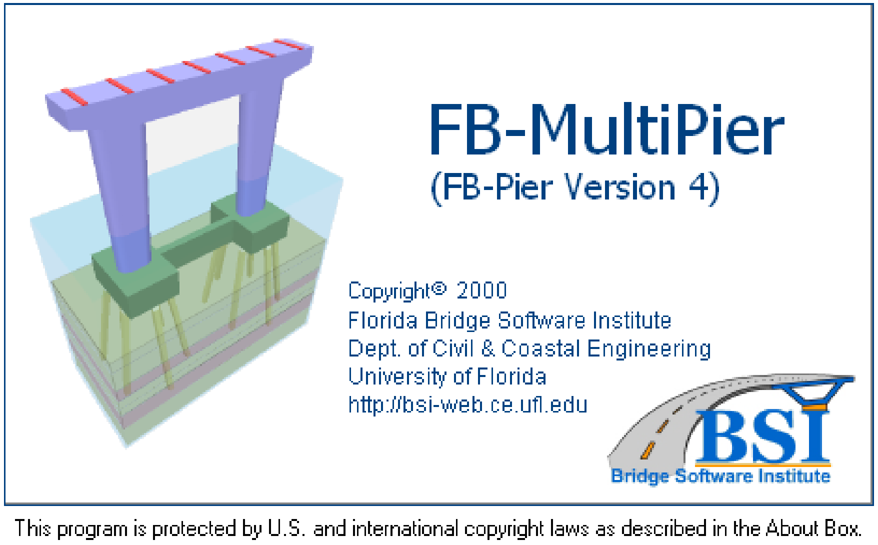
AUBURN
UNIVERSITY

Soil-Pile Interaction in FB-MultiPier

Dr. J. Brian Anderson, P.E.



FB-MultiPier
(FB-Pier Version 4)

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Florida Bridge Software Institute
Dept. of Civil & Coastal Engineering
University of Florida
http://bsi-web.ce.ufl.edu

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Developed by: Florida Bridge Software Institute

CIVIL ENGINEERING

Session Outline

- Introduce FB-MultiPier Software
- Identify and Discuss Soil-Pile Interaction Models
  - Precast & Cast Insitu Axial T-Z & Q-Z Models
  - Torsional T-θ Models
  - Lateral P-Y Models
  - Nonlinear Pile Structural Models
- FB-MultiPier Input and Output
  - Example #1 Single Pile

FB-MultiPier

- Nonlinear finite element analysis program capable of analyzing multiple bridge pier structures interconnected by bridge spans.
- The full structure can be subject to a full array AASHTO load types in a static analysis or time varying load functions in a dynamic analysis.

FB-MultiPier

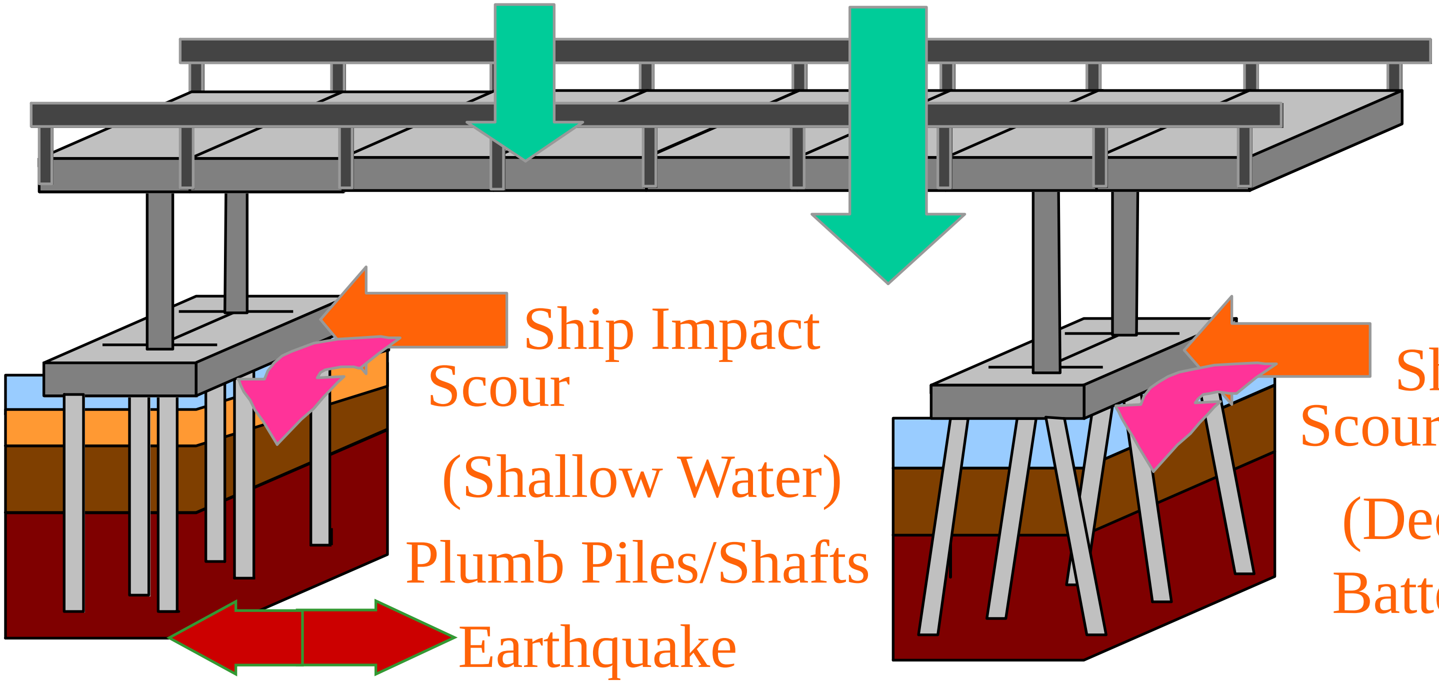
- Each pier structure is composed of pier columns and cap supported on a pile cap and piles/shafts with nonlinear soil.
- FB-Multipier couples nonlinear structural finite element analysis with nonlinear static soil models for axial, lateral and torsional soil behavior to provide a robust system of analysis for coupled bridge pier structures and foundation systems.

FB-MultiPier

- FB-MultiPier performs the generation of the finite element model internally given the geometric definition of the structure and foundation system as input graphically by the designer.

Coupled Soil-Structure Interaction

Live and Dead Loading



Ship Impact

Scour

(Shallow Water)

Plumb Piles/Shafts

Earthquake

Ship Impact

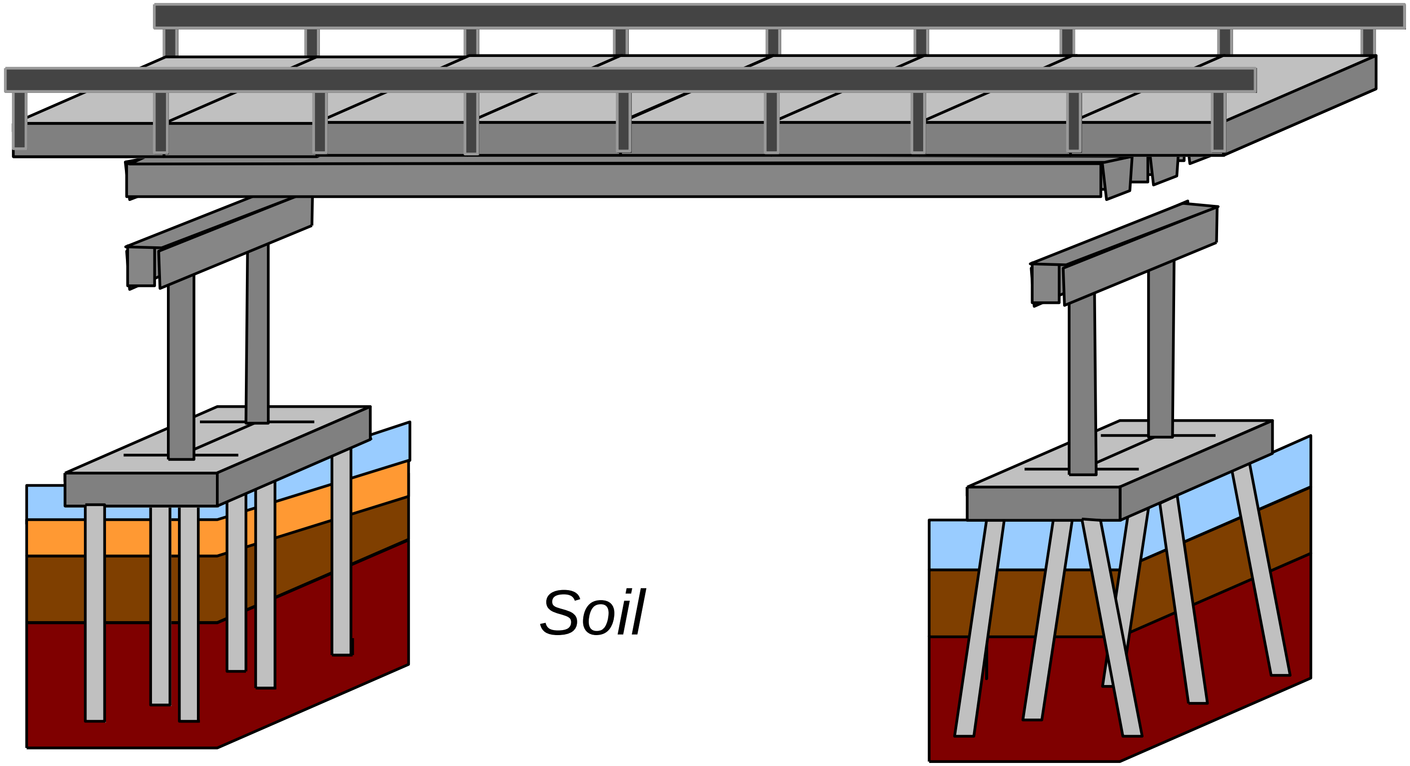
Scour

(Deep Water)

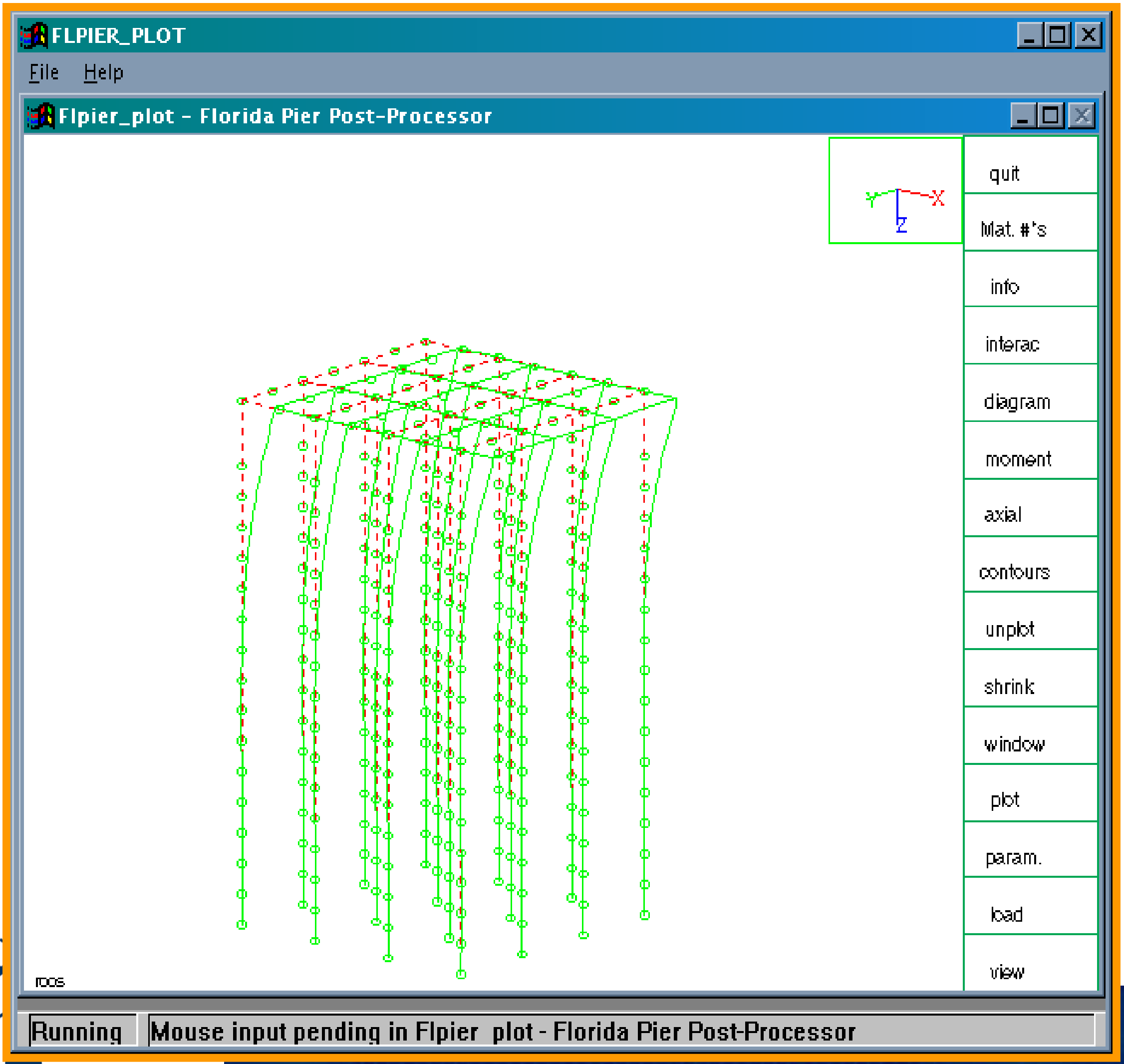
Battered Piles

or Shafts

Coupled Soil-Structure Interaction



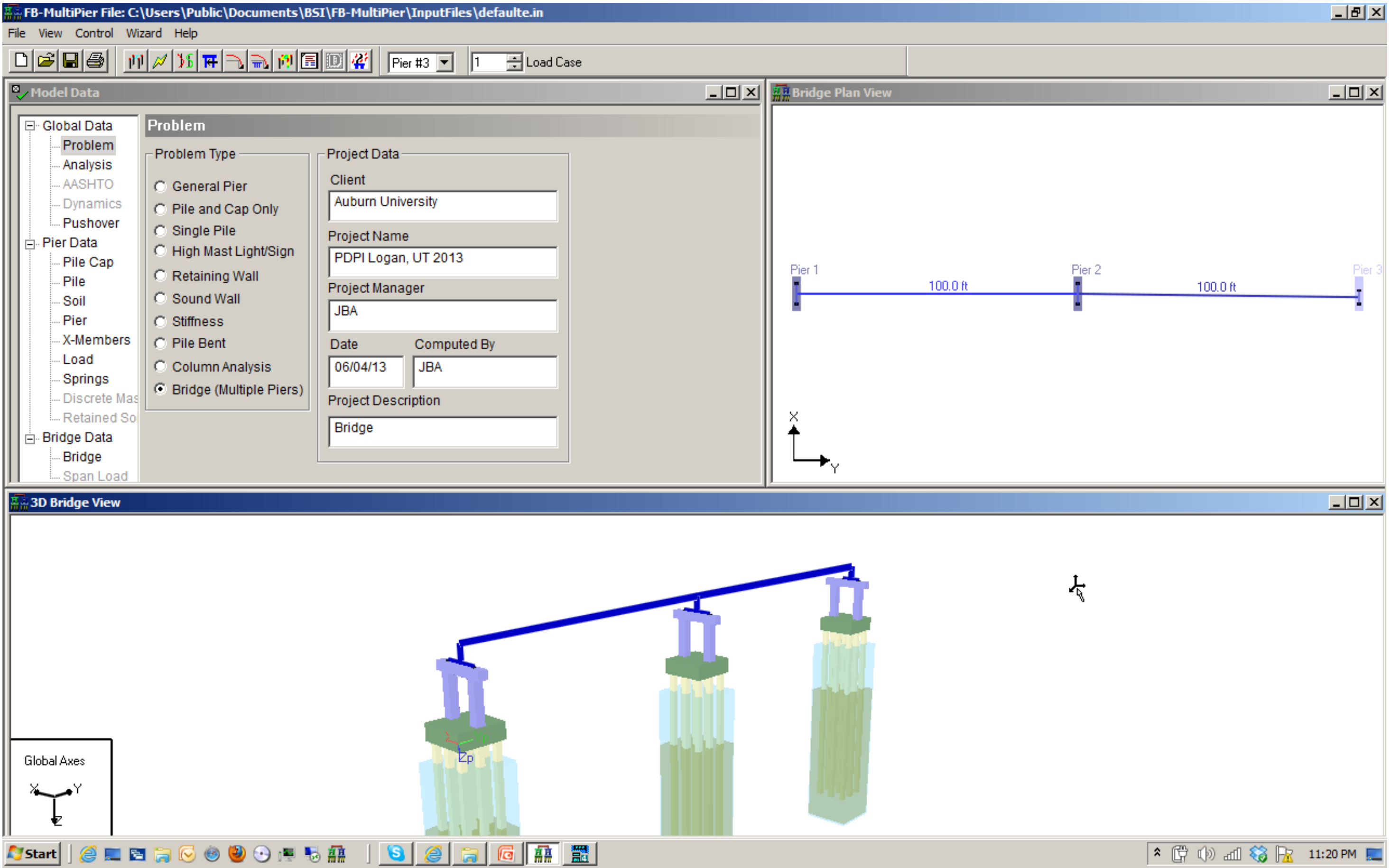
Florida Pier



Running

Mouse input pending in Flpier plot - Florida Pier Post-Processor

FB-MultiPier



FB-MultiPier File: C:\Users\Public\Documents\BSI\FB-MultiPier\InputFiles\defaulte.in

Problem

Problem Type

○ General Pier
○ Pile and Cap Only
○ Single Pile
○ High Mast Light/Sign
○ Retaining Wall
○ Sound Wall
○ Stiffness
○ Pile Bent
○ Column Analysis
● Bridge (Multiple Piers)

Project Data

Client: Auburn University
Project Name: PDPI Logan, UT 2013
Project Manager: JBA
Date: 06/04/13
Computed By: JBA
Project Description: Bridge

Florida Bride Software Institute

- FB-MultiPier and other software for bridge analysis and design developed and supported by BSI
- http://bsi-web.ce.ufl.edu
- Good *educational* discounts (free)

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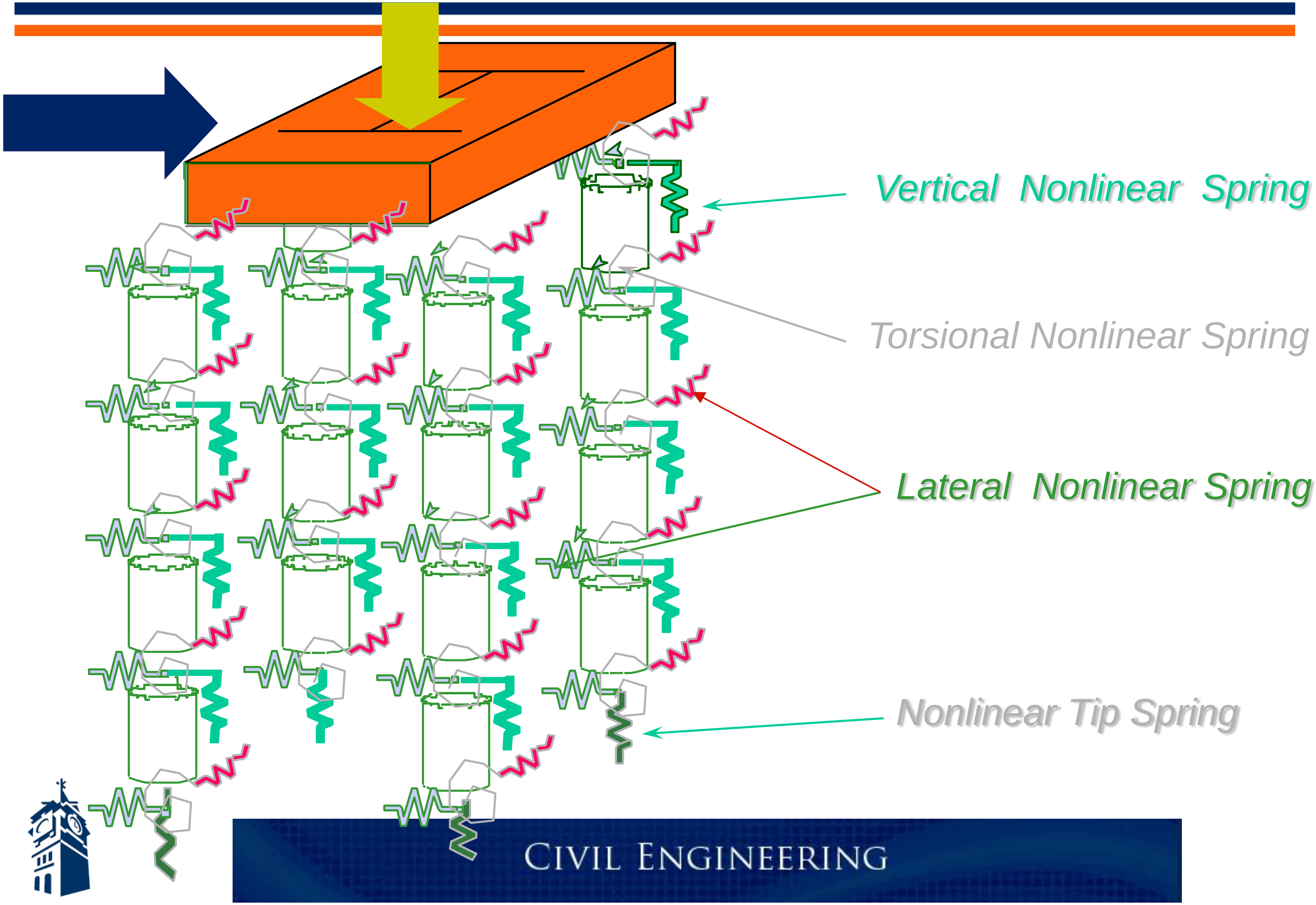
Soil-Structure Interaction



