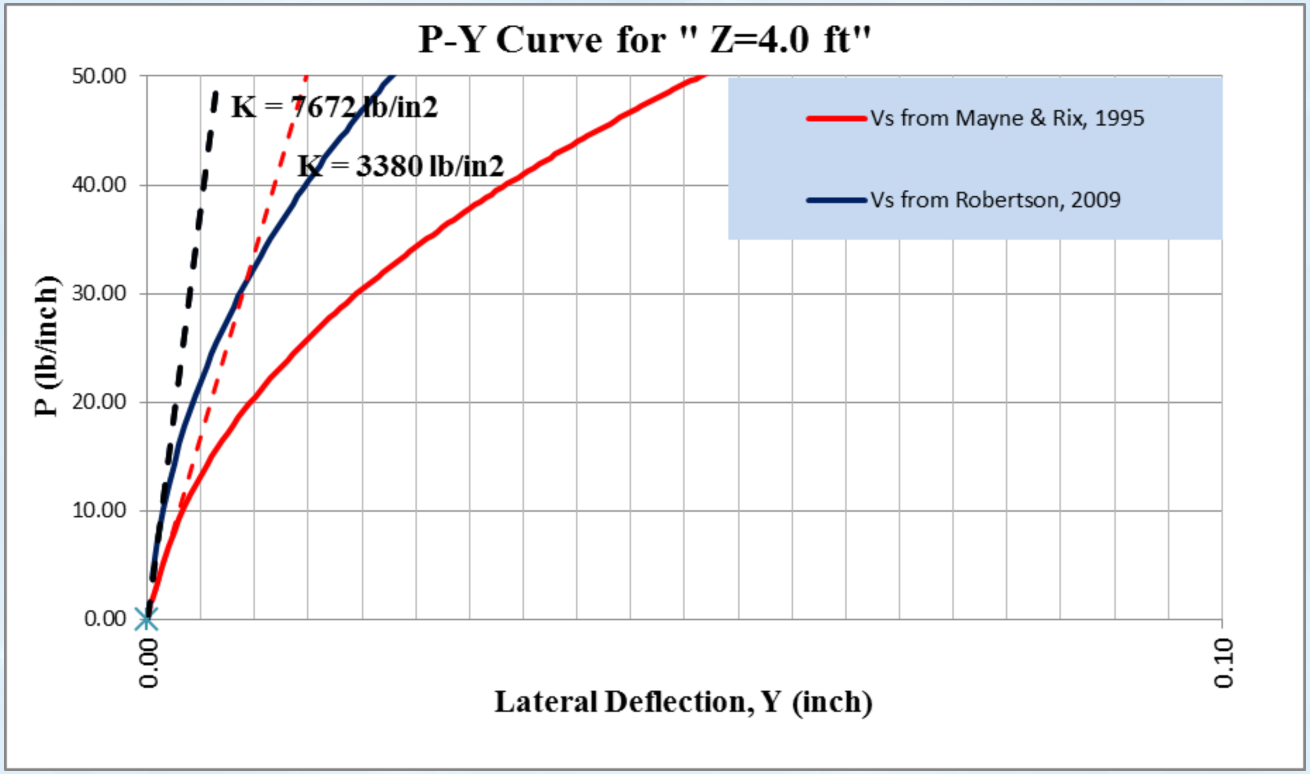

Site 4 - Lateral Load-Displacement at Ground Surface
Lateral Load at Pile Top (kips)
Pile Displacement at Ground Surface (inches)
0
5
10
15
20
25
30
35
40
45
50
0
0.5
1
1.5
2
2.5
Pile T
Pile V
Pile W
Pile P
Pile H
Pile L
Pile Y
Pile K
Pile N
The "Model"
LPILE

Caltrans Test Site 4 – Oakland *p-y* Curves

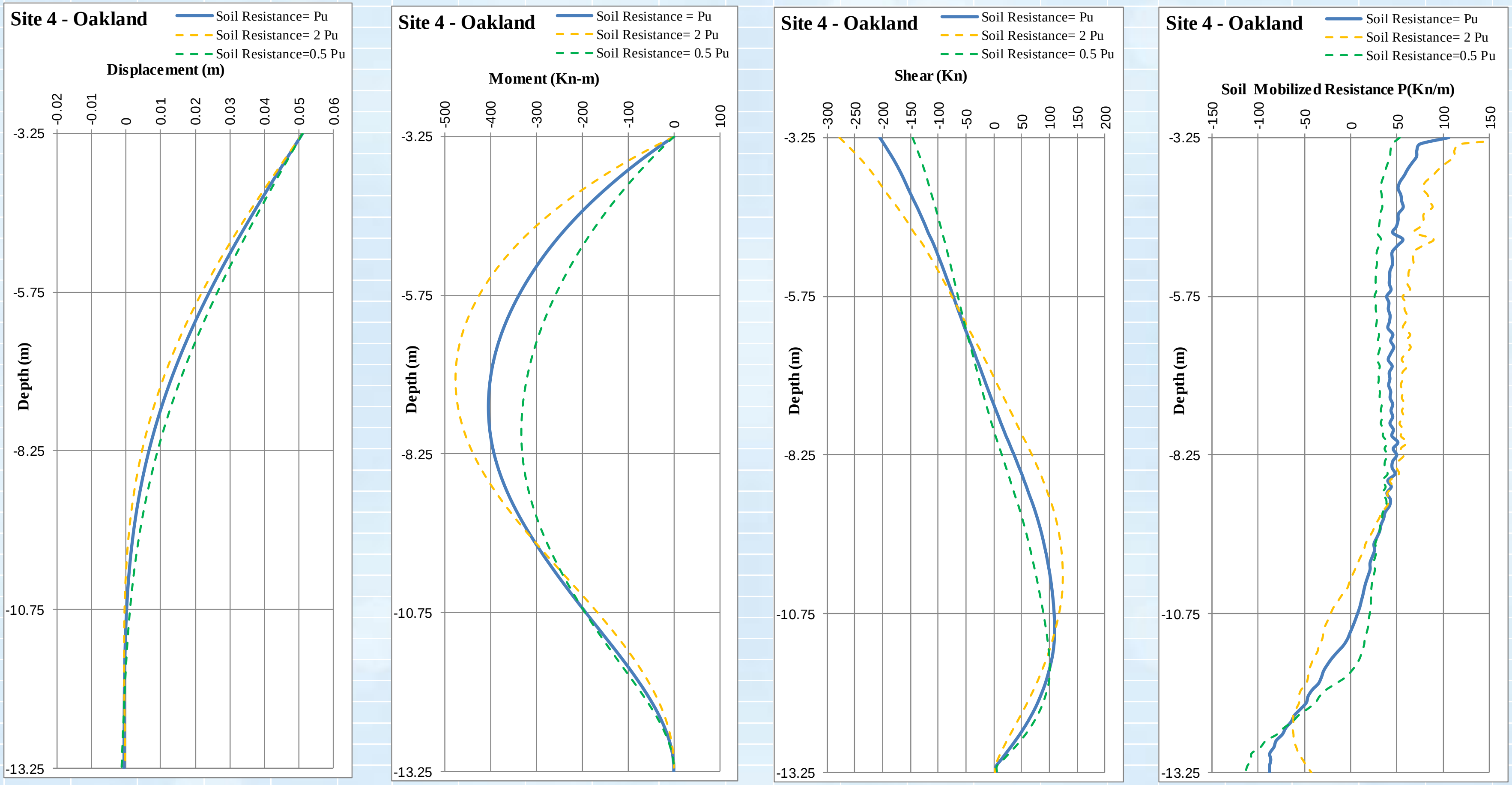




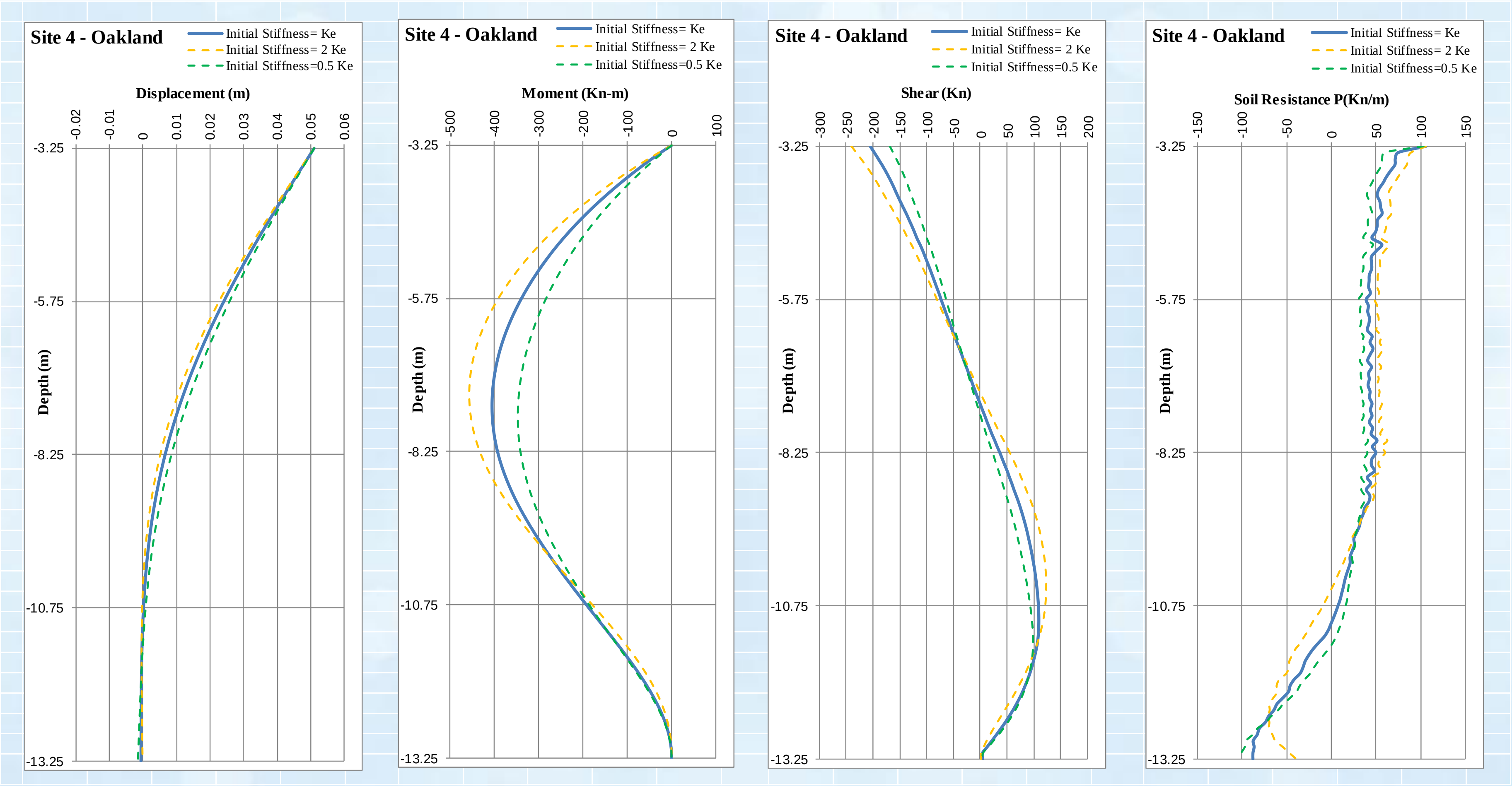
Caltrans Test Site 4 – Oakland Initial Stiffness Variation



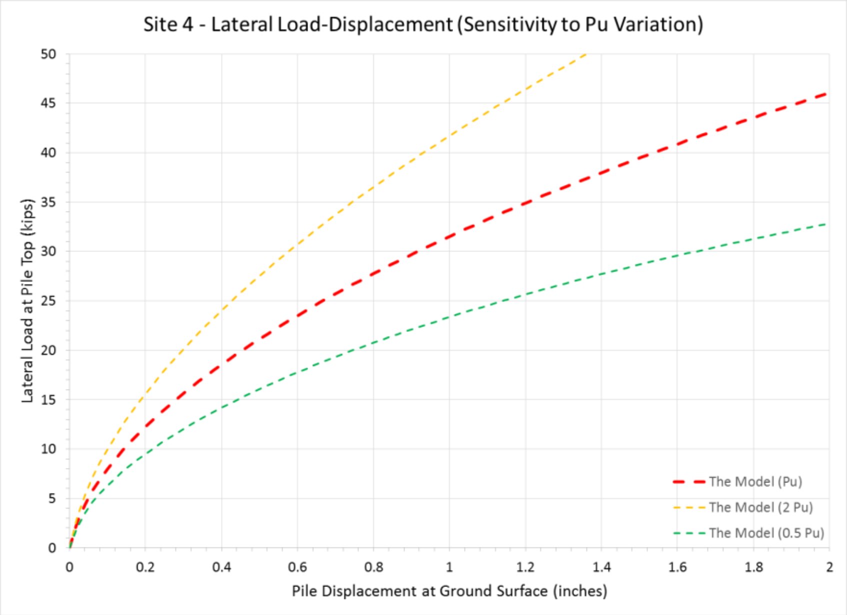
Site 4 - Oakland
Sensitivity of Pile Response to Pu