Vertical Nonlinear Spring

Torsional Nonlinear Spring

Lateral Nonlinear Spring

Nonlinear Tip Spring

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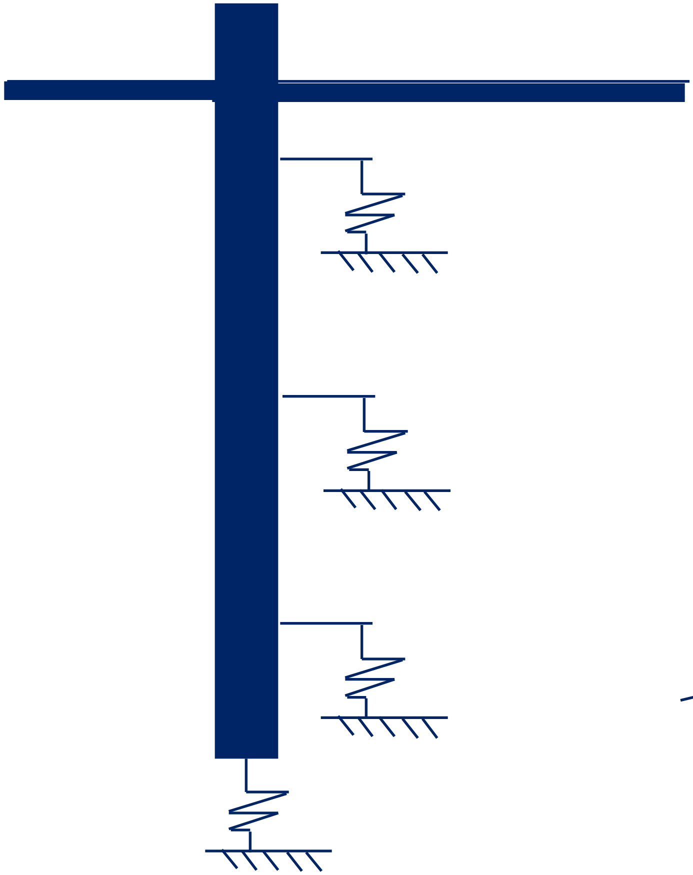
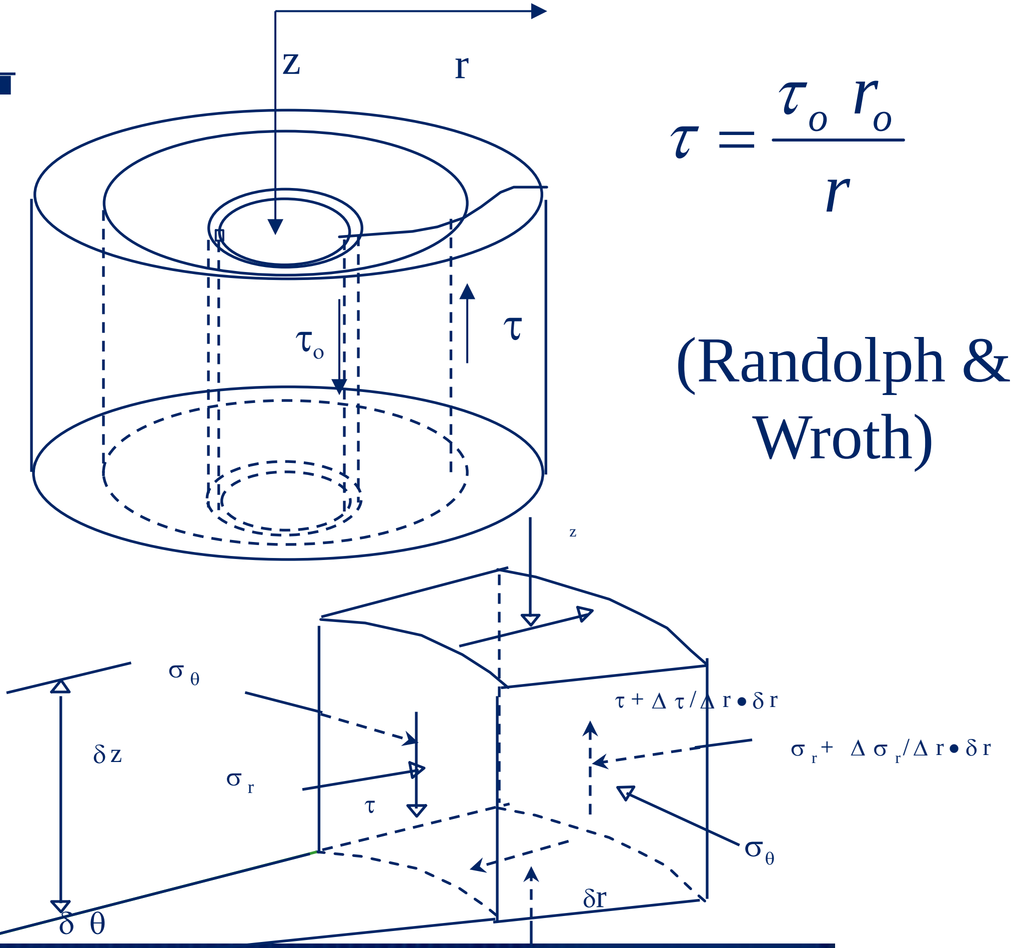
Driven Piles - Axial Side Model

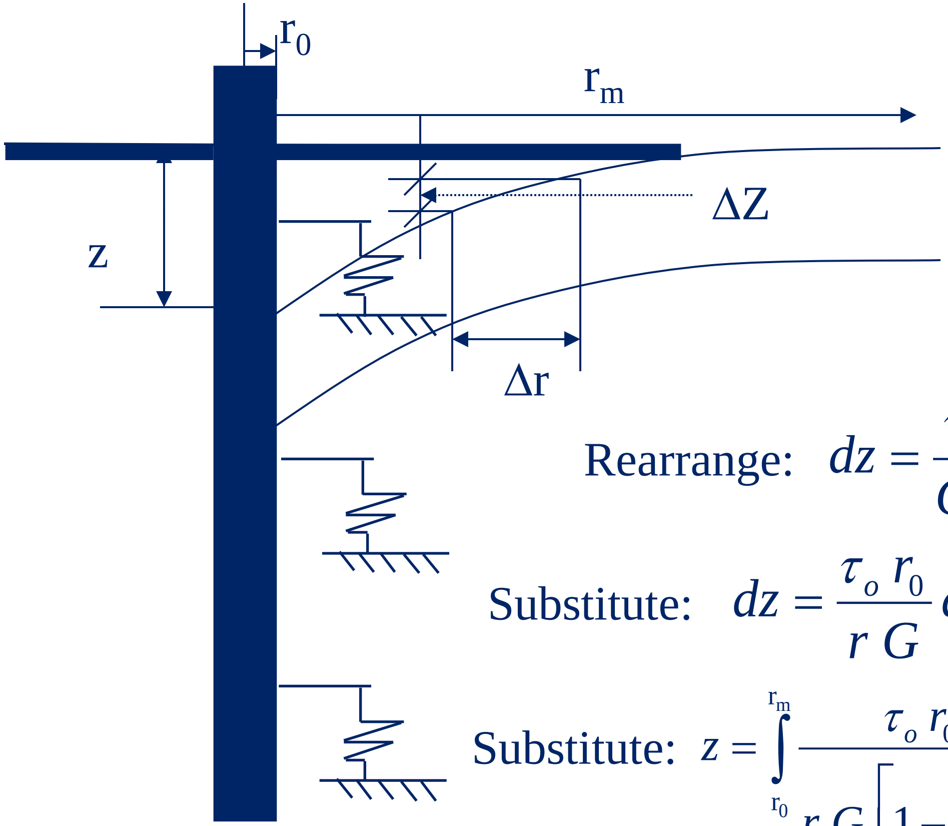




$$\tau = \frac{\tau_o \, r_o}{r}$$

(Randolph & Wroth)

Driven Piles - Axial Side Model



$$\frac{\Delta z}{\Delta r} = \frac{d\,z}{d\,r} = \gamma$$

Also: $$\tau = \gamma\, G$$

Substitute: $$\tau = \frac{d\,z}{d\,r}\, G$$

Rearrange: $$dz = \frac{\tau}{G}\, dr$$

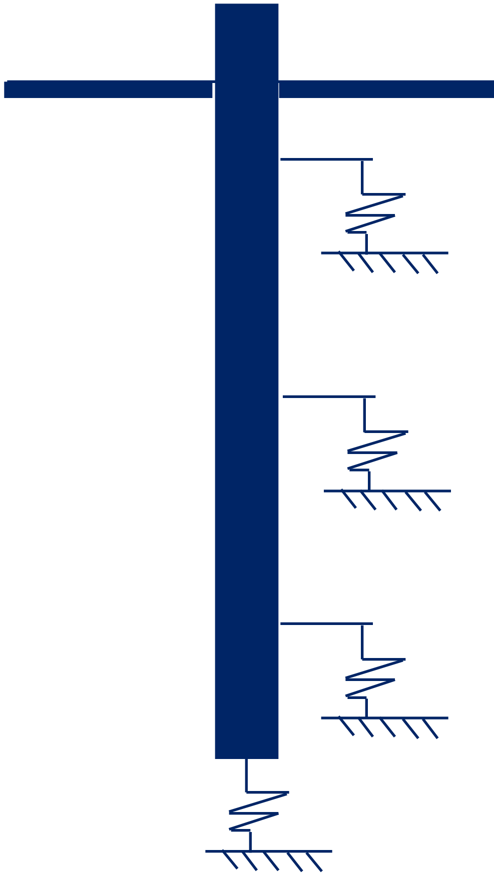
Previous $$\tau = \frac{\tau_o\, r_o}{r}$$

Substitute: $$dz = \frac{\tau_o\, r_0}{r\, G}\, dr$$

Also: $$G = G_i \left[1 - \frac{\tau}{\tau_f}\right]^2$$

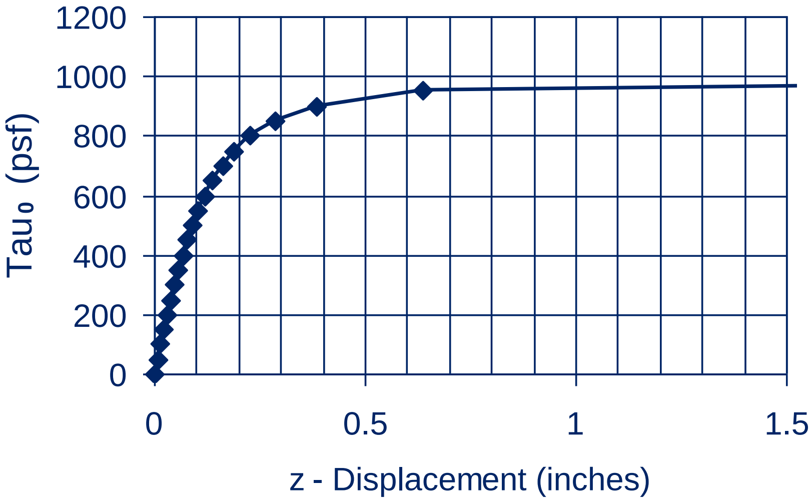
Substitute: $$z = \int_{r_0}^{r_m} \frac{\tau_o\, r_0}{r\, G_i \left[1 - \frac{\tau}{\tau_f}\right]^2}\, dr$$

Driven Piles - Axial Side Model



$$z = \frac{\tau_0 r_0}{G_i}\left[\ln\left(\frac{r_m-\beta}{r_0-\beta}\right)+\frac{\beta\left(r_m-r_0\right)}{\left(r_m-\beta\right)\left(r_0-\beta\right)}\right], \qquad \beta = \frac{r_0\ \tau_0}{\tau_f}$$

T-Z (Along Pile)



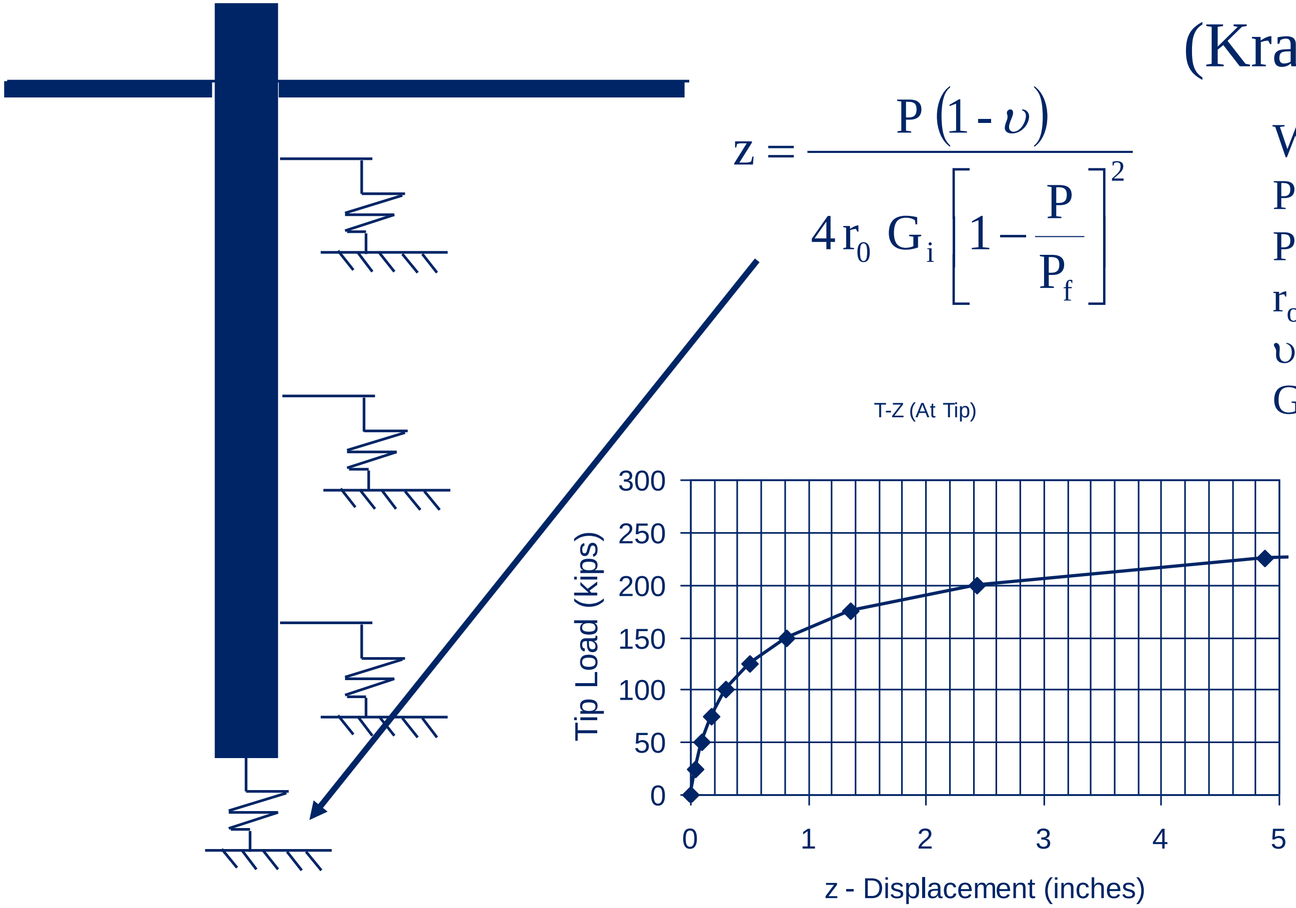
τ_f = 1000psf

G_i = 3 ksi

Driven Piles - Axial Tip Model

(Kraft, Wroth, etc.)

$$z = \frac{P(1-\upsilon)}{4 r_0 \, G_i \left[1 - \frac{P}{P_f}\right]^2}$$



Where:

P = Mobilized Base Load

P_f = Failure Tip Load

r_o = effective pile radius

υ = Poisson ratio of Soil

G_i = Shear Modulus of Soil

P_f = 250 kips

G_i = 10 ksi

υ = 0.3

r_0 = 12 inches

Driven Piles - Axial Properties

- Ultimate Skin Friction (stress), Tau_f , along side of pile (input in layers).
- Ultimate Tip Resistance (Force), P_f , at pile tip .
- Compressibility of individual soil layers, I.e. Shear Modulus, G_i , and Poisson’s ratio, ν .

Driven Piles - Axial Properties

- From Insitu Data:
  - Using SPT “N” Values run SPT97, DRIVEN, UNIPILE, etc. to Obtain: Tau_f , and P_f
  - Using Electric Cone Data run PL-AID, LPC, FHWA etc. to Obtain: Tau_f , and P_f
  - Determine G or E from SPT correlations, i.e. Mayne, O’Neill, etc.