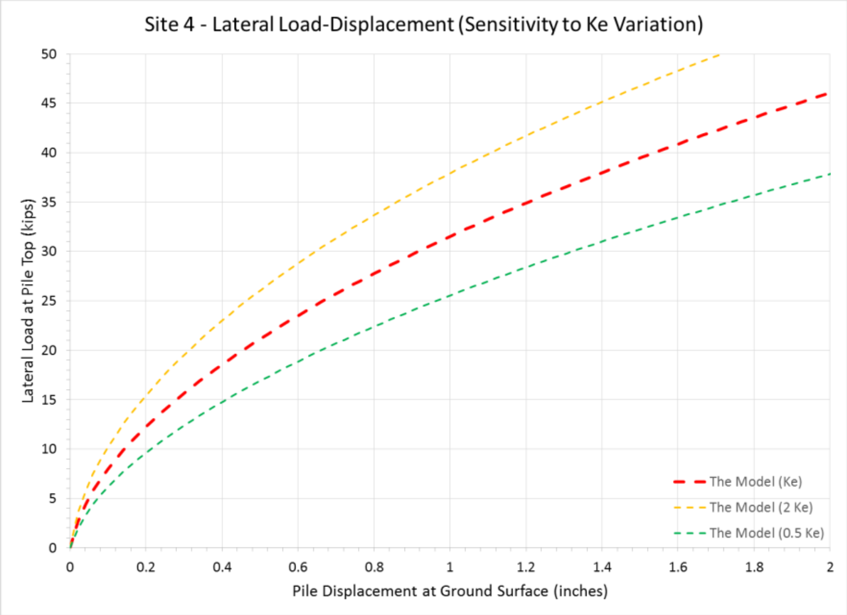


Site 4 - Oakland
Sensitivity of Pile Response to ke

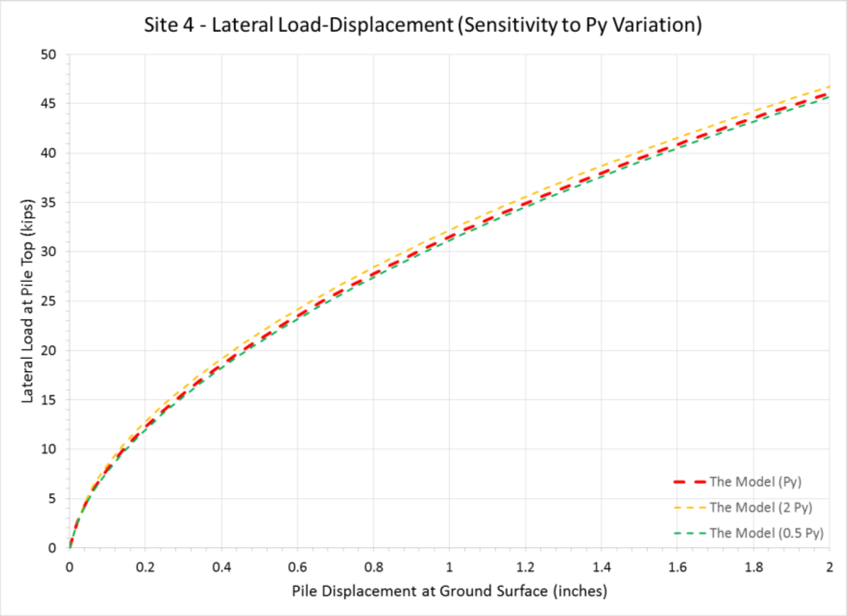


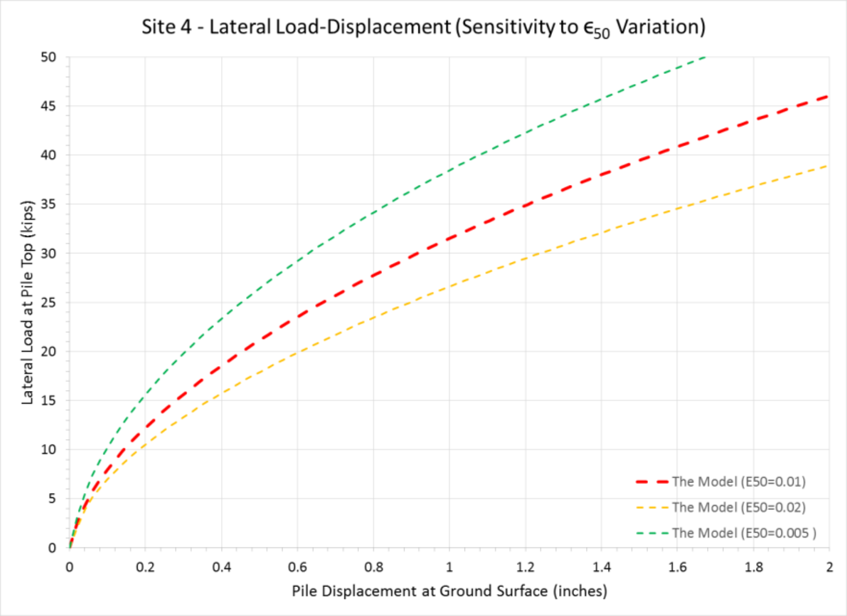
Site 4 - Oakland
Sensitivity of Pile Head Deflection to P_u and K_e