Florida: SPT 97 Concrete Piles

Skin Friction, τ_f (TSF)

- Plastic Clay:
  - $\tau_f = 2N(110-N)/4006$
- Sand, Silt Clay Mix:
  - $\tau_f = 2N(110-N)/4583$
- Clean Sand:
  - $\tau_f = 0.019N$
- Soft Limestone
  - $\tau_f = 0.01N$

Ultimate Tip, P_f/Area(tsf)

- Plastic Clay:
  - $q = 0.7\ N$
- Sand, Silt Clay Mix:
  - $q = 1.6\ N$
- Clean Sand:
  - $q = 3.2\ N$
- Soft Limestone
  - $q = 3.6\ N$

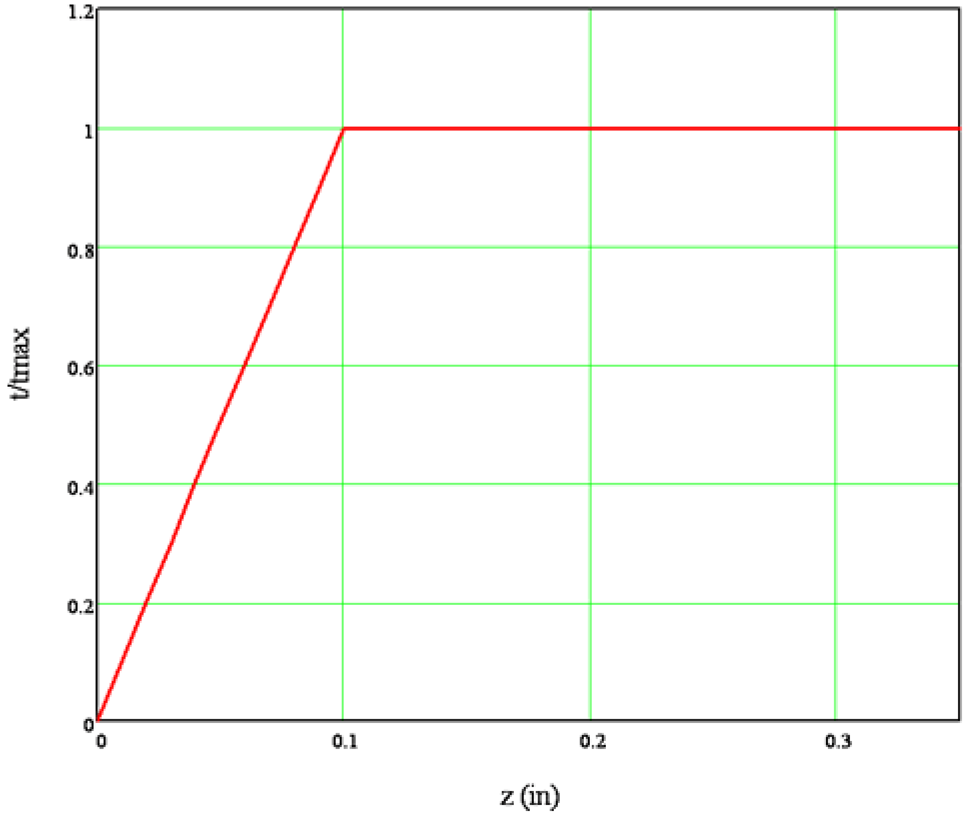
API Side Friction Model - Sand

- $\tau_f = K\, p'_0 \tan \delta$

where

- k = dimensionless coefficient of lateral earth pressure (ratio of horizontal to vertical normal effective stress(for unplugged K=0.8 and for plugged K=1.0)
- p'_0 = effective overburden pressure in stress units
- δ = friction angle between the soil and pile wall, which is defined as $\delta = \phi - 5^o$

API Side Friction Model - Sand



z (in)	t/t_{max}
0.00	0.00
0.10	1.00
∞	1.00

API Side Friction Model - Clay

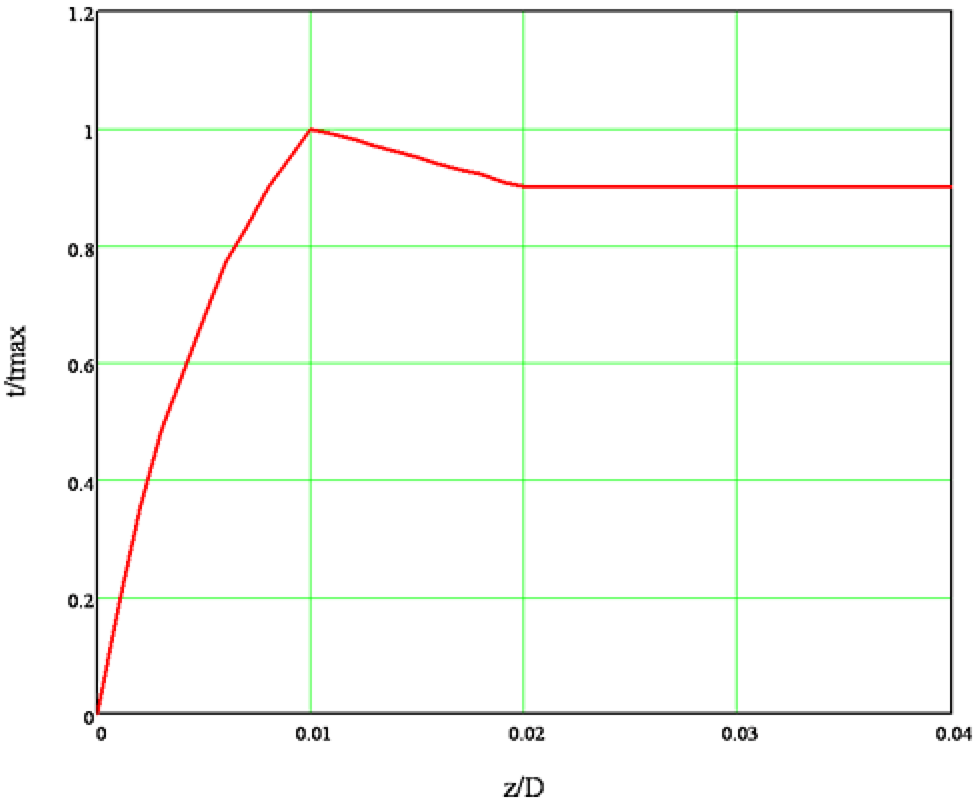
- $\tau_f = \alpha c_u$

where

- c_u = undrained shear strength
- α = a dimensionless factor, which is defined as
  - $\alpha = 0.5\Psi^{-0.5} \leq 1.0$ for $\Psi \leq 1.0$
  - $\alpha = 0.5\Psi^{-0.25} \leq 1.0$ for $\Psi > 1.0$

  $\Psi = c_u/p'_0$

API Side Friction Model - Clay



z/D	t/t_{max}
0.0016	0.30
0.0031	0.50
0.0057	0.75
0.0080	0.90
0.0100	1.00
0.0200	0.90
∞	0.90

API Tip Model - Sand

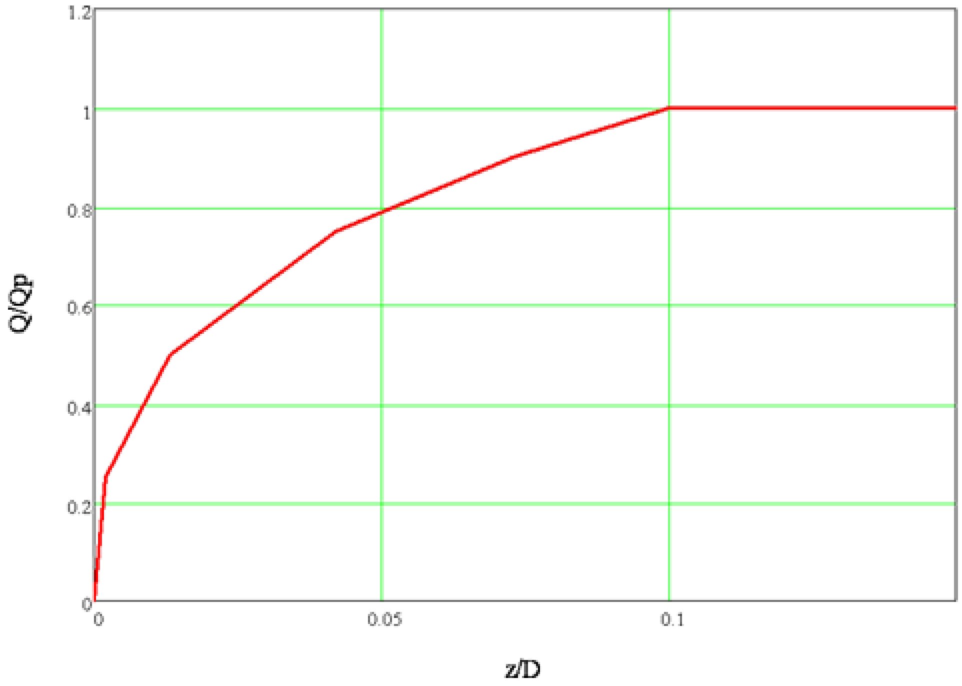
- $q = p'_0 \, N_q$

where

  - p'_0 = effective overburden pressure in stress units
  - $N_q = e^{\pi \tan(\phi')} \tan^2(45 + \phi'/2)$

- $Q_p = qA$
- Where
  - Qp is the total end bearing capacity
  - A is the cross sectional area

API Tip Model Sand



z/D	Q/Q_p
0.002	0.25
0.013	0.50
0.042	0.75
0.073	0.90
0.100	1.00
∞	1.00

API Tip Model - Clay

- $q = 9c_u$

where

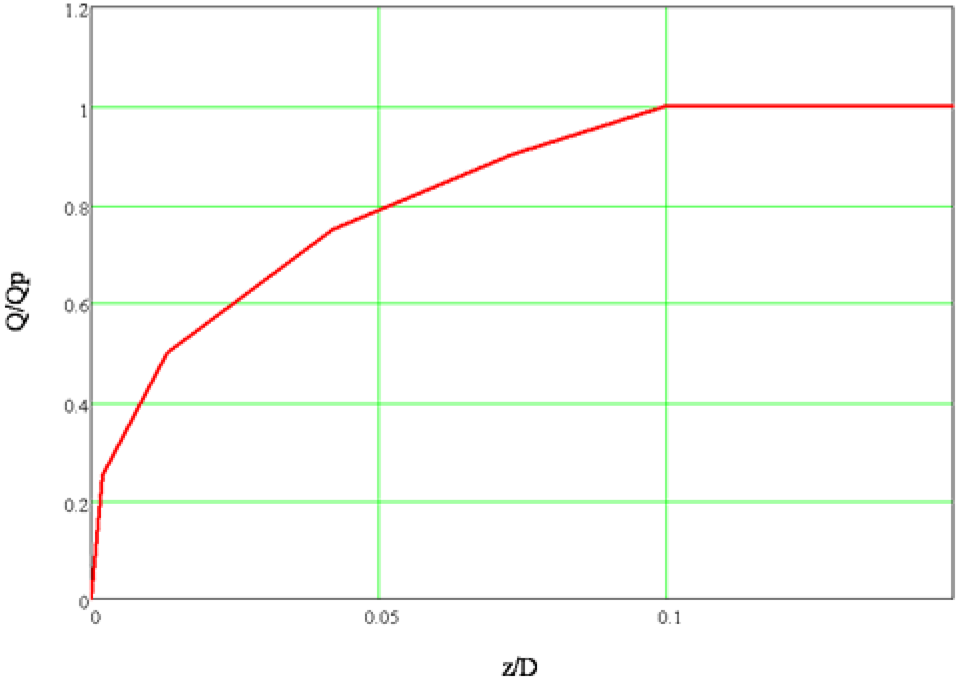
- c_u = undrained shear strength

- $Q_p = qA$

where

  - Qp is the total end bearing capacity
  - A is the cross sectional area

API Tip Model Clay

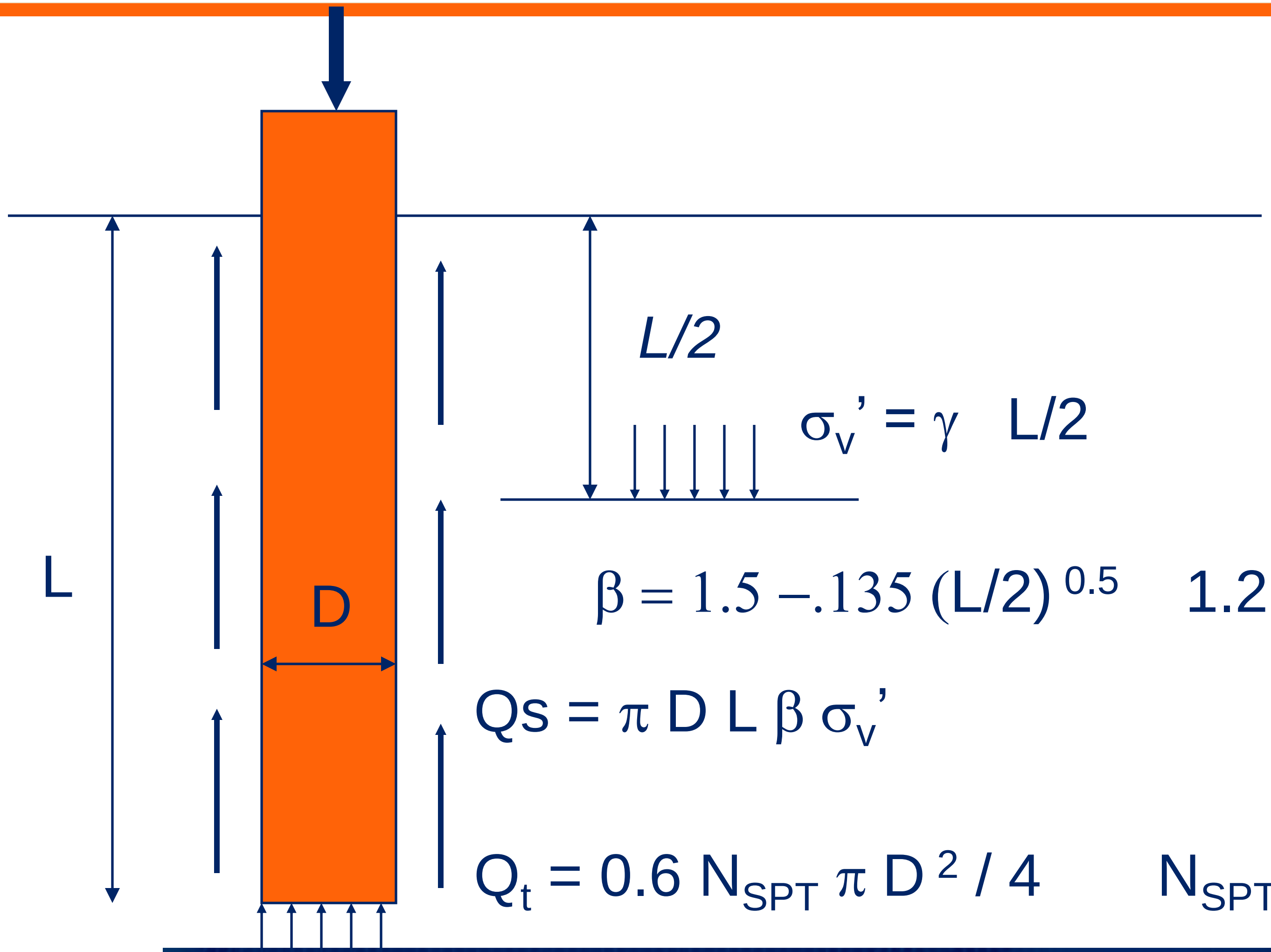


z/D	Q/Q_p
0.002	0.25
0.013	0.50
0.042	0.75
0.073	0.90
0.100	1.00
∞	1.00

Cast Insitu Axial Side and Tip Models

- For soil (sands and clays)
  - Follow FHWA Drilled Shaft Manual For Sands and Clays to Obtain Tau_f and P_f (γ and c_u)
  - Shape of T-Z cuve is given by FHWA's Trend Lines.
- User has Option of inputting custom T-z / Q-z curves

Cast Insitu - Sand (FHWA):



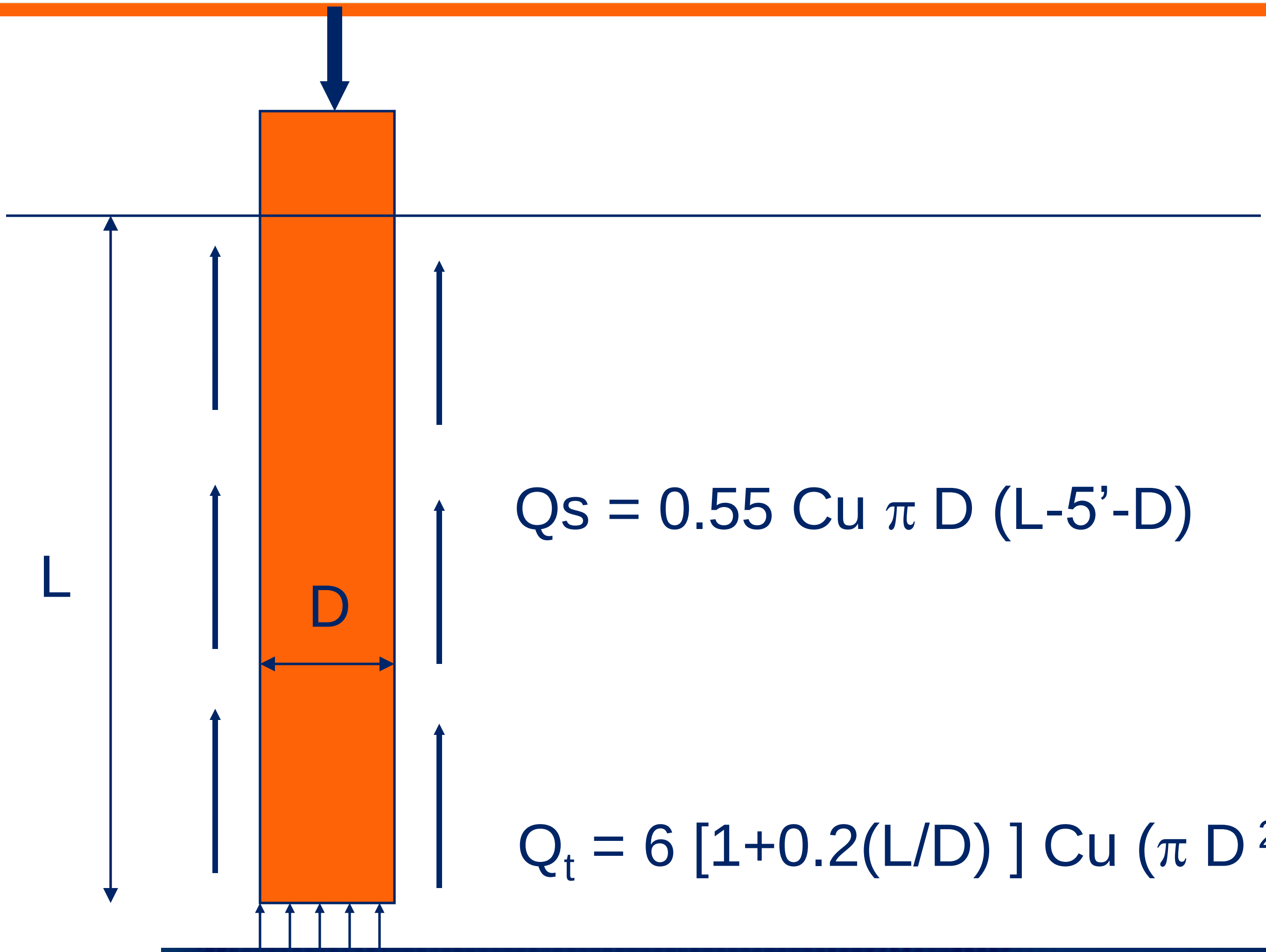
$\sigma_v' = \gamma \quad L/2$

$\beta = 1.5 - .135\,(L/2)^{0.5} \qquad 1.2 > \beta > 0.25$

$Qs = \pi\, D\, L\, \beta\, \sigma_v'$

$Q_t = 0.6\, N_{SPT}\, \pi\, D^2 / 4 \qquad N_{SPT} < 75$

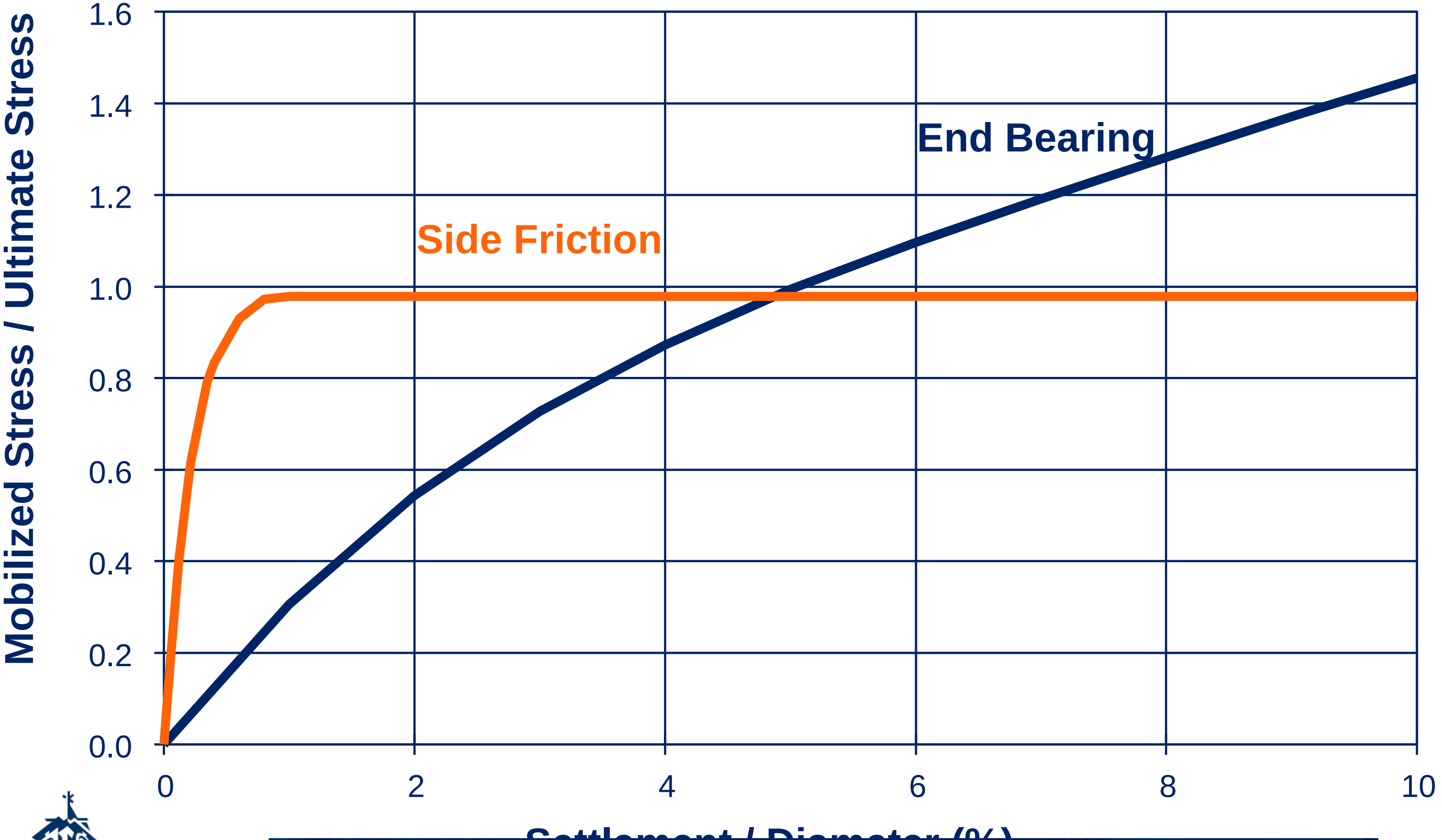
Cast Insitu - Clay (FHWA):