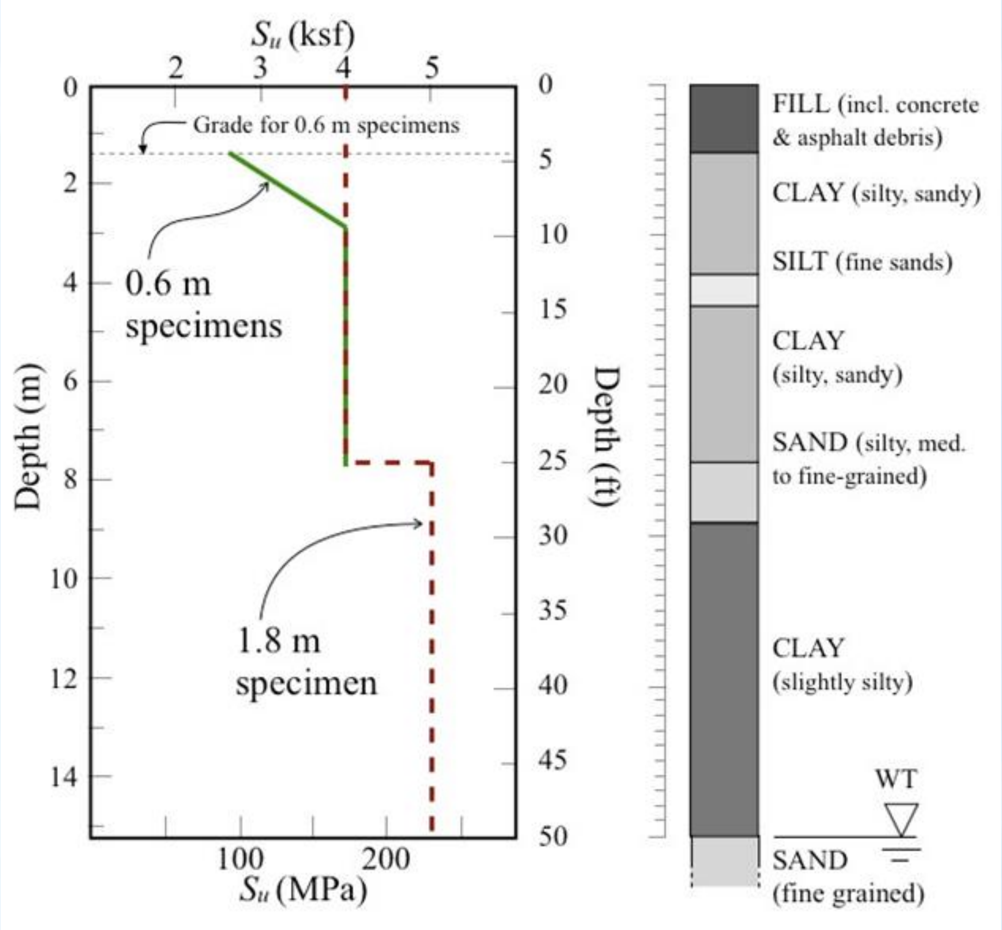


Site 4 - Oakland
Sensitivity of Pile Head Deflection to P_y and ϵ_{50}



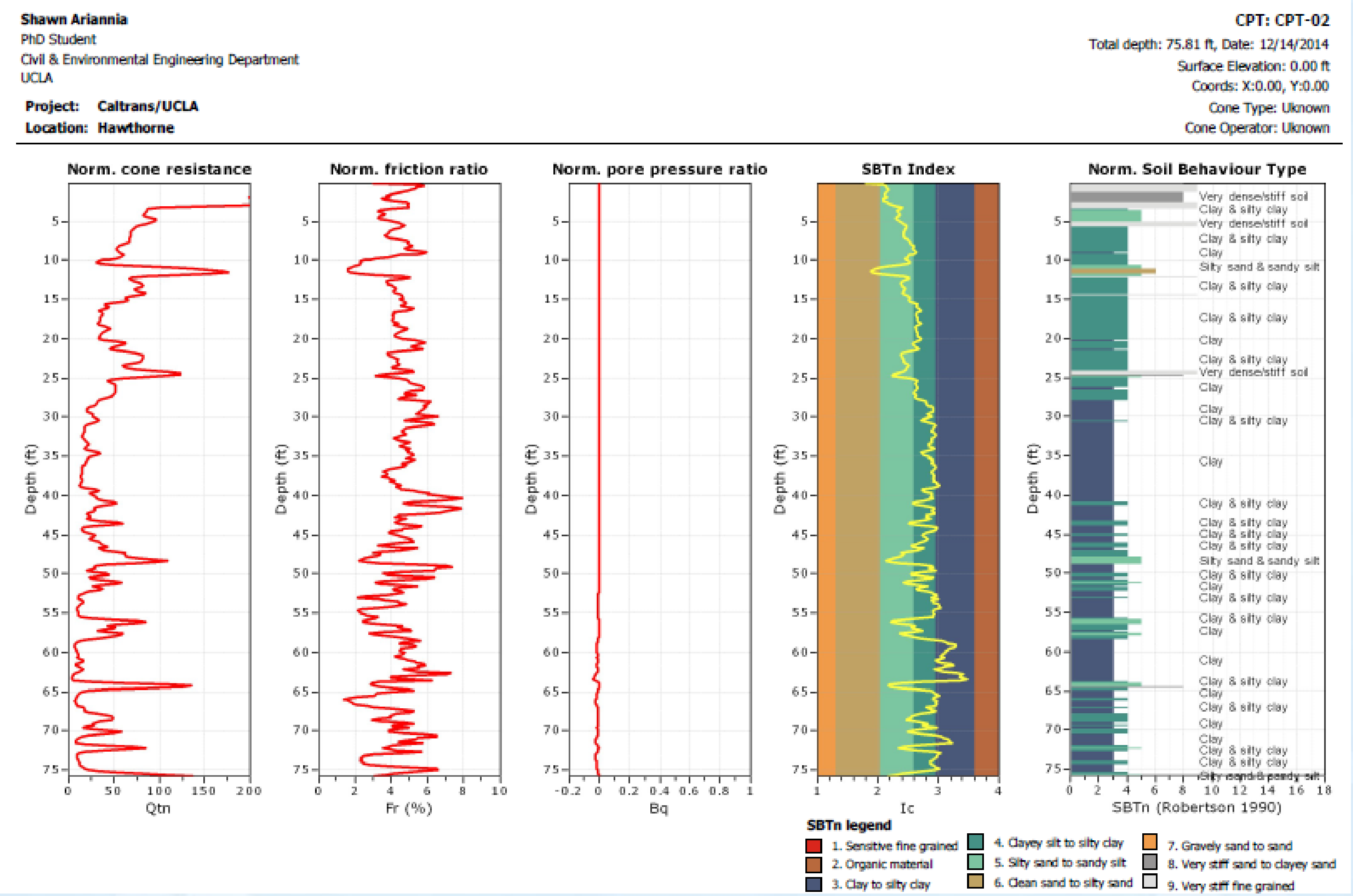


Hawthorne Site- Los Angeles

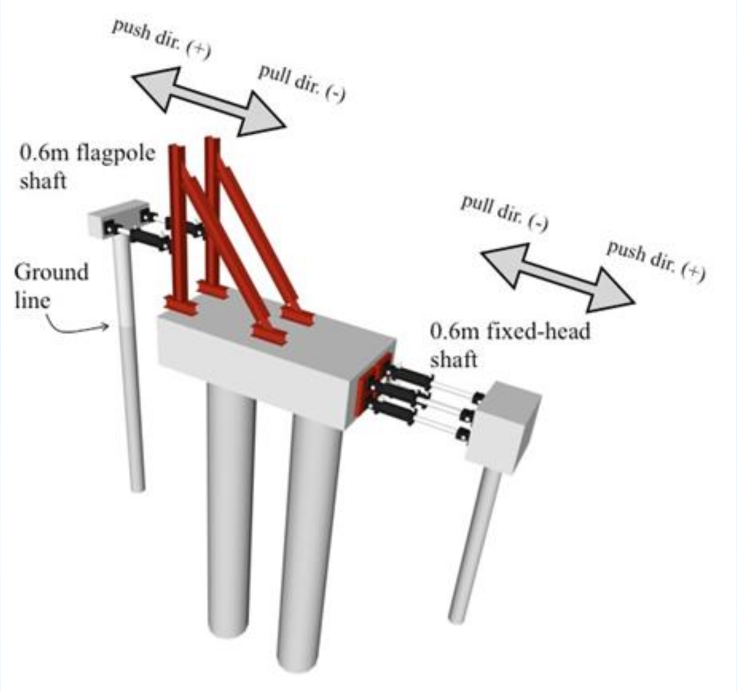


Simplified representation of soil undrained shear strength (Su) profile and stratigraphy at Hawthorne site
(Khalili Tehrani et al., 2012)
(Lemnitzer et al., 2010)

Hawthorne Site- Los Angeles

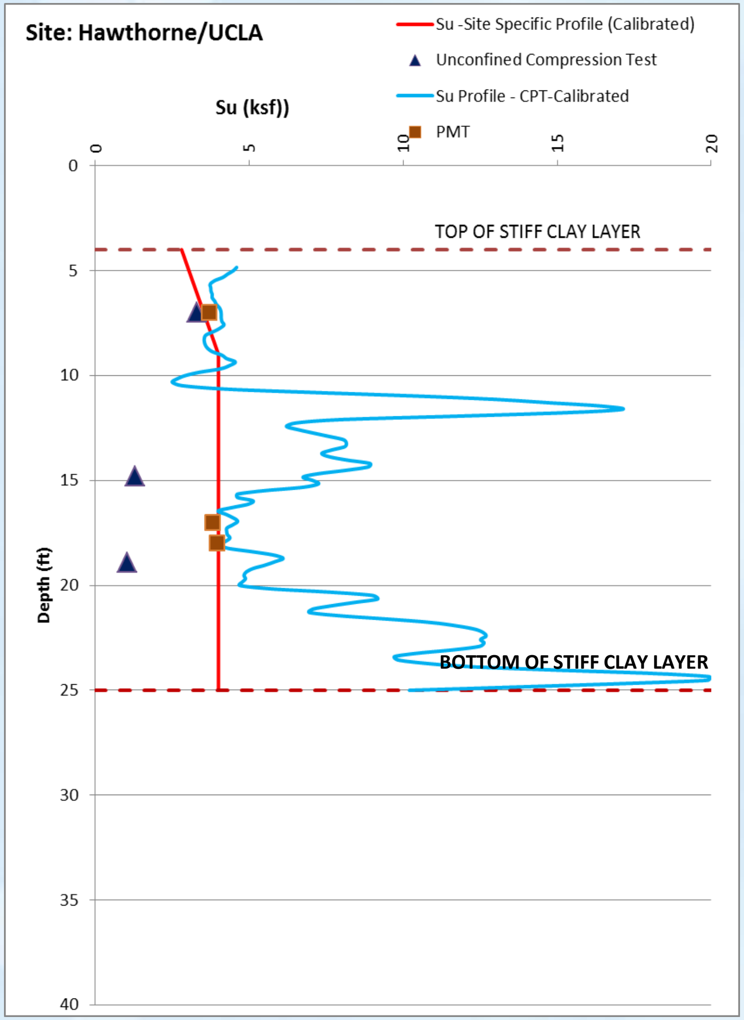


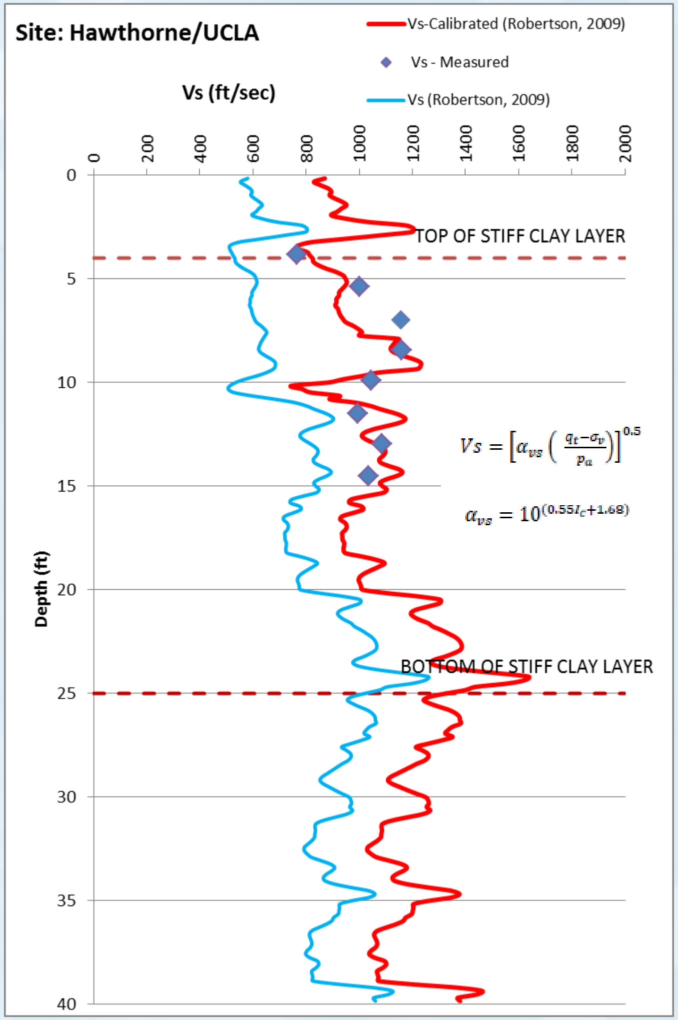
Hawthorne Site- Los Angeles
Test Set Up



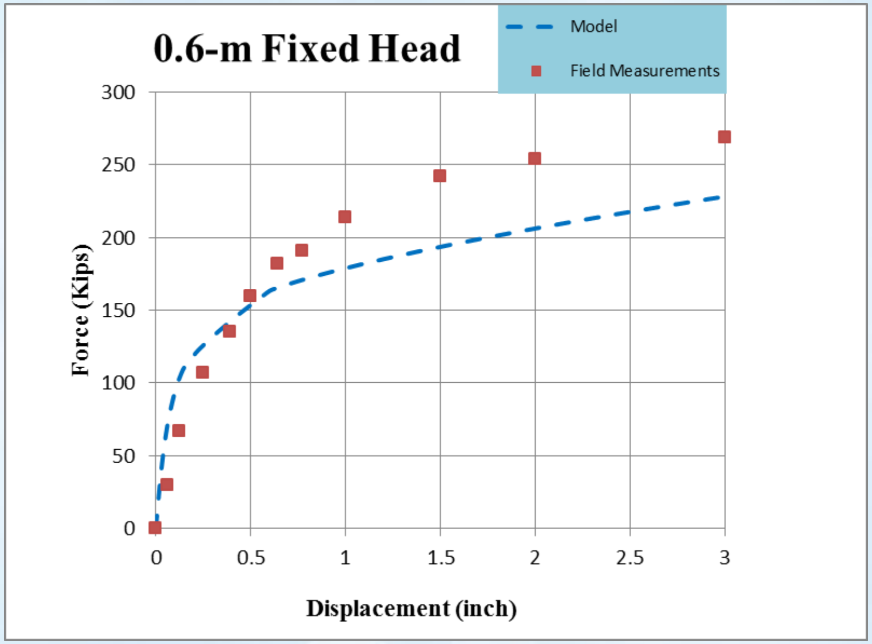
The reaction block and the configuration of 0.6m diameter specimens (Khalili Tehrani et al., 2012)