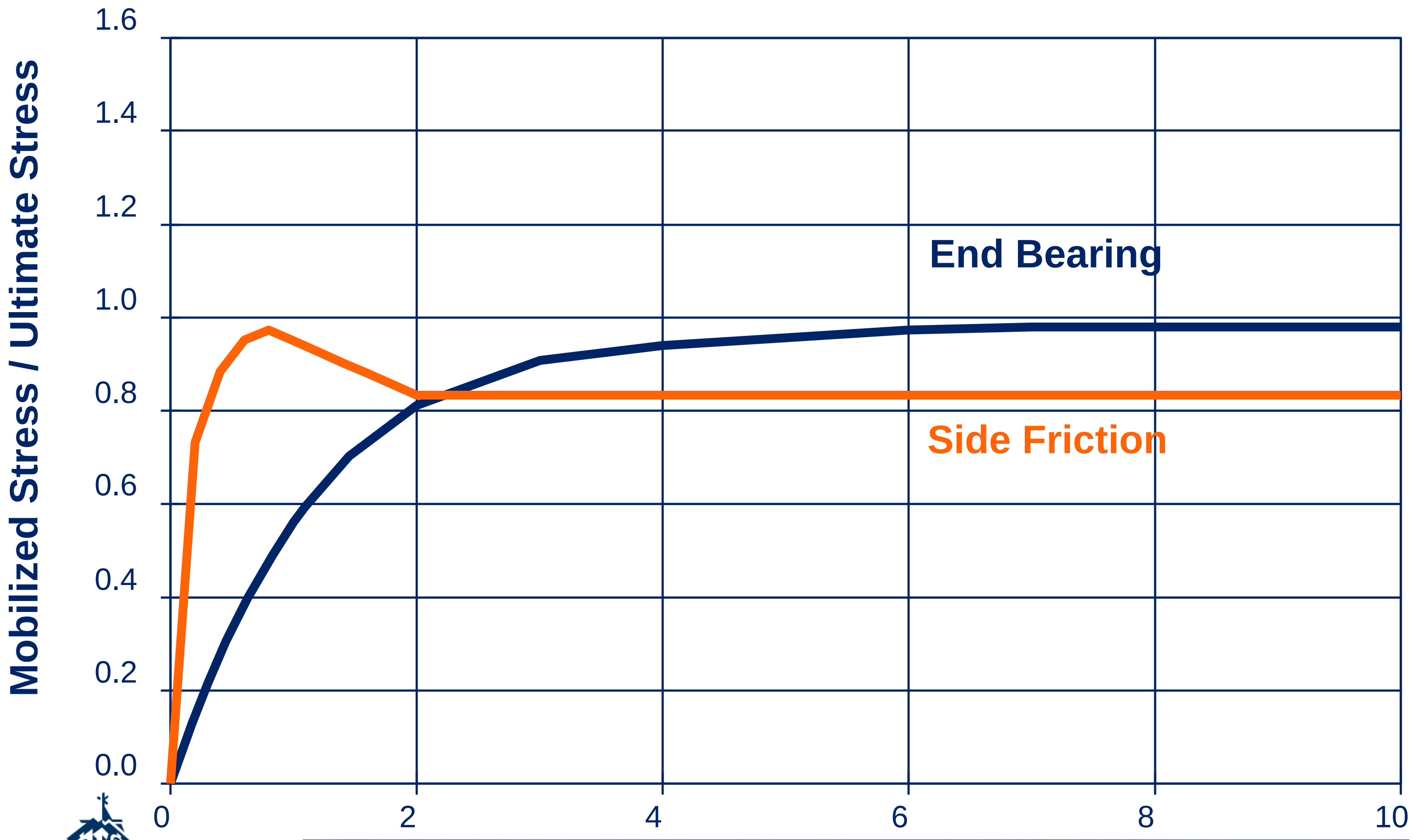
$Qs = 0.55\ Cu\ \pi\ D\ (L\text{-}5'\text{-}D)$

$Q_t = 6\ [1+0.2(L/D)\ ]\ Cu\ (\pi\ D^2\ /\ 4)$

Cast Insitu trend line for Sand



Cast Insitu trend line for Clay



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  - – Precast & Cast Insitu Axial T-Z & Q-Z Models
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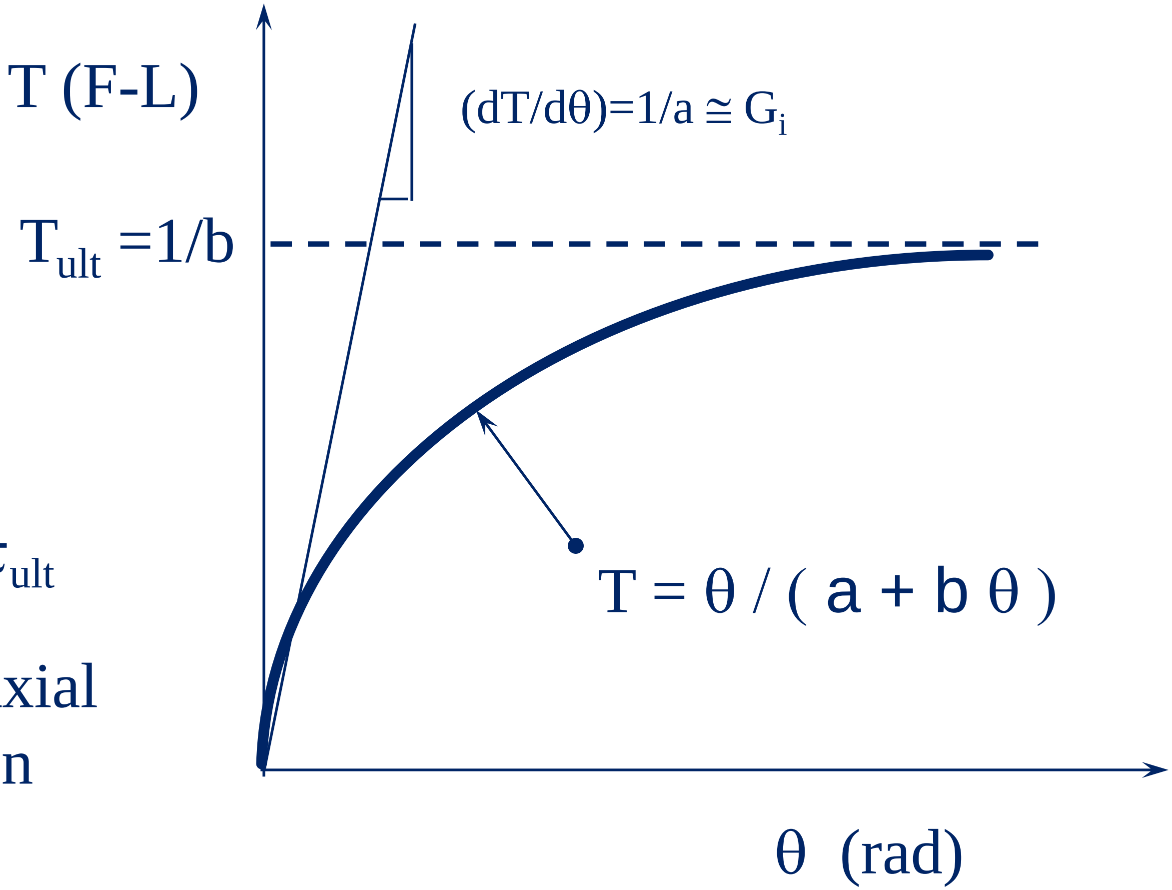
Torsional Model (Pile/Shaft)

- Hyperbolic Model
  - G and Tau$_f$
- Custom T-θ

Torsional Model (Pile/Shaft)



$T_{ult} = \tau_f A_{surf}\, r$

$T_{ult} = 2\pi r^2 \Delta L\, \tau_{ult}$

τ_{ult} = Ultimate Axial Skin Friction (stress)

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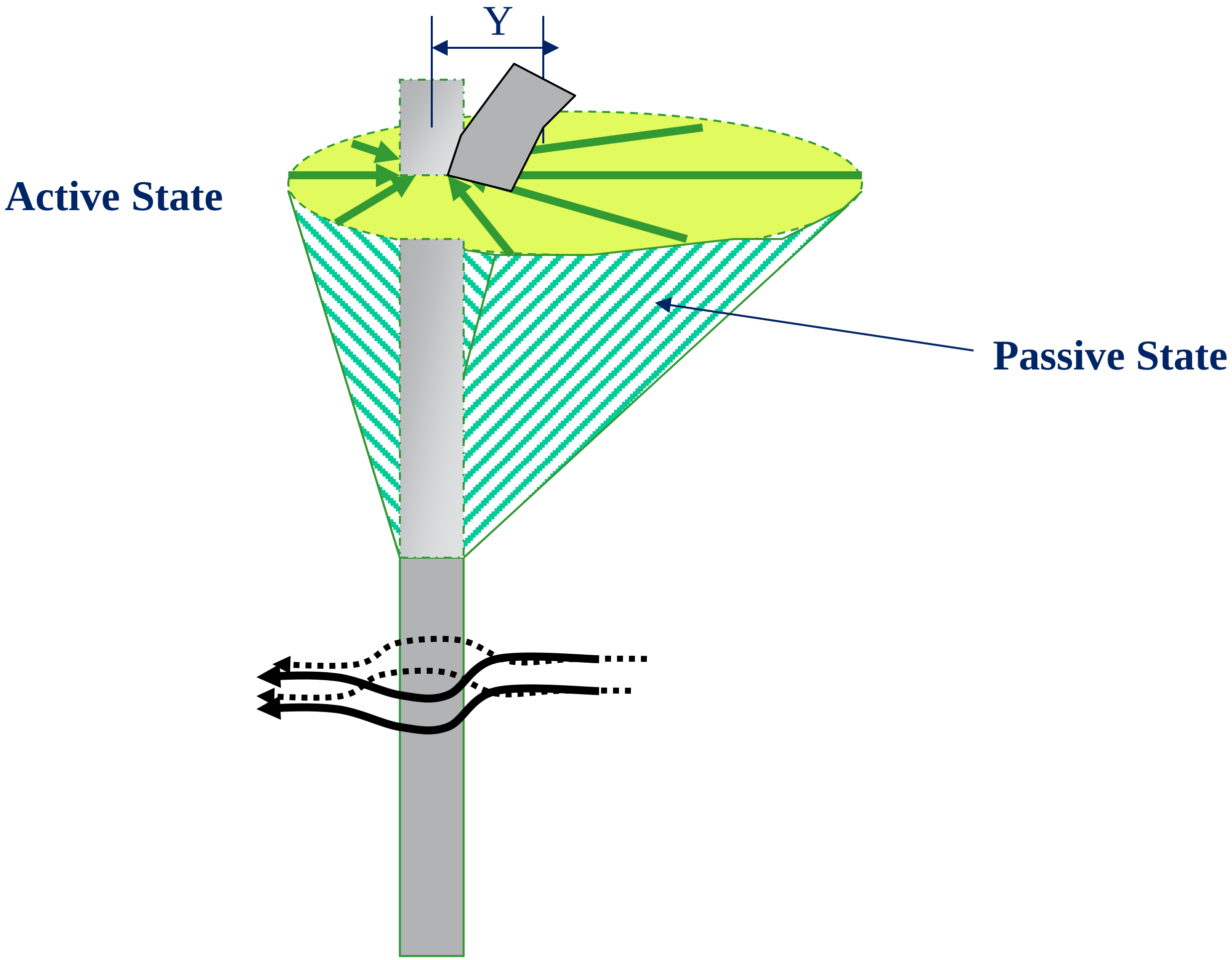
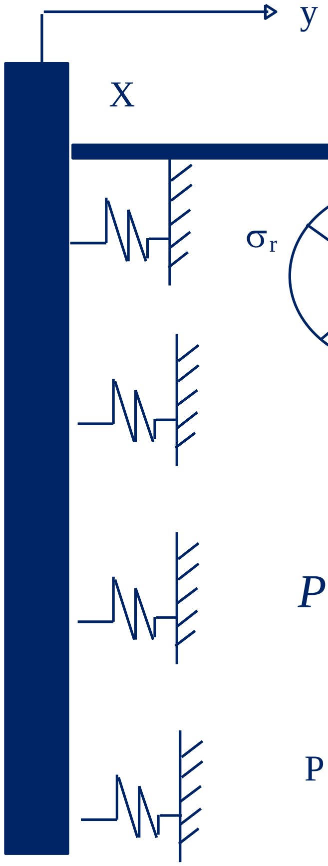
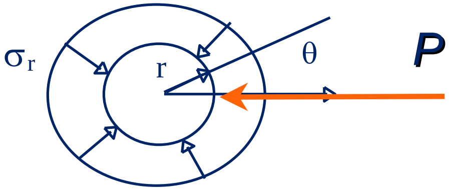
Lateral Soil-Structure Interaction



Near Field: Lateral (Piles/Shafts)

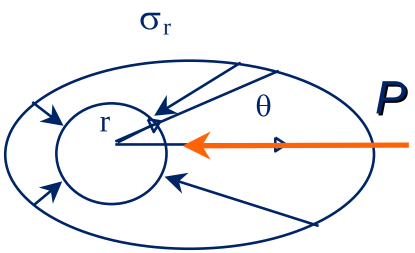




Y=0

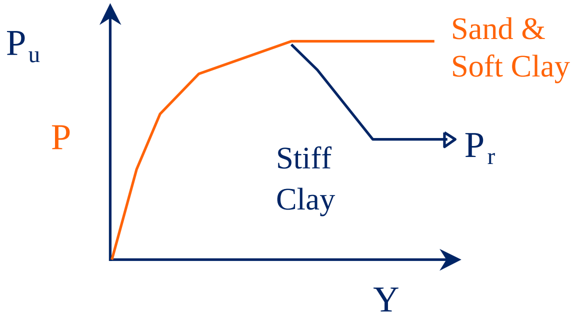
$$P\left(\frac{F}{L}\right)=\int_{0}^{2\pi}\sigma_r\, r\, d\theta$$

P = 0



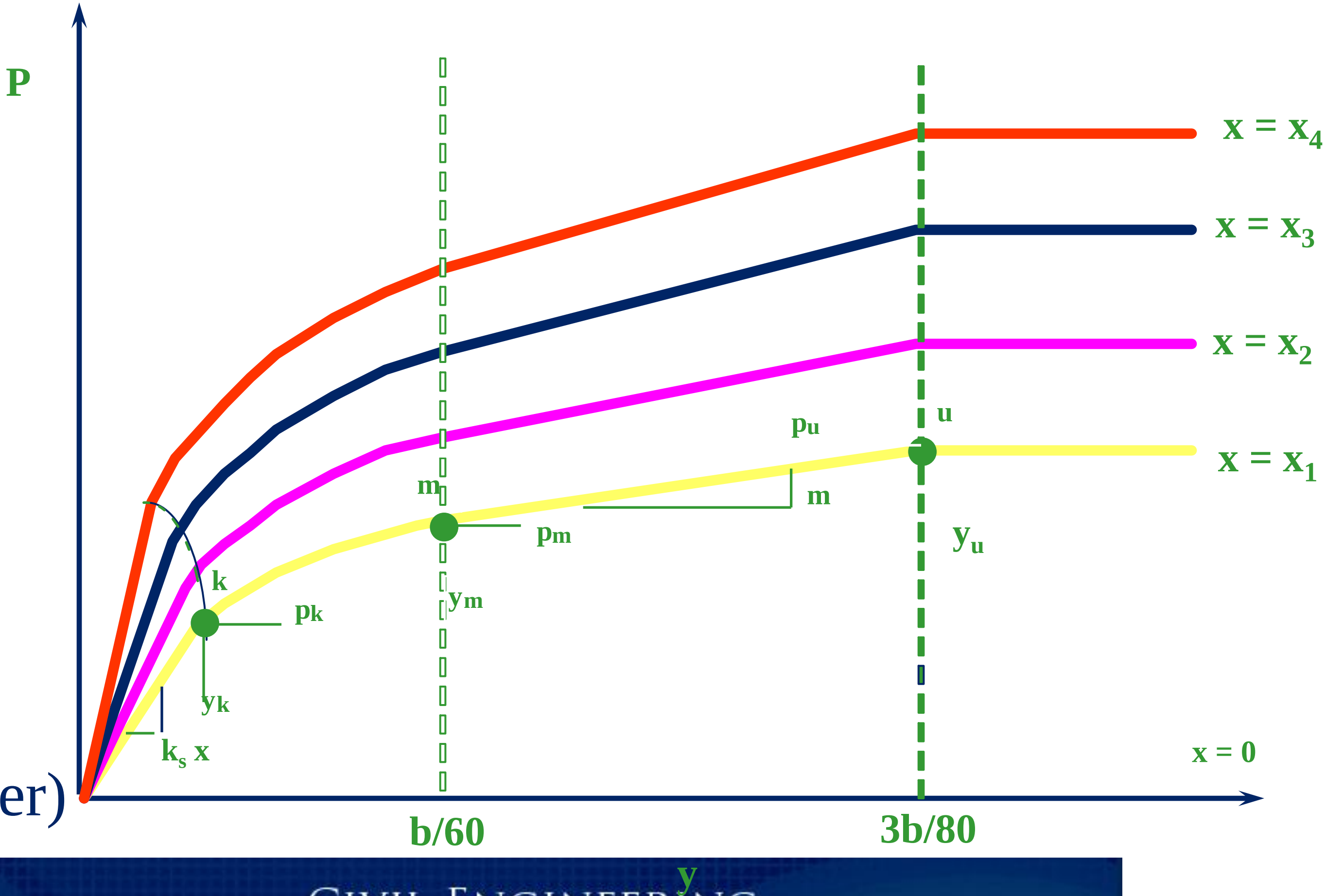
Y=5”

$$P\left(\frac{F}{L}\right)=\int_{0}^{2\pi}\sigma_r\, r\, d\theta$$



P-y Curves - Reese’s Sand

Pu is a function of ϕ, γ, and b



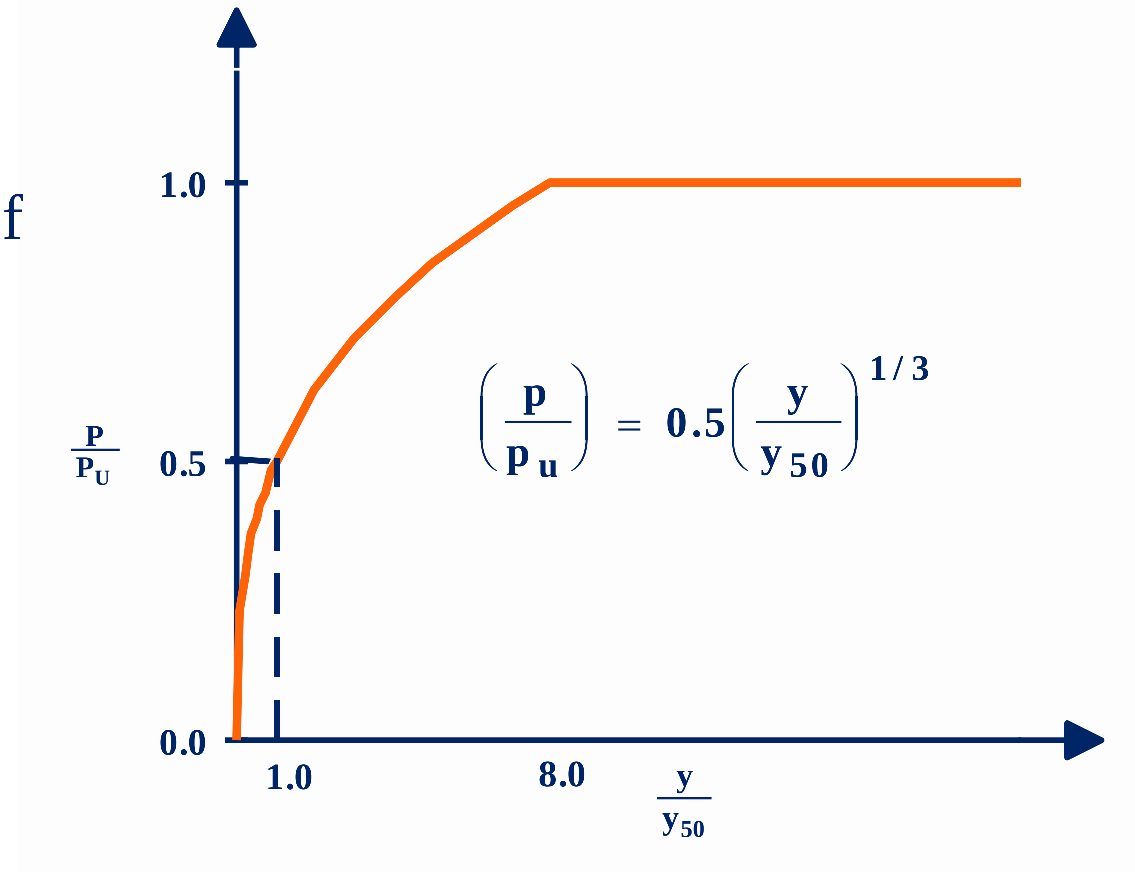
Y is a function of b (pile diameter)

Matlock's Soft Clay

Pu is a function of C_u, γ, and b

Y is a function of

y_{50} (ε_{50})



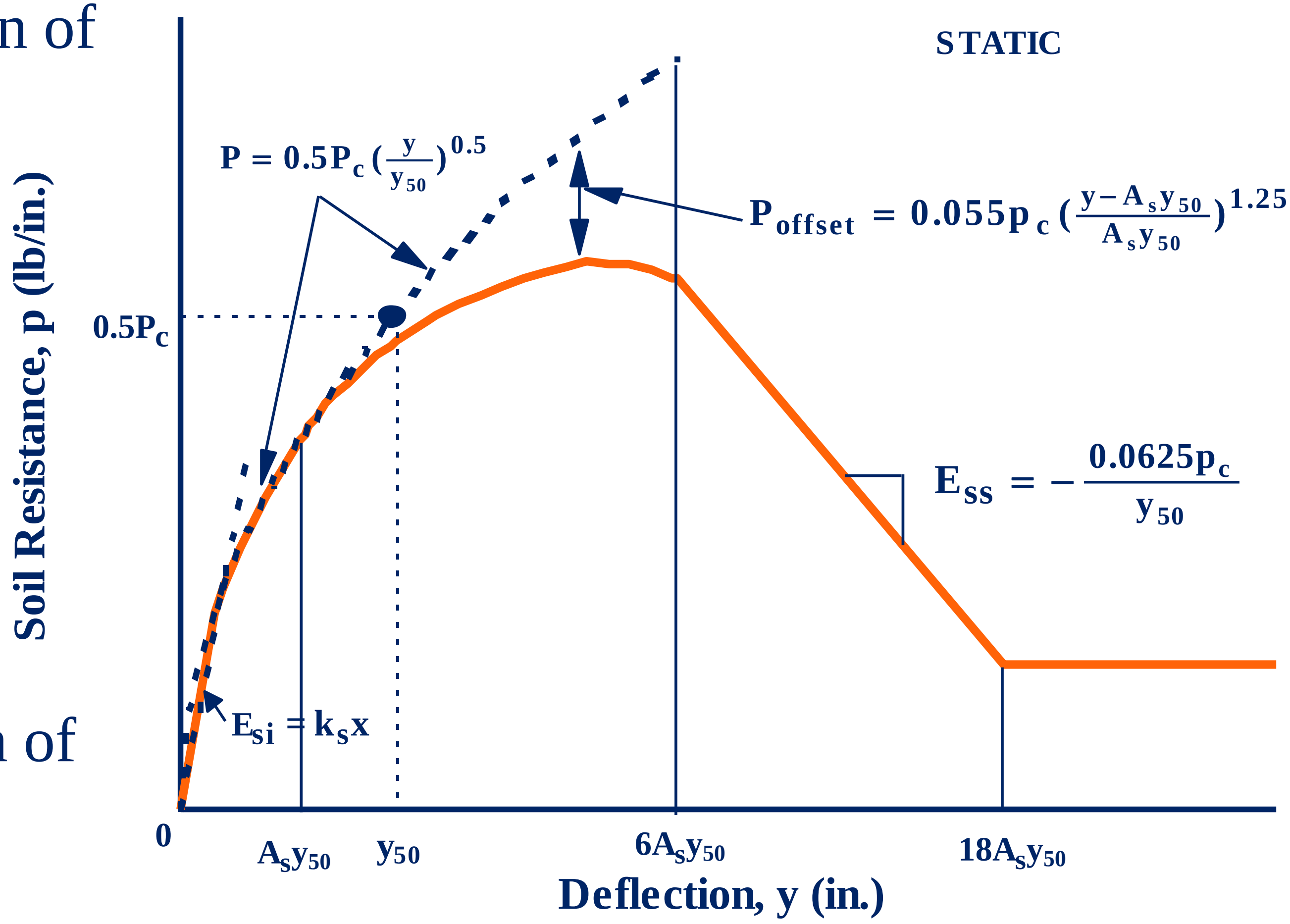
$$\left(\frac{p}{p_u}\right) = 0.5\left(\frac{y}{y_{50}}\right)^{1/3}$$

Reese's Stiff Clay Below Water

Pc is a function of C, γ, k_s and b

Y is a function of

y_{50} (ε_{50})



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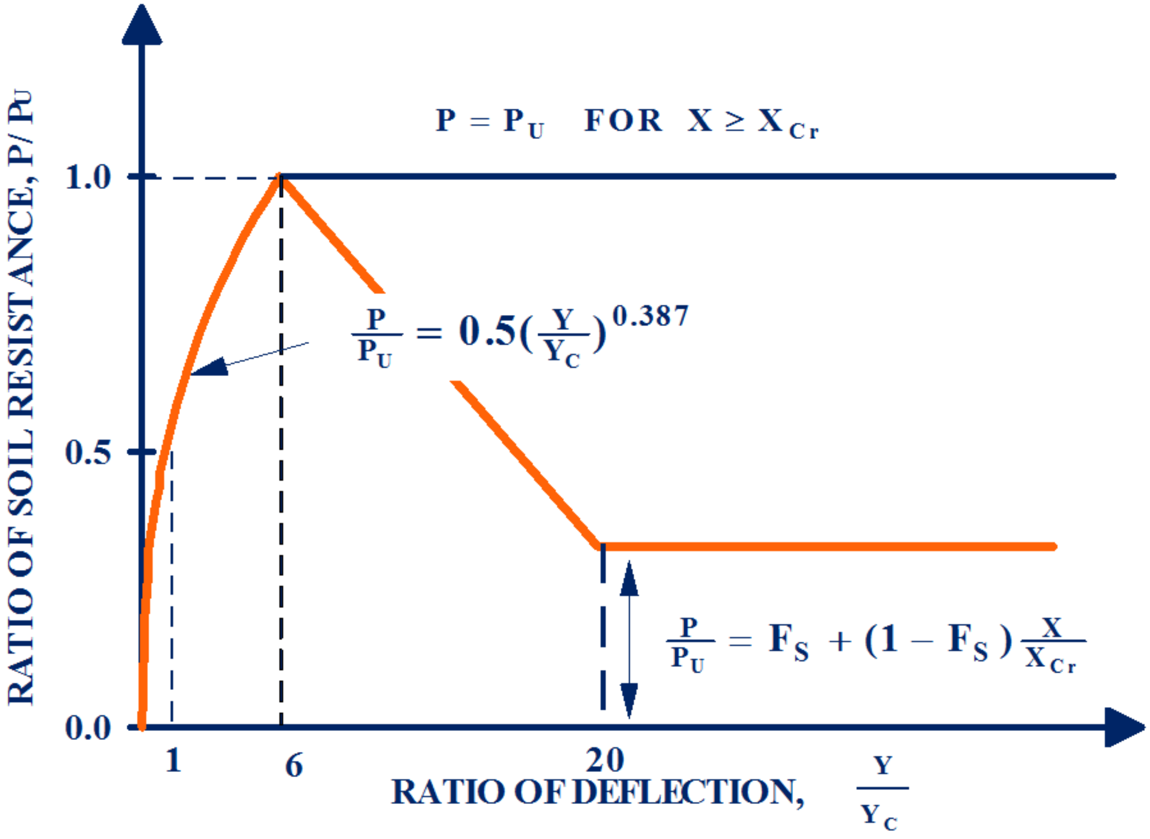
O’Neill’s Integrated Clay

Pu is a func
c, and b



F_s is a funct

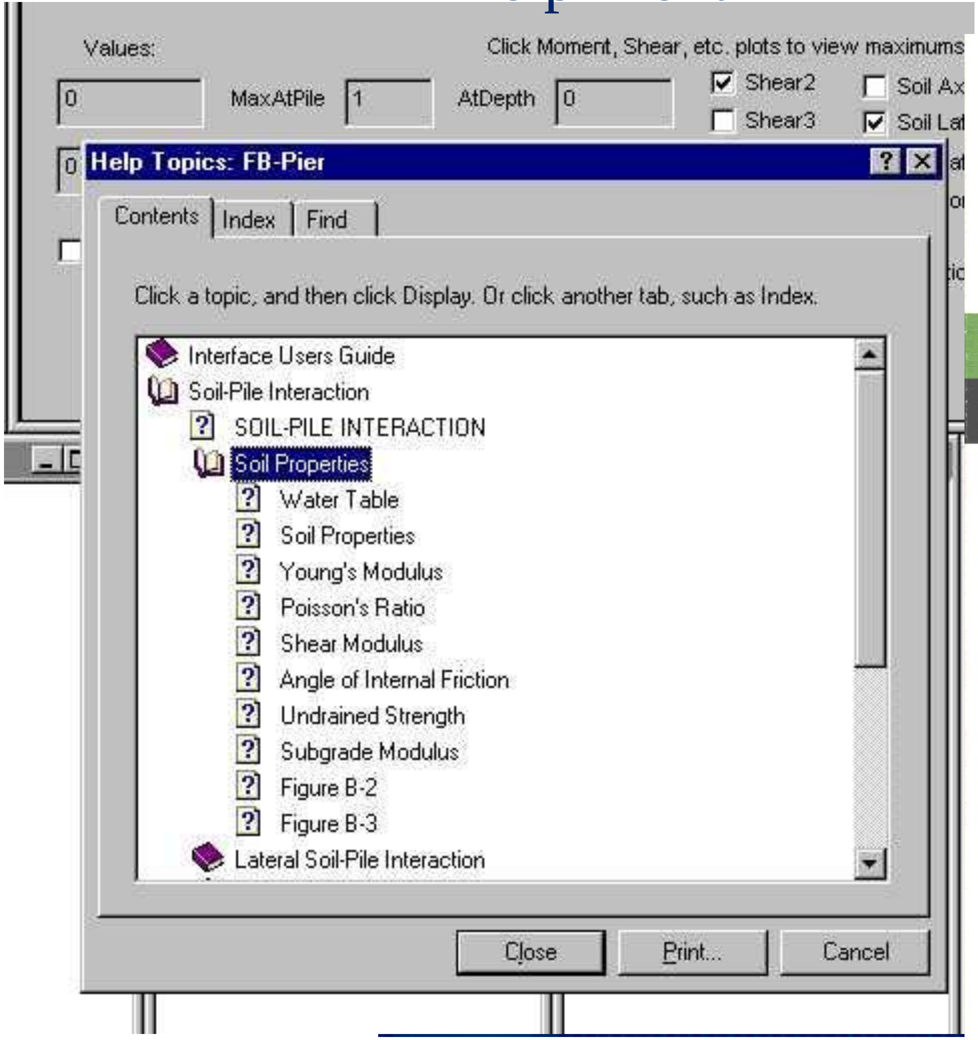
Y_c is a function of b and ε_{50}

Soil Properties for Standard Curves

- Sand:
  - Angle of internal friction, $\boldsymbol{\phi}$
  - Total unit weight, γ
  - Modulus of Subgrade Reaction, k
- Clay or Rock:
  - Undrained Strength, Cu
  - Total Unit Weight, γ
  - Strain at 50% of Failure Stress, $\boldsymbol{\varepsilon}_{50}$
  - Optional: k, and $\boldsymbol{\varepsilon}_{100}$

Soil Information

Help Menu



Values:

Click Moment, Shear, etc. plots to view maximums

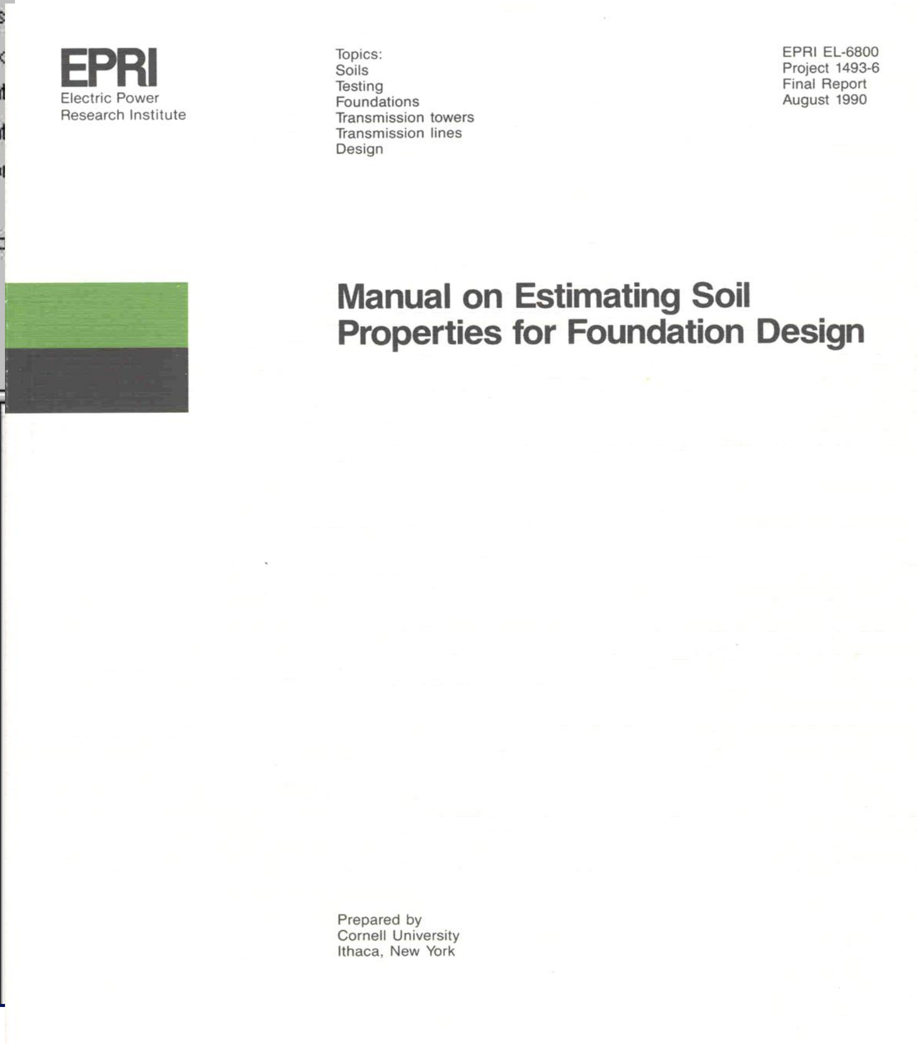
0 MaxAtPile 1 AtDepth 0

☑ Shear2 ☐ Shear3 ☐ Soil Ax ☑ Soil Lat

Help Topics: FB-Pier

Click a topic, and then click Display. Or click another tab, such as Index.

EPRI (Kulhawy & Mayne)