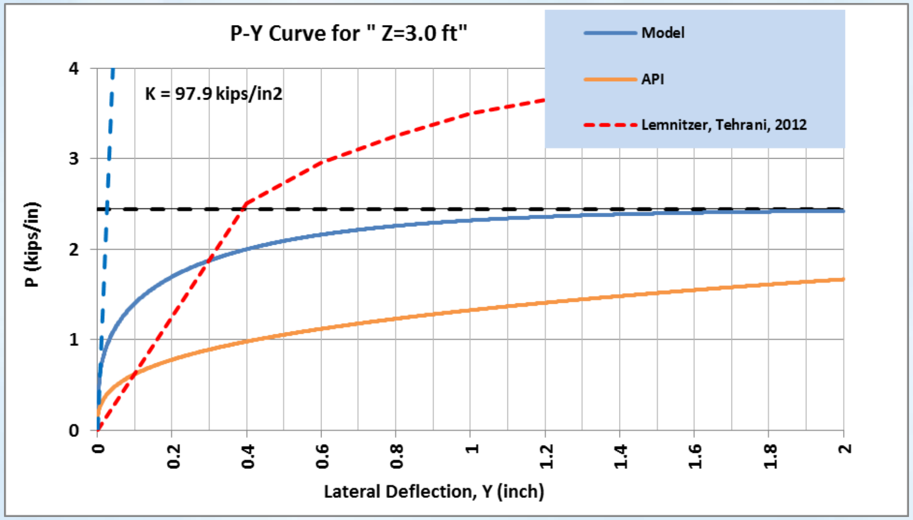
Hawthorne Site- Los Angeles
Site Calibration for Su and Vs