EPRI
Electric Power
Research Institute

Topics:
Soils
Testing
Foundations
Transmission towers
Transmission lines
Design

EPRI EL-6800
Project 1493-6
Final Report
August 1990

Manual on Estimating Soil Properties for Foundation Design

Prepared by
Cornell University
Ithaca, New York

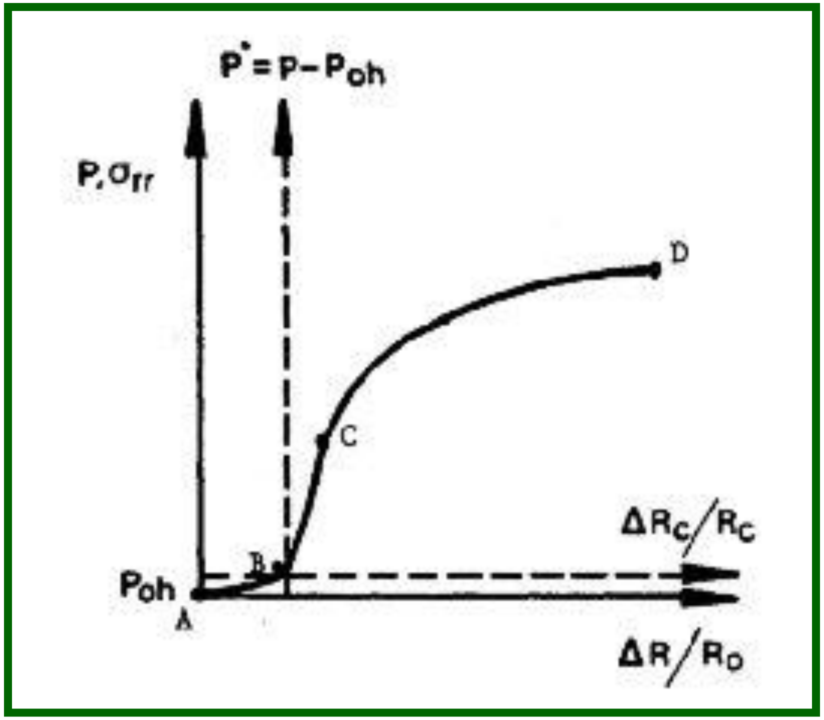
P-y Curves from Insitu Tests

- Cone Pressuremeter
- Marchetti Dilatometer

Insitu PMT & DMT Testing

ENGINEERING

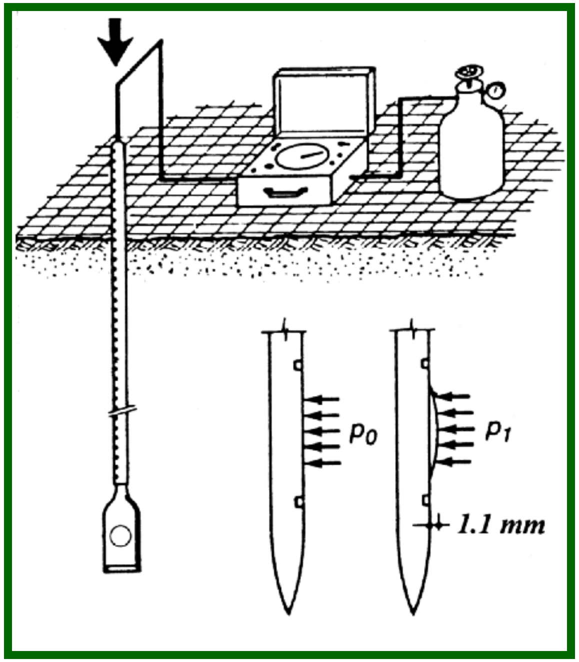
Cone Pressuremeter

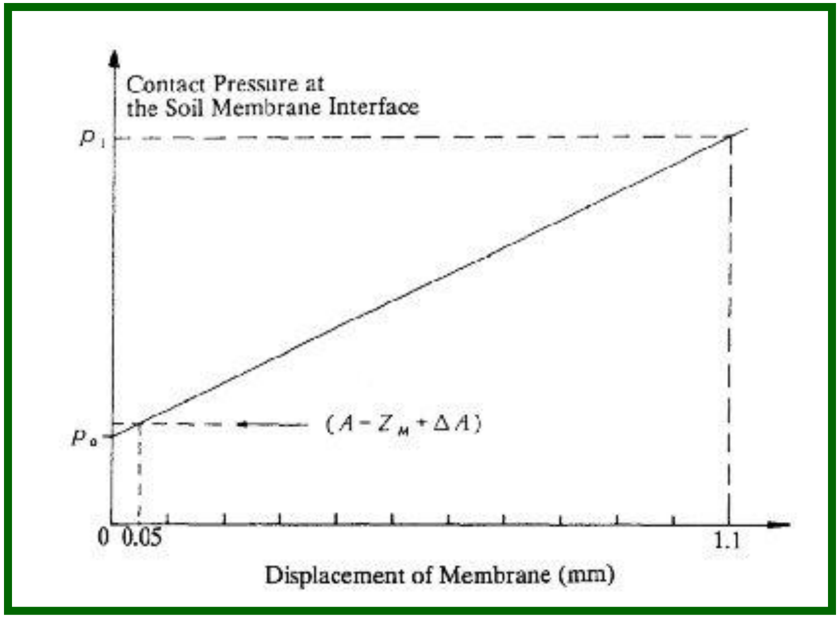


Cone Pressuremeter

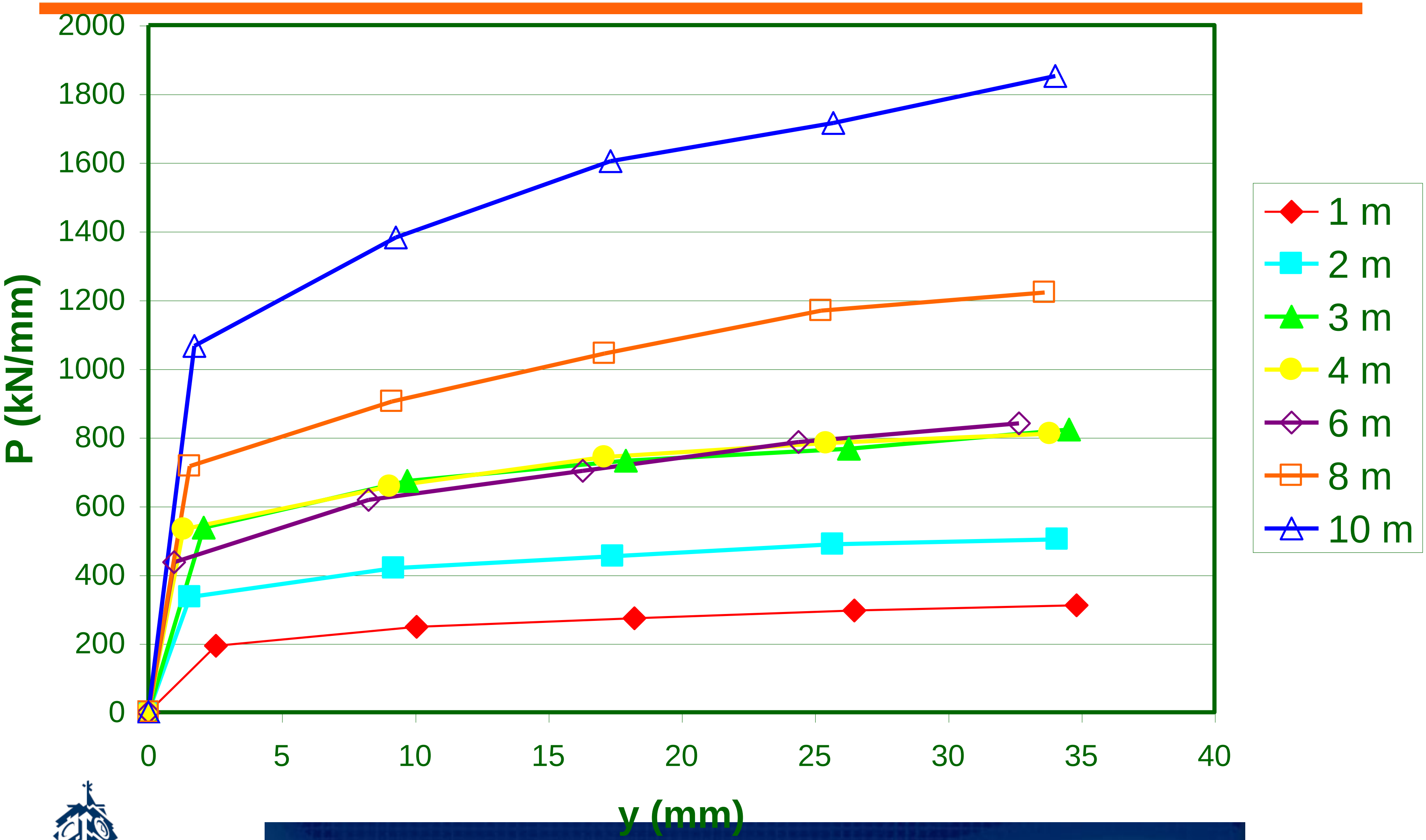
(Robertson, Briaud, etc.)

Marchetti Dilatometer



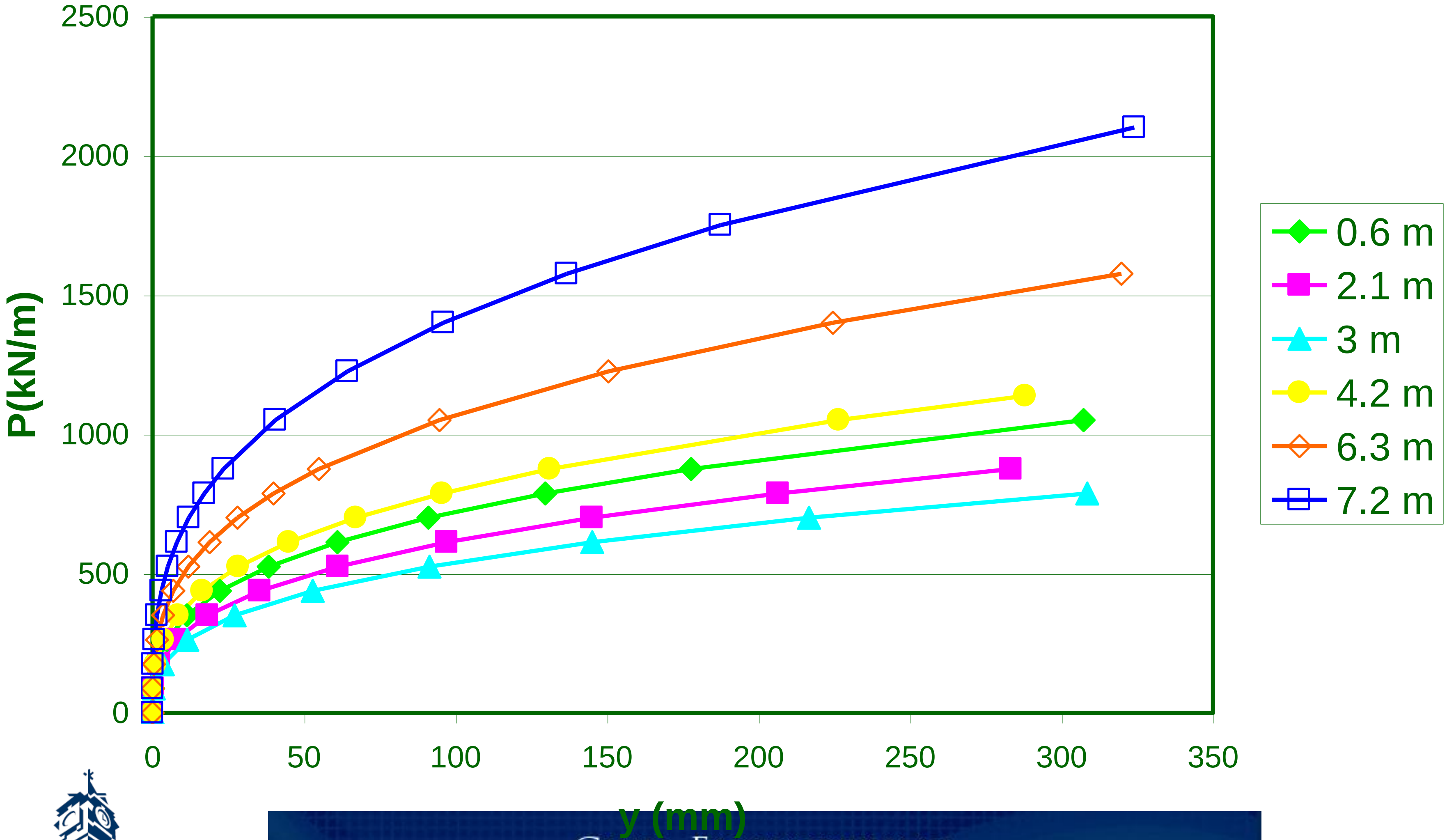


PMT P-y Curves - Auburn



Civil Engineering

DMT P-y Curves - Auburn



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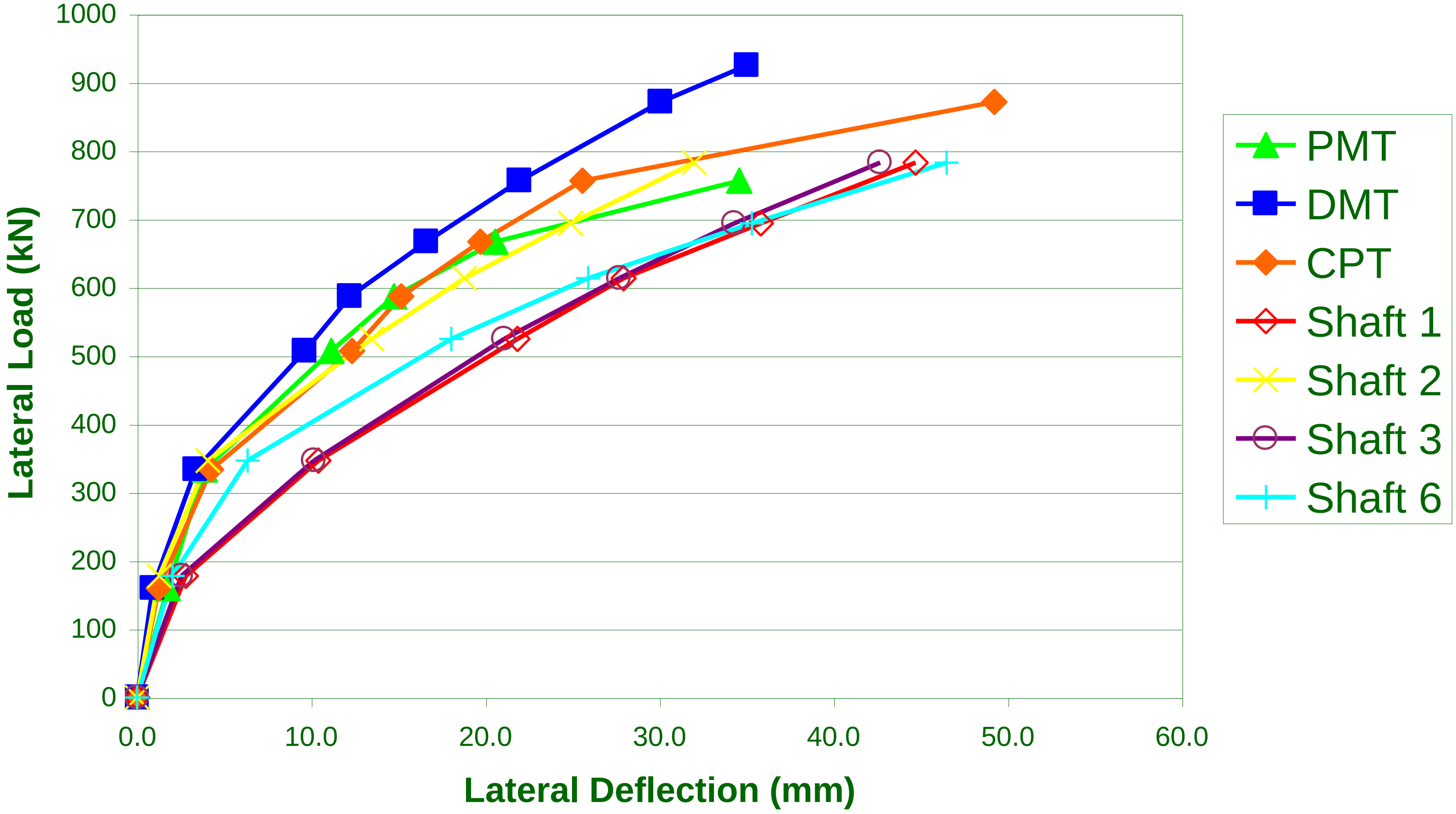
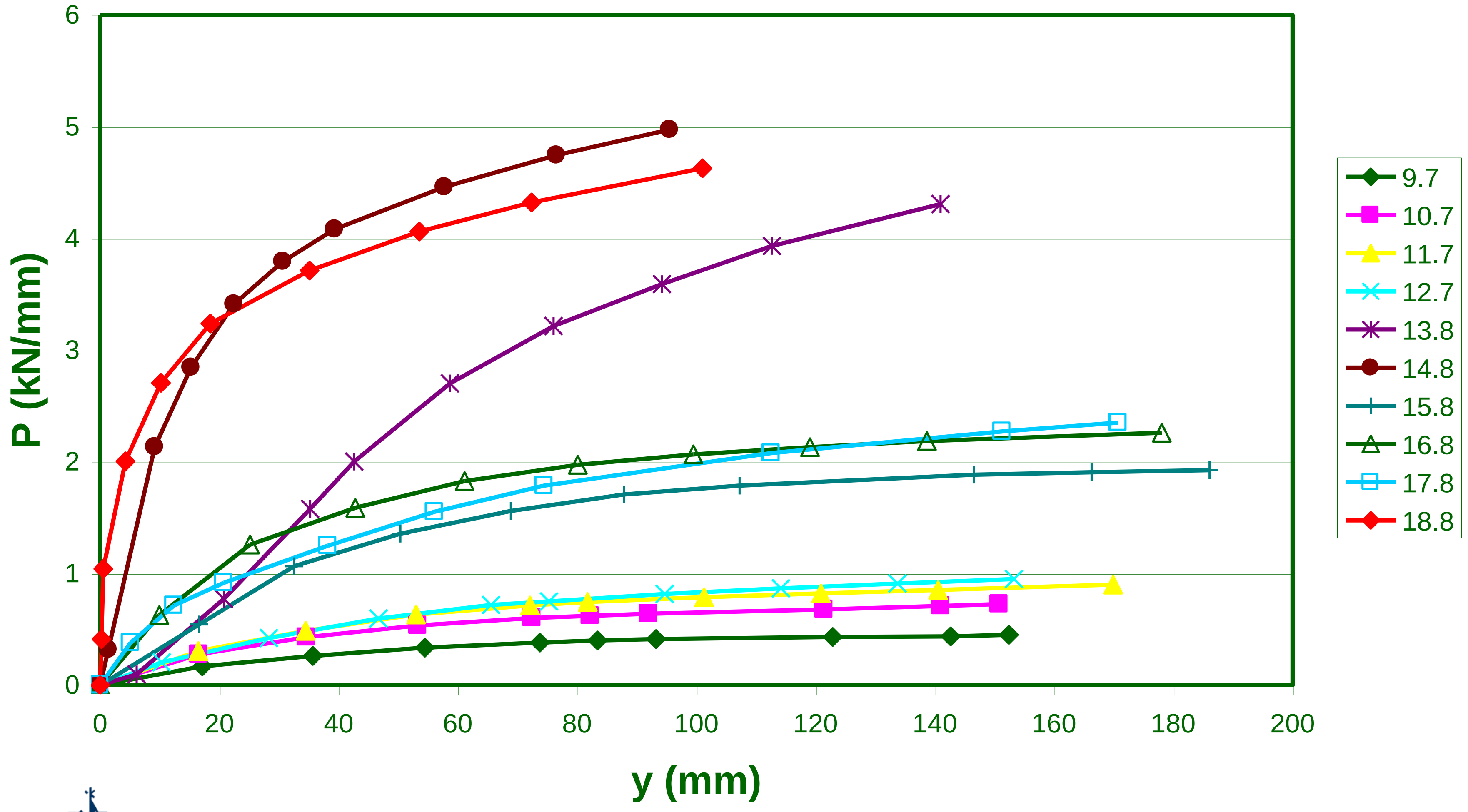
Auburn Predictions



PMT P-y Curves Pascagoula



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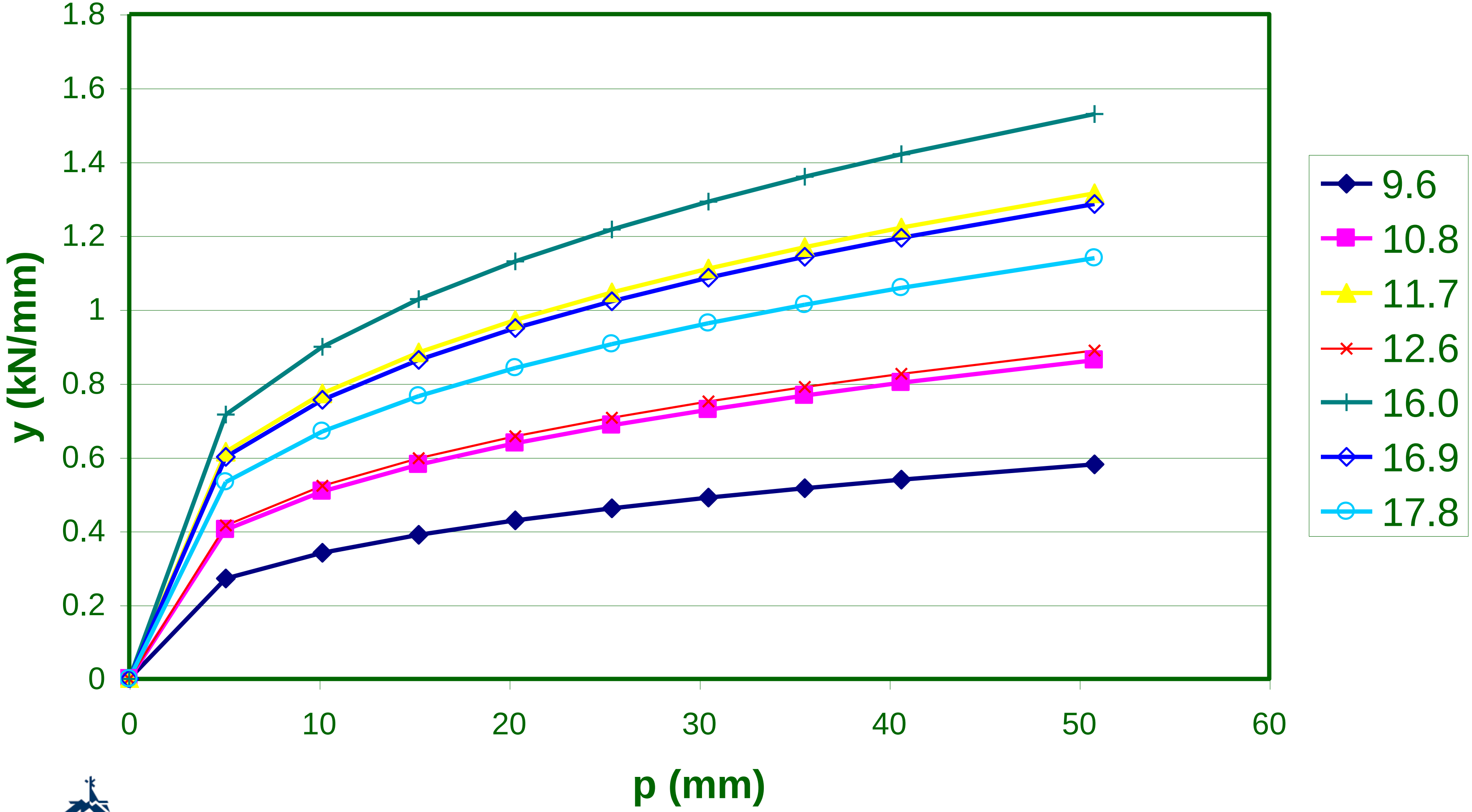
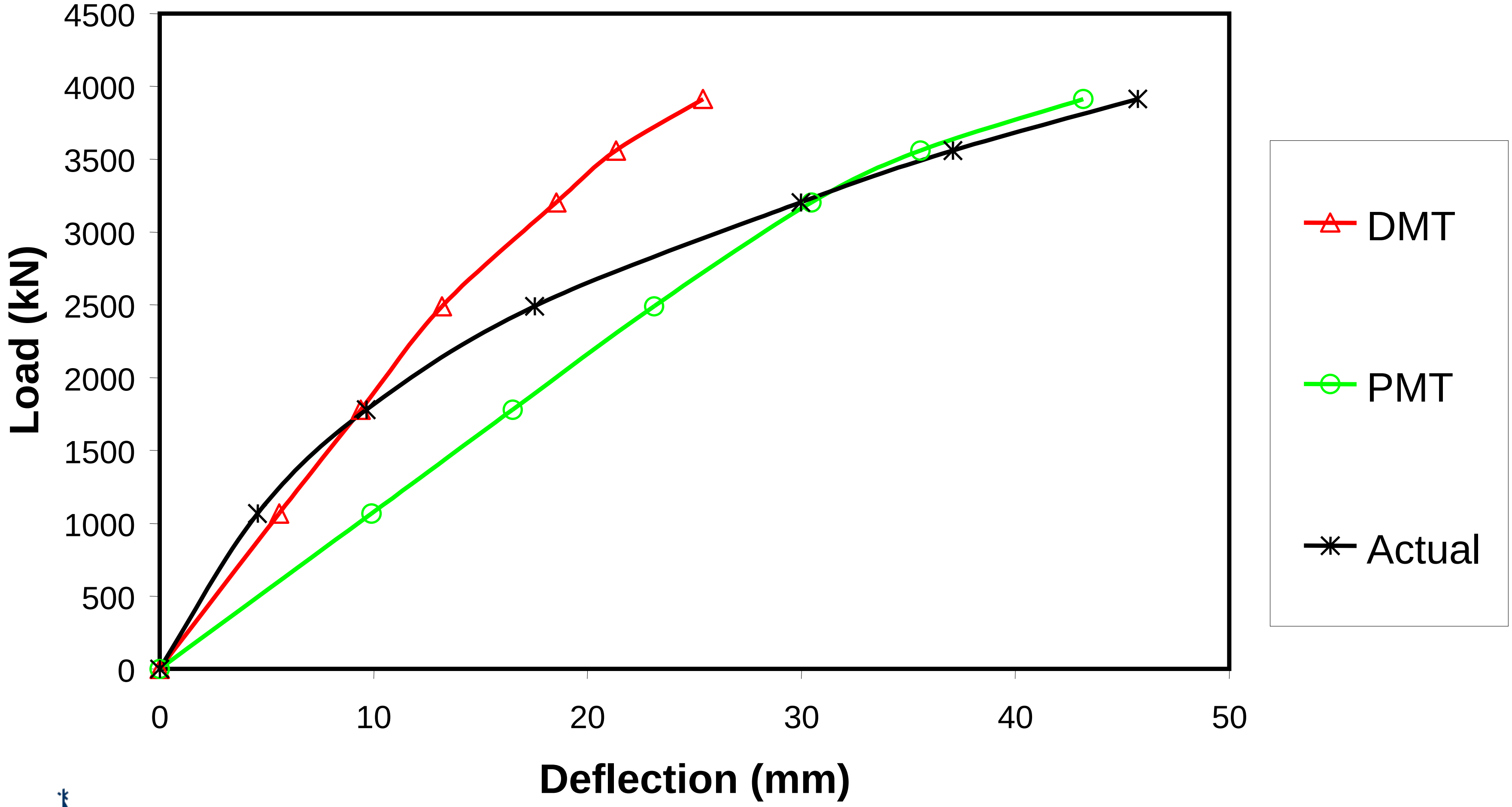
DMT P-y Curves Pascagoula



Pascagoula Predictions

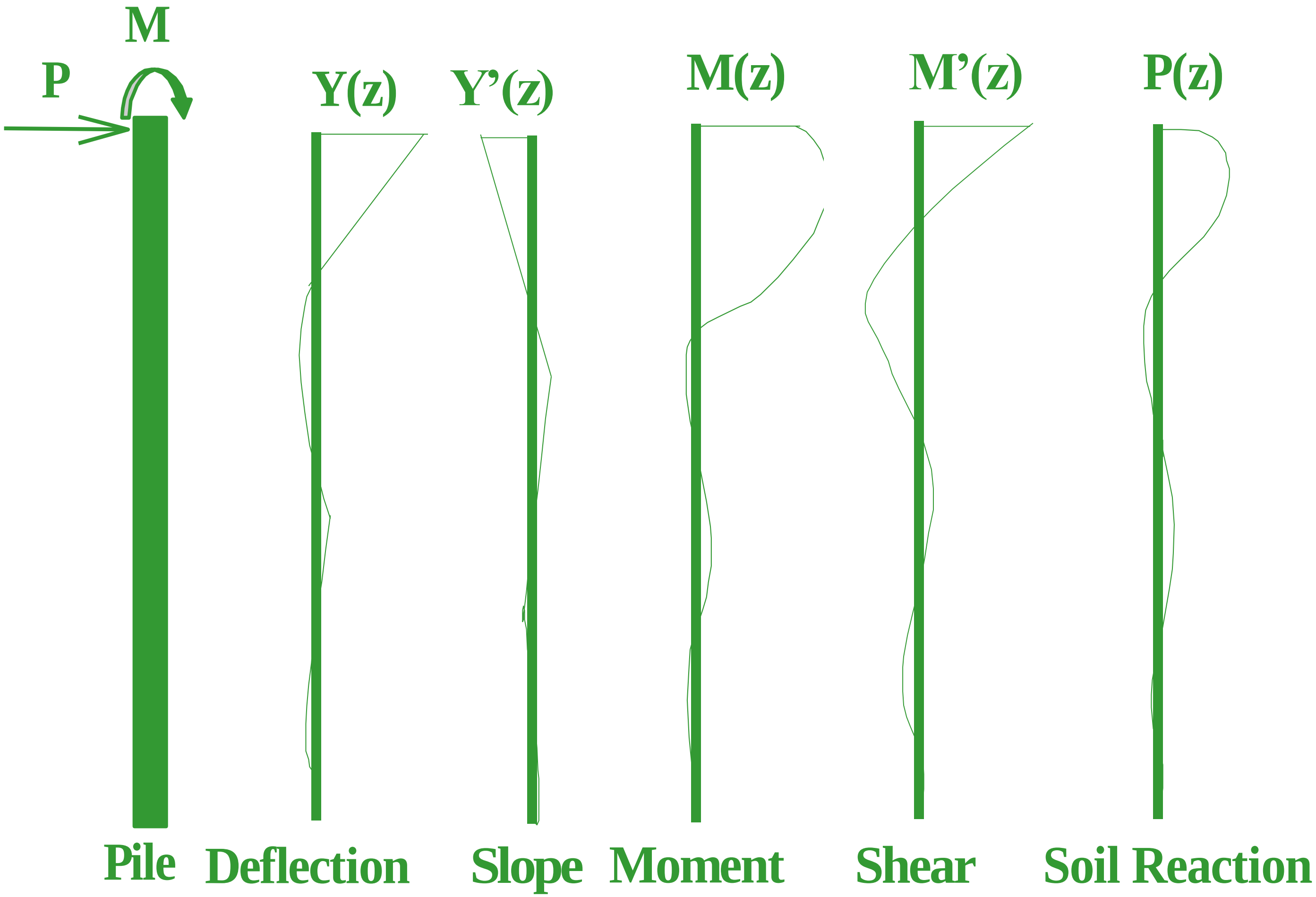


CIVIL ENGINEERING

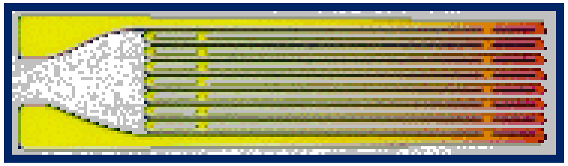
Instrumentation & Measurements

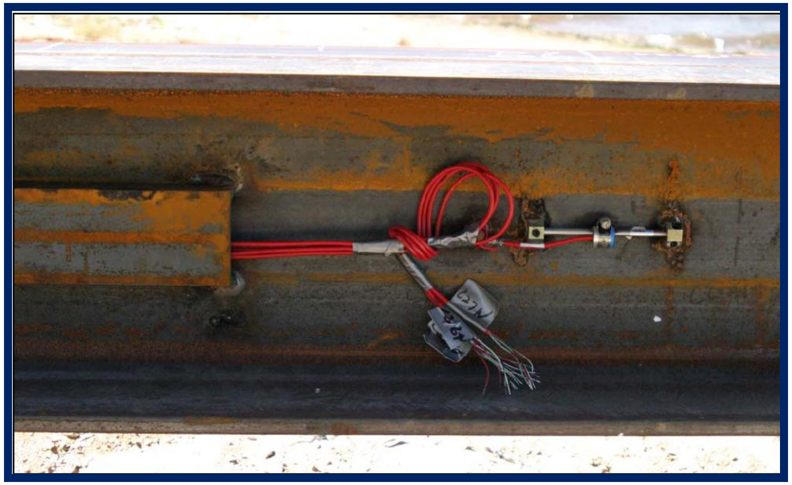
- Strain gages
  - – Measure strain
  - – Calculate bending moment, $M = \varepsilon(EI/c)$, if EI of section known
  - – “high tech”
- Slope inclinometer
  - – Measures slope
  - – Relatively “low tech”