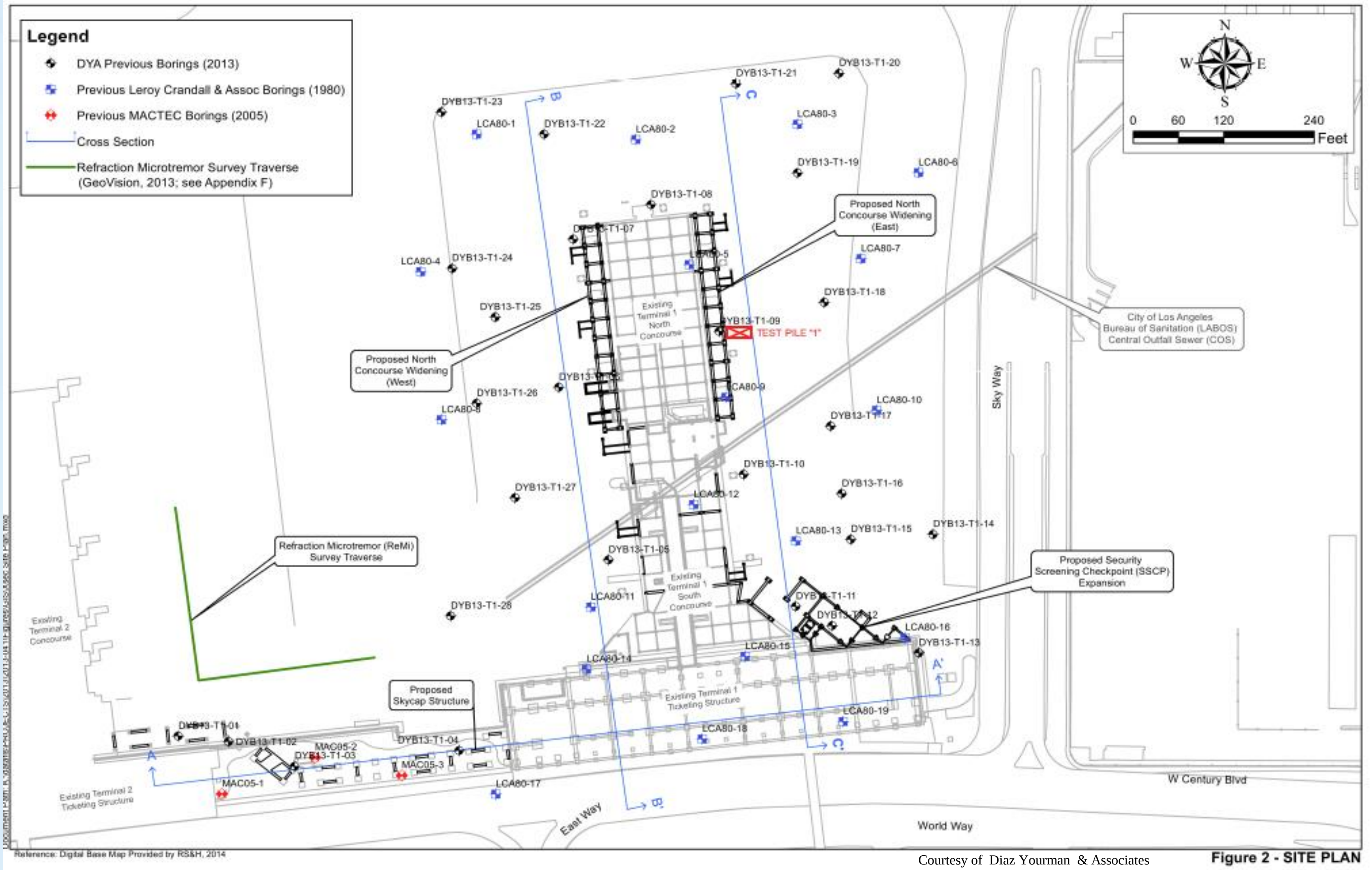


Hawthorne Site - Los Angeles



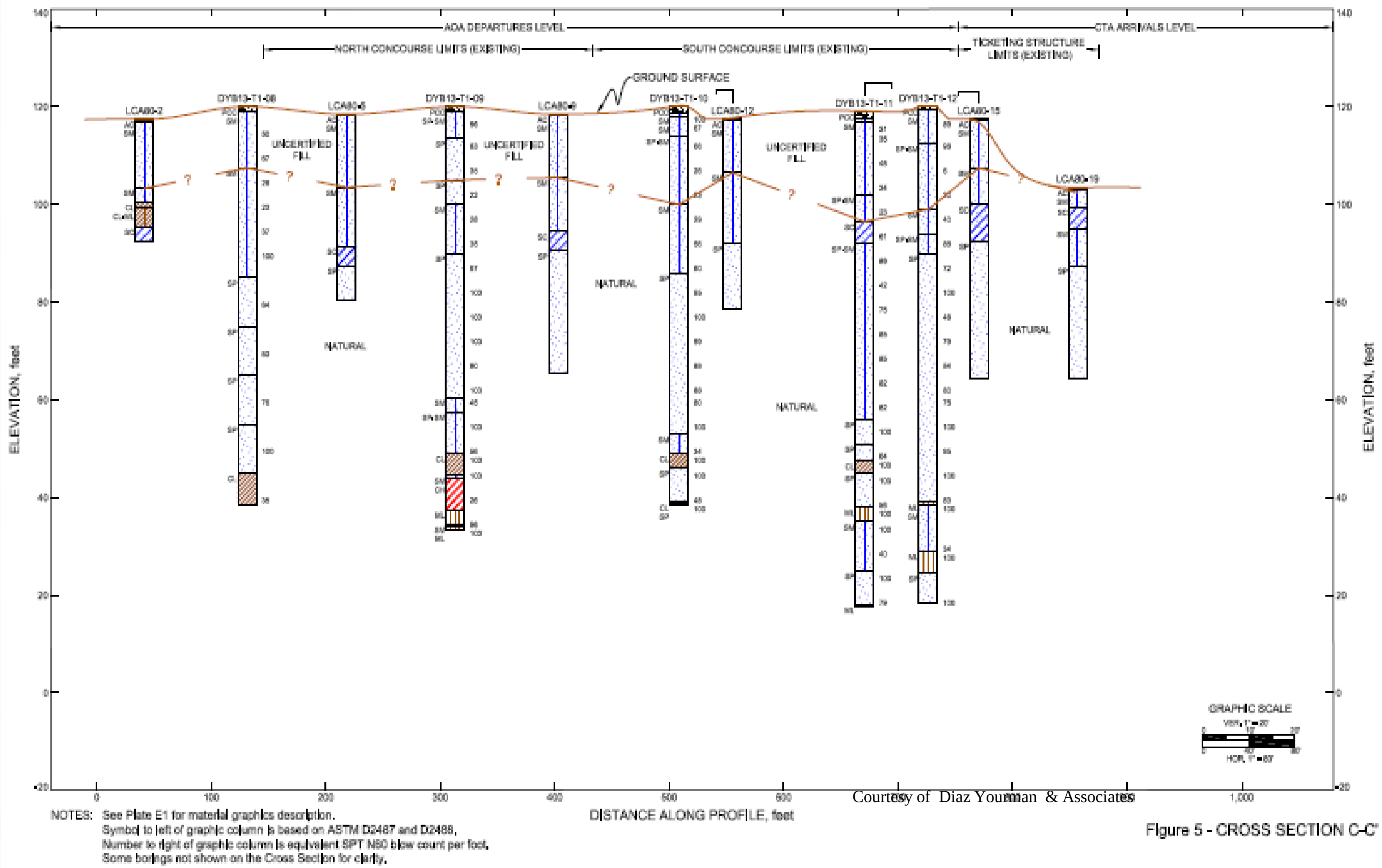


LAX Site - Los Angeles



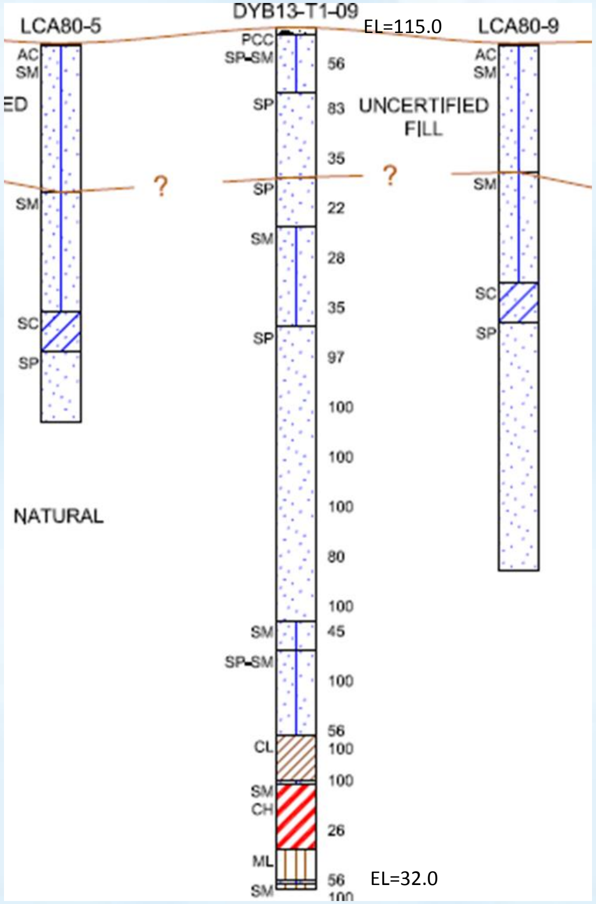
Courtesy of Diaz Yourman & Associates

LAX Site - Los Angeles
Soils Stratification

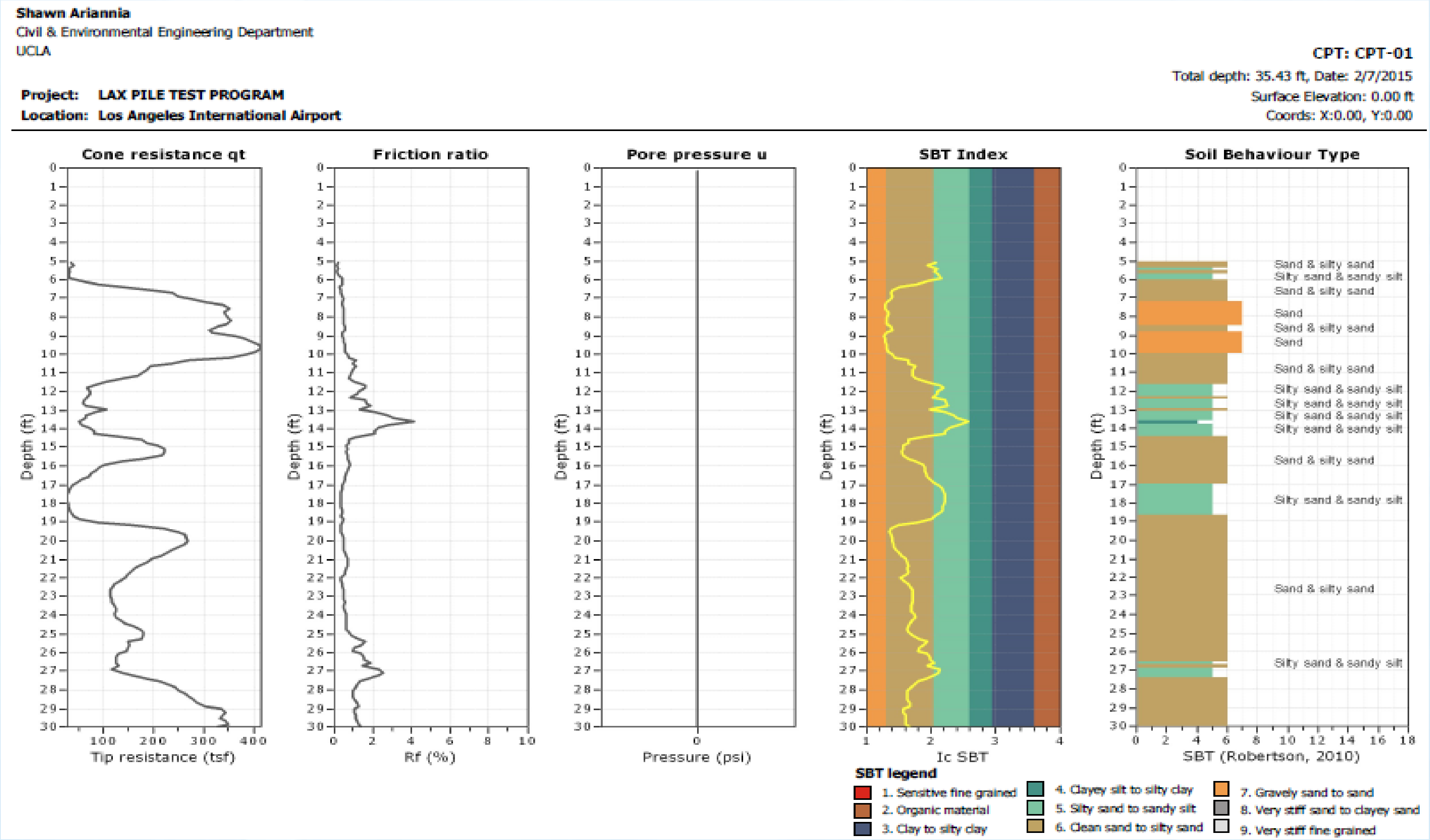


Courtesy of Diaz Yourman & Associates

LAX Site - Los Angeles
Soils Stratification



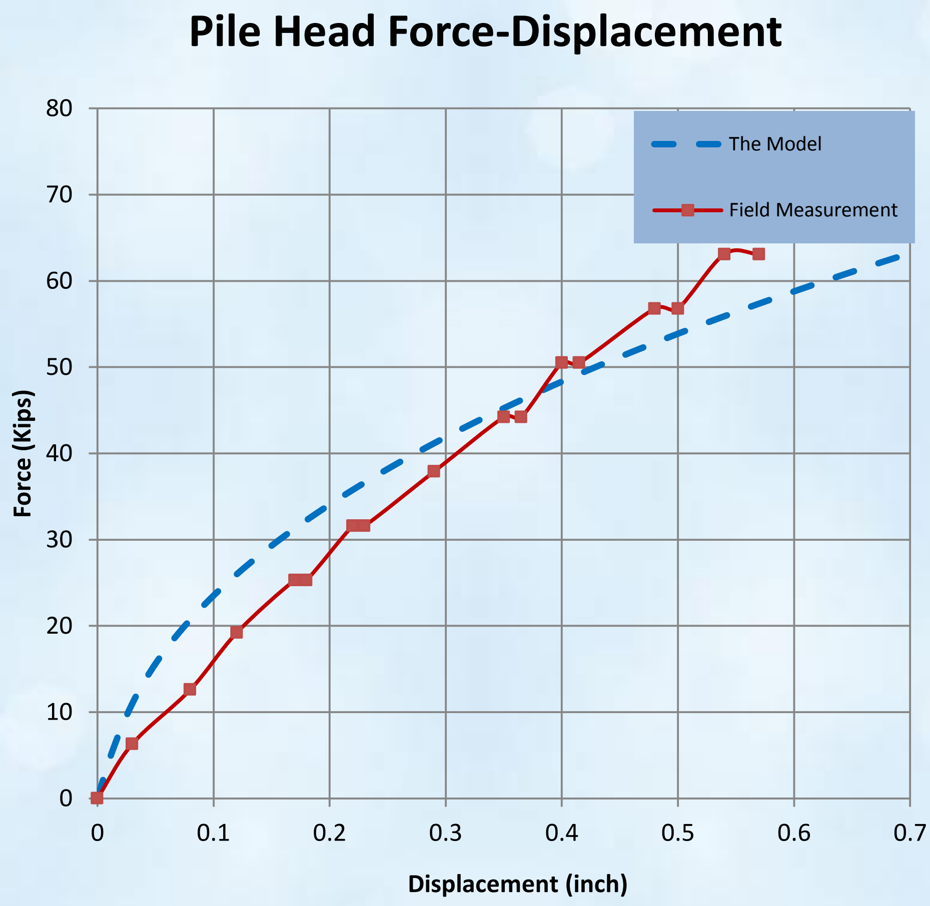
LAX Site - Los Angeles
CPT



LAX Site - Los Angeles
Test Set Up

Lateral load testing set up for pile test 1 at LAX

LAX Site - Los Angeles



Summary

- Mapping algorithm involves smoothing procedure that takes into consideration the layering effect
- Real or close to real initial stiffness of the soil at each depth
- Overcomes to the common problem of the currently in practice p-y curves by explicitly including a finite elastic stiffness and small-strain nonlinearity.
- Unlike other models, predetermination of soil type/behavior is not required.
- Predicted pile head load-displacement vs. field measurements: Good Agreement
- Predicted p-y curves from the model vs. backcalculated p-y curves from case histories: Good Agreement

References

Ahmadi, M.M. and Robertson, P.K. (2005). "Thin-layer effects on the CPT q_c measurement." Canadian Geotechnical Journal. 42: 1302-1317.

API (1993). Recommended practice for planning, design, and constructing fixed offshore platforms. API RP 2A-WSD, 20th ed. American Petroleum Institute, API Publishing Services, Washington D.C.

Choi, J.-I., Kim, M.M., and Brandenberg, S.J. (2015). "Cyclic p-y plasticity model applied to pile foundations in sand." *Journal of Geotechnical and Geoenvironmental Engineering*, 141(5), 04015013.

Dobry, R.M., O'Rourke, M.J., and Roesset, J.M. (1982). "Horizontal stiffness and damping of single piles." *Journal of the Geotechnical Division*, ASCE, 108(GT3), 439-459.