Theoretical Pile Behavior

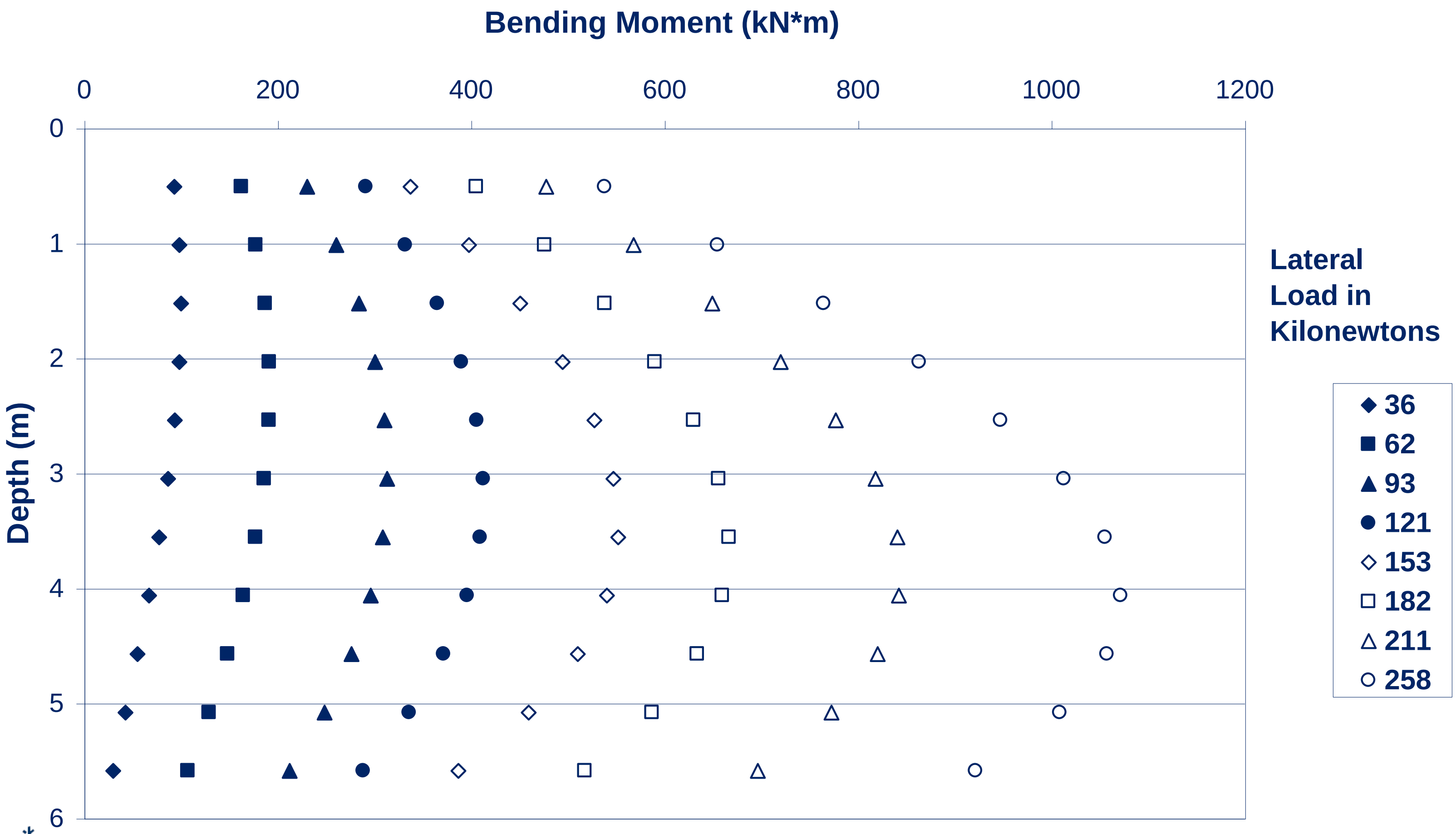


Strain Gages → Bending Moment

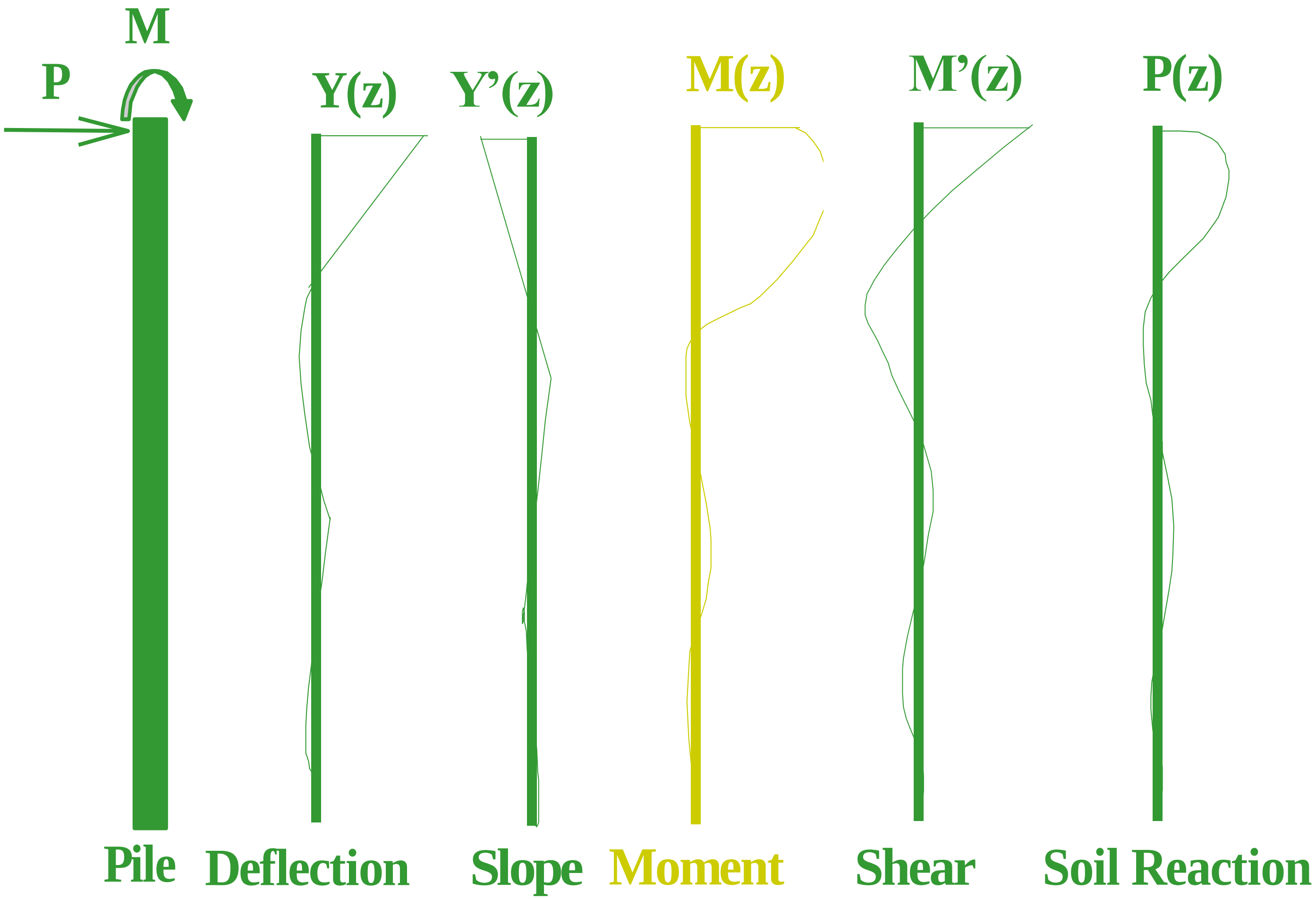




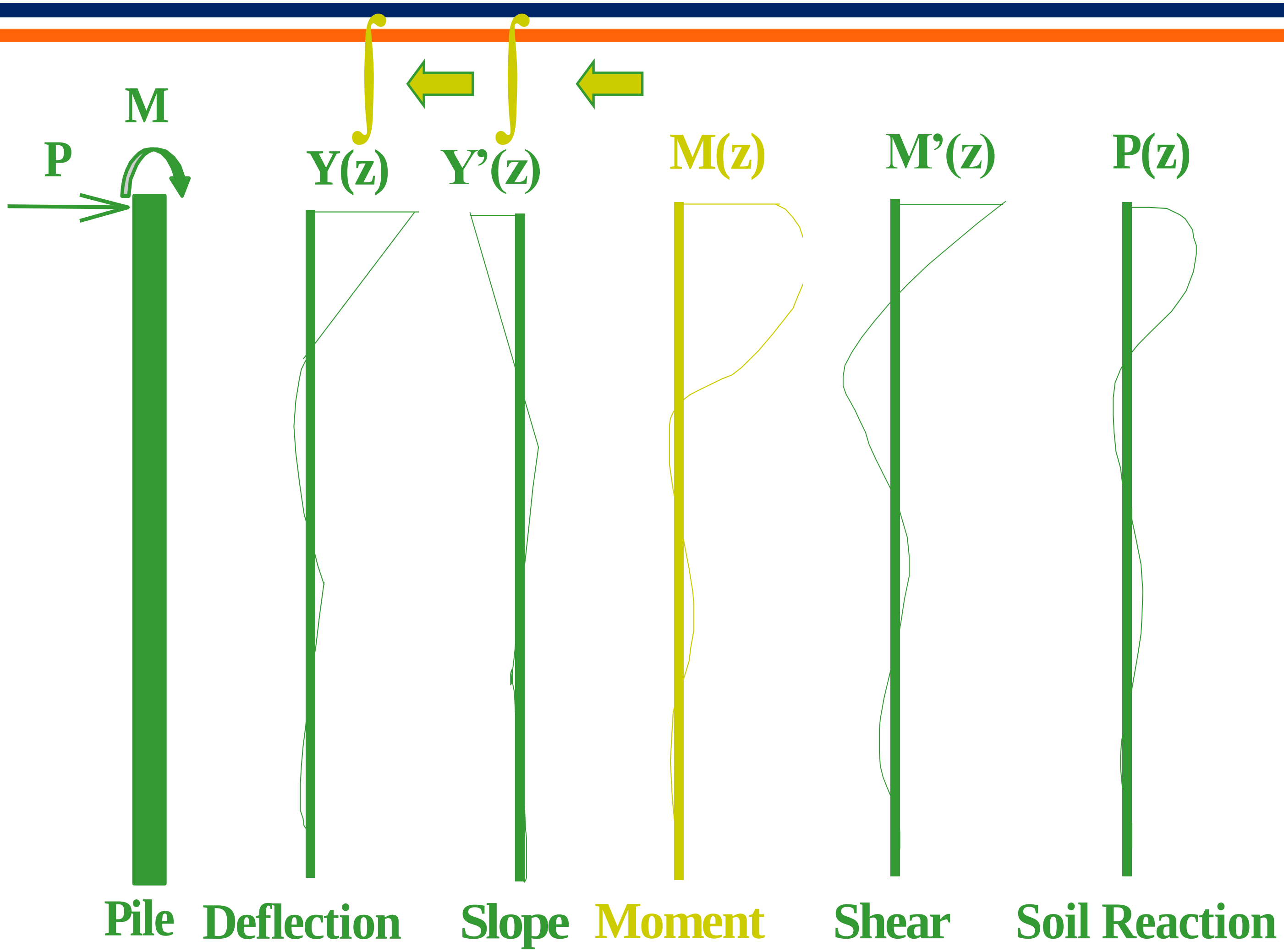
Bending Moment versus Depth



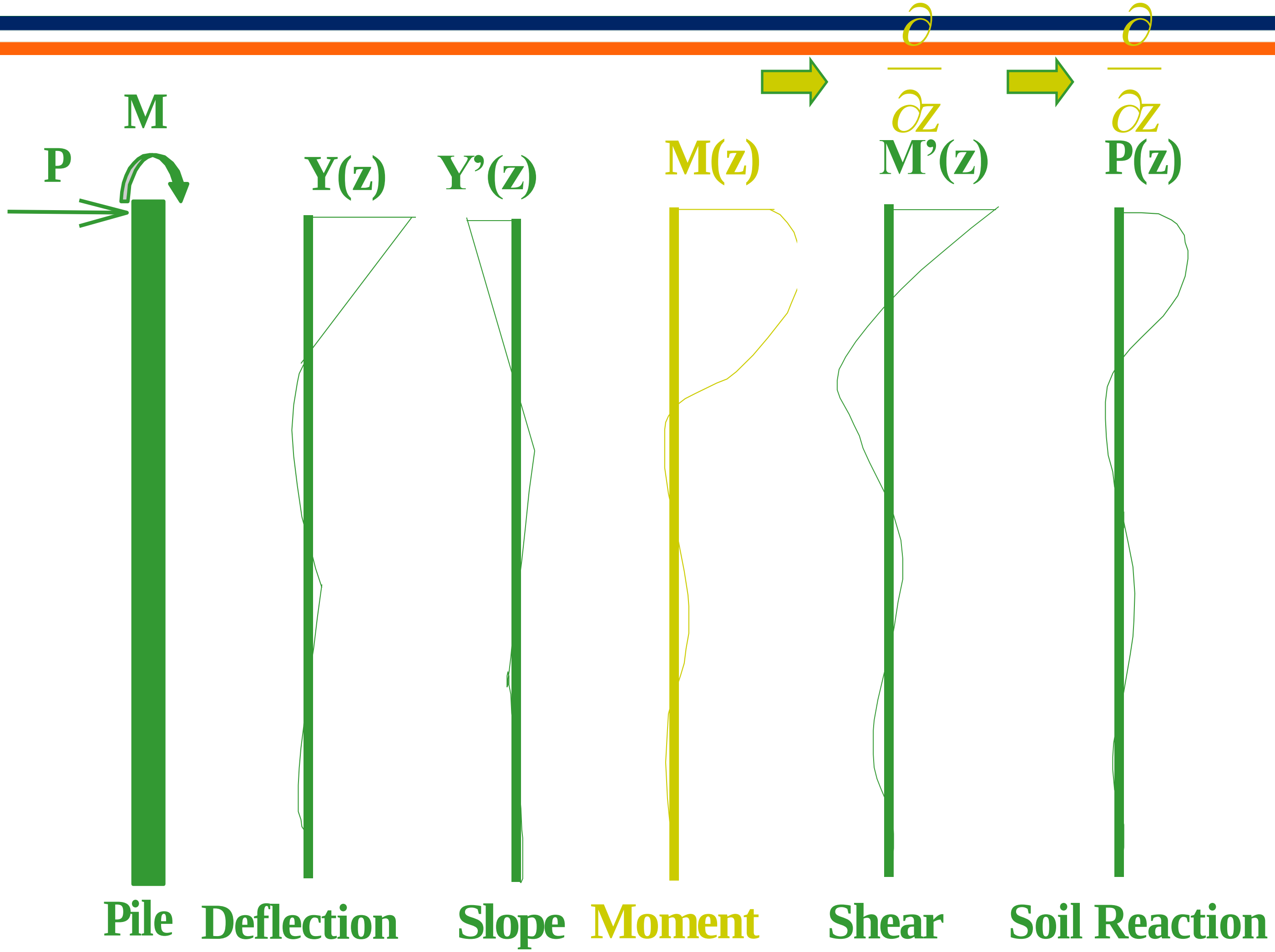
Bending Moment vs. Depth



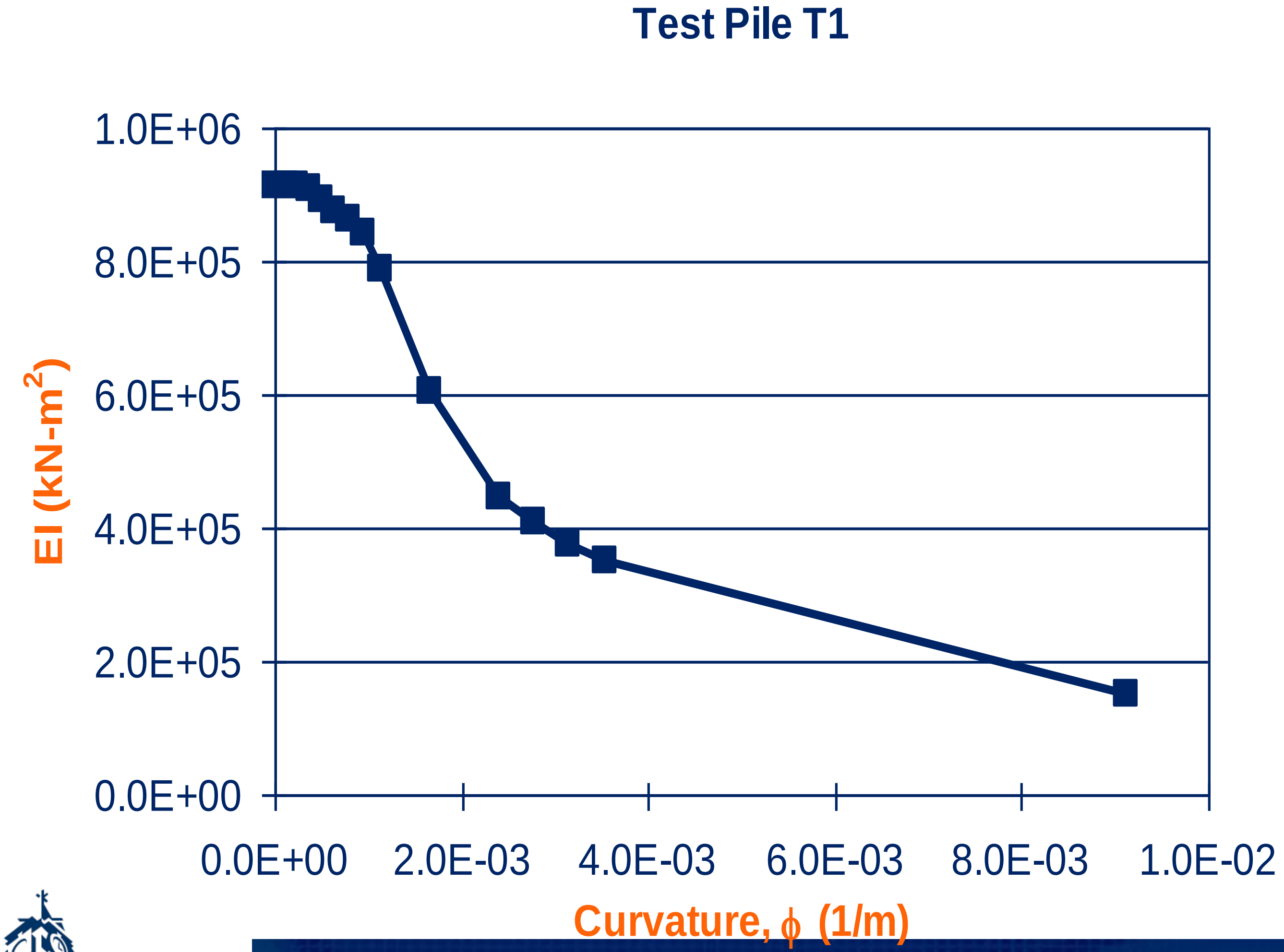
Two Integrals to Deflection



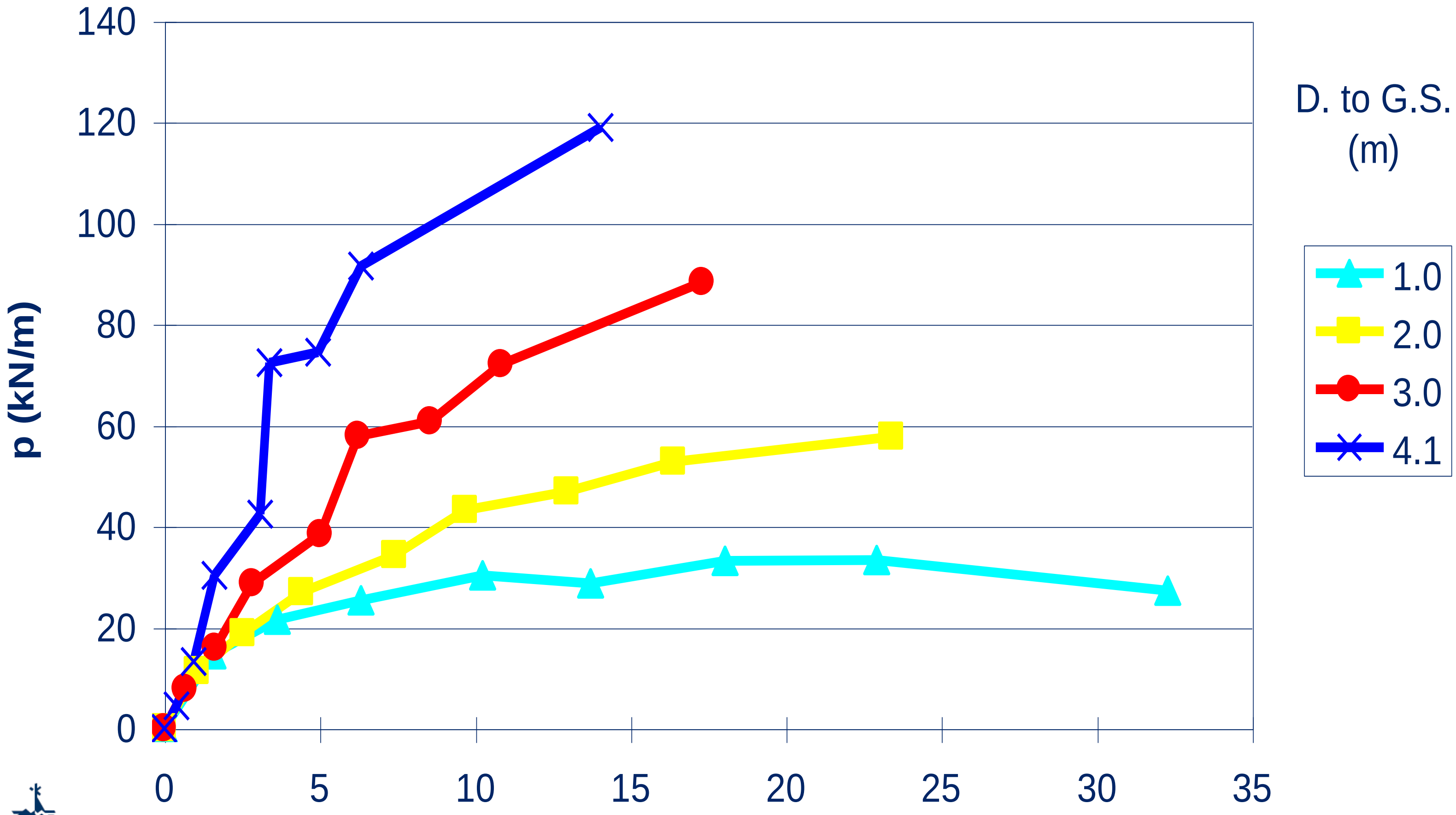
Two Derivatives to Load



Non-linear Concrete Model

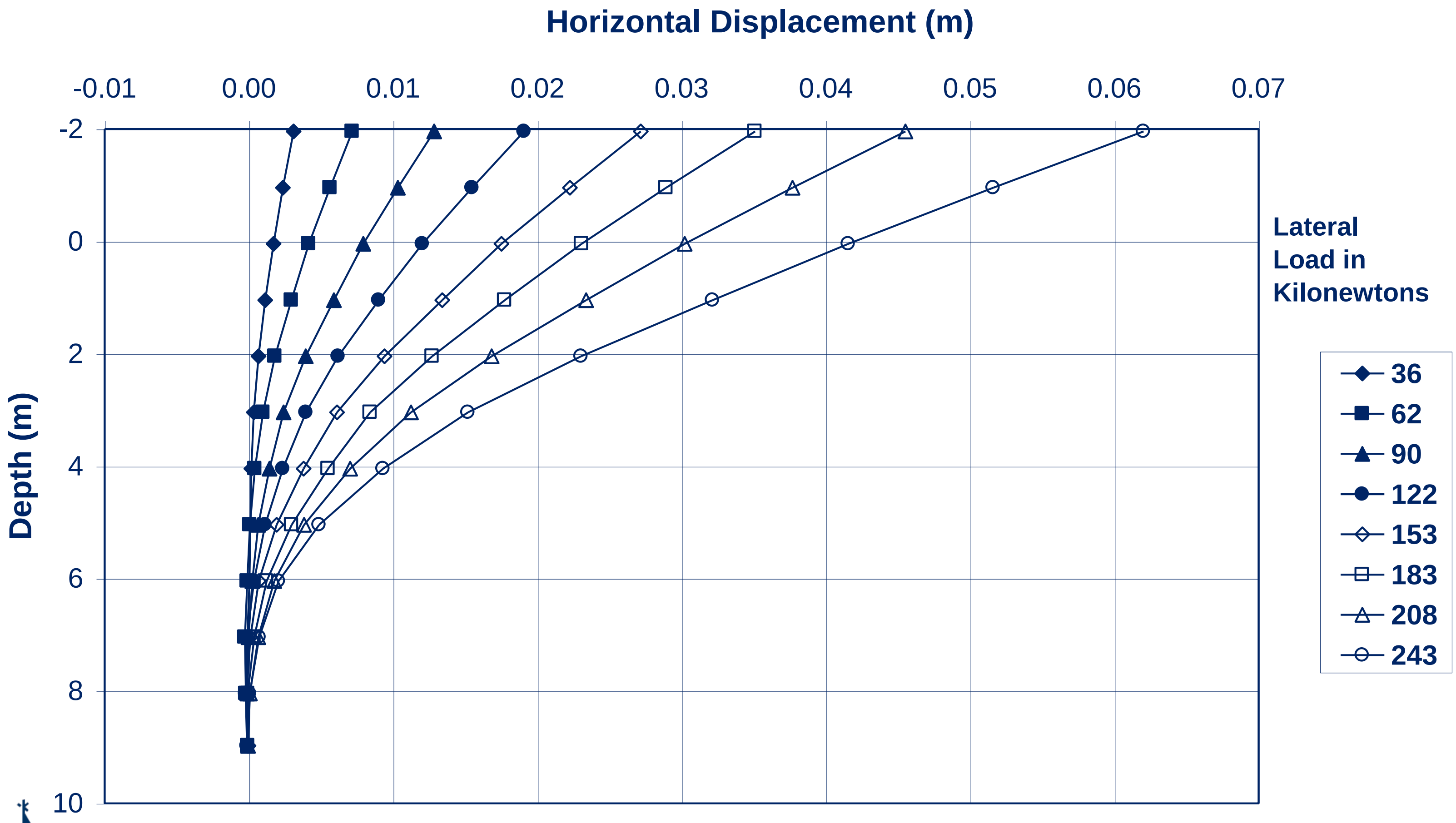


P-y Curves from Strain Gages



Slope Inclinometer → Slope

Deflection versus Depth



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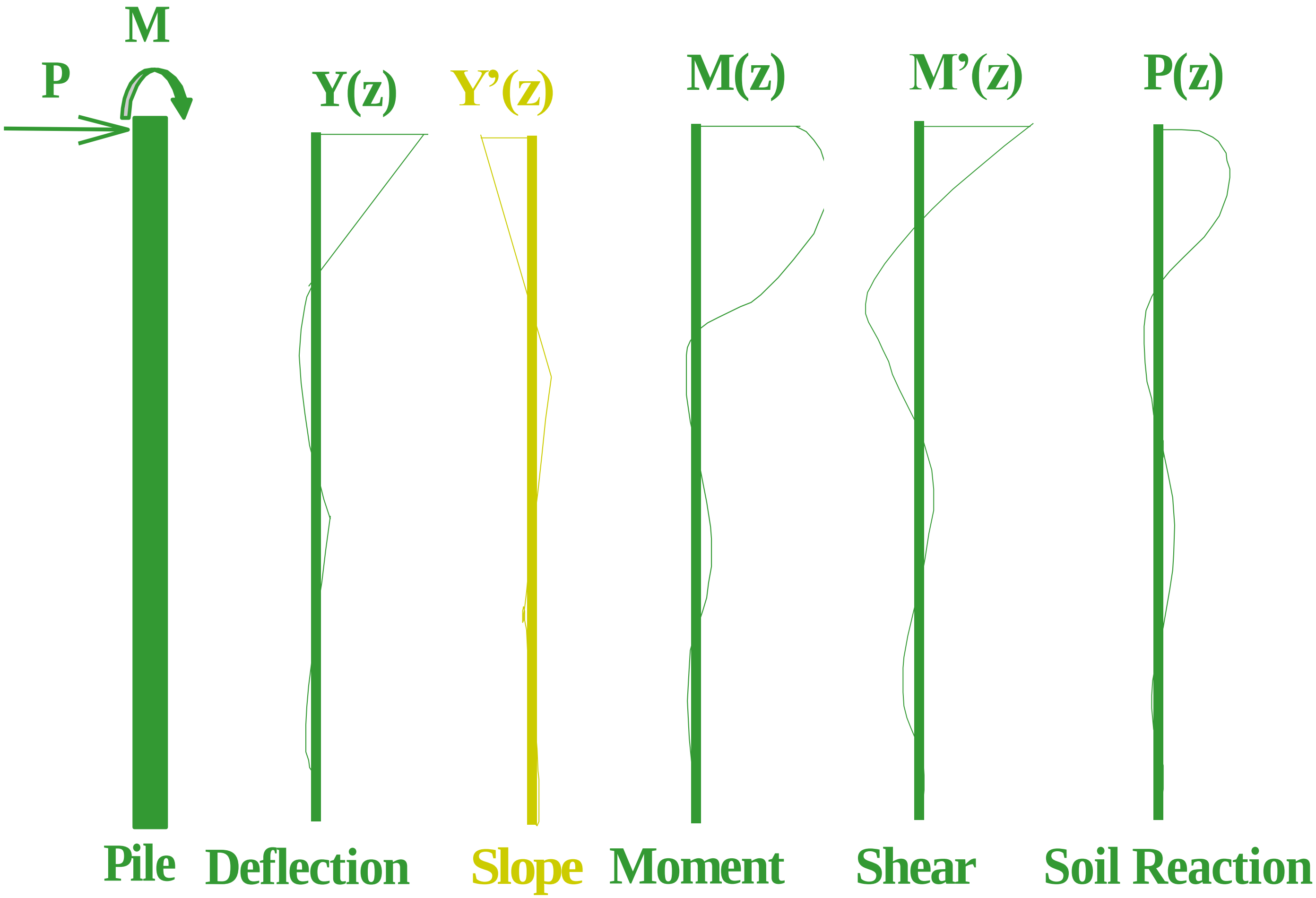