Gazetas, G., and Dobry, R. (1984). "Horizontal response of piles in layered soils." *Journal of Geotechnical Engineering*, 110(1), 20-40.

Kagawa, T., and Kraft, L.M. (1980). "Seismic p-y response of flexible piles." *Journal of the Soil Mechanics and Foundation Division*, 98(SM6), 603-624.

Matlock, H. (1970). "Correlations for design of laterally loaded piles in soft clay." *Proc. 2nd Annual Offshore Technology Conference,* Houston, TX, 577-594.

Robertson (2012)

Syngros, C. (2004). "Seismic response of piles and pile-supported bridge piers evaluated through case histories." *Ph.D. Thesis*, Civil Engineering Dept., City University of New York, NY.

Turner, B.J. (2016). "Kinematic pile-soil interaction in liquefied and non-liquefied ground." *Ph.D. Dissertation*, University of California, Los Angeles. 422 p.

Wair, B.R., DeJong, J.T., and Shantz, T. (2012). "Guidelines for estimation of shear wave velocity profiles." *PEER 2012/08*, Pacific Earthquake Engineering Research Center, Berkeley, CA.

Yang, Z., and Jeremic, B. (2002). "Numerical analysis of pile behavior under lateral loads in layered elastic-plastic soils." *International Journal for Numerical and Analytical Methods in Geomechanics*, 03(22), 1-31.

Araiannia , S.(2015). Determination of p-y Curves by Direct Use of Cone Penetration Test (CPT) Data-A dissertation submitted in partial satisfaction of the requirement for the degree Doctor of Philosophy in Civil Engineering, UCLA

Lemnitzer, A., et al. (2010), "Nonlinear Efficiency of Bored Pile Group under Lateral Loading", ASCE Journal of the Geotechnical Engineering Division, December 2010, pp. 1673-1685.

Lemke, J., (1997)"Lateral Pile Load Test Report I-880 Replacement Project Sites 1 through 4 Oakland, California". Report Prepared for Caltrans, by Delta Geotechnical Services.

Questions?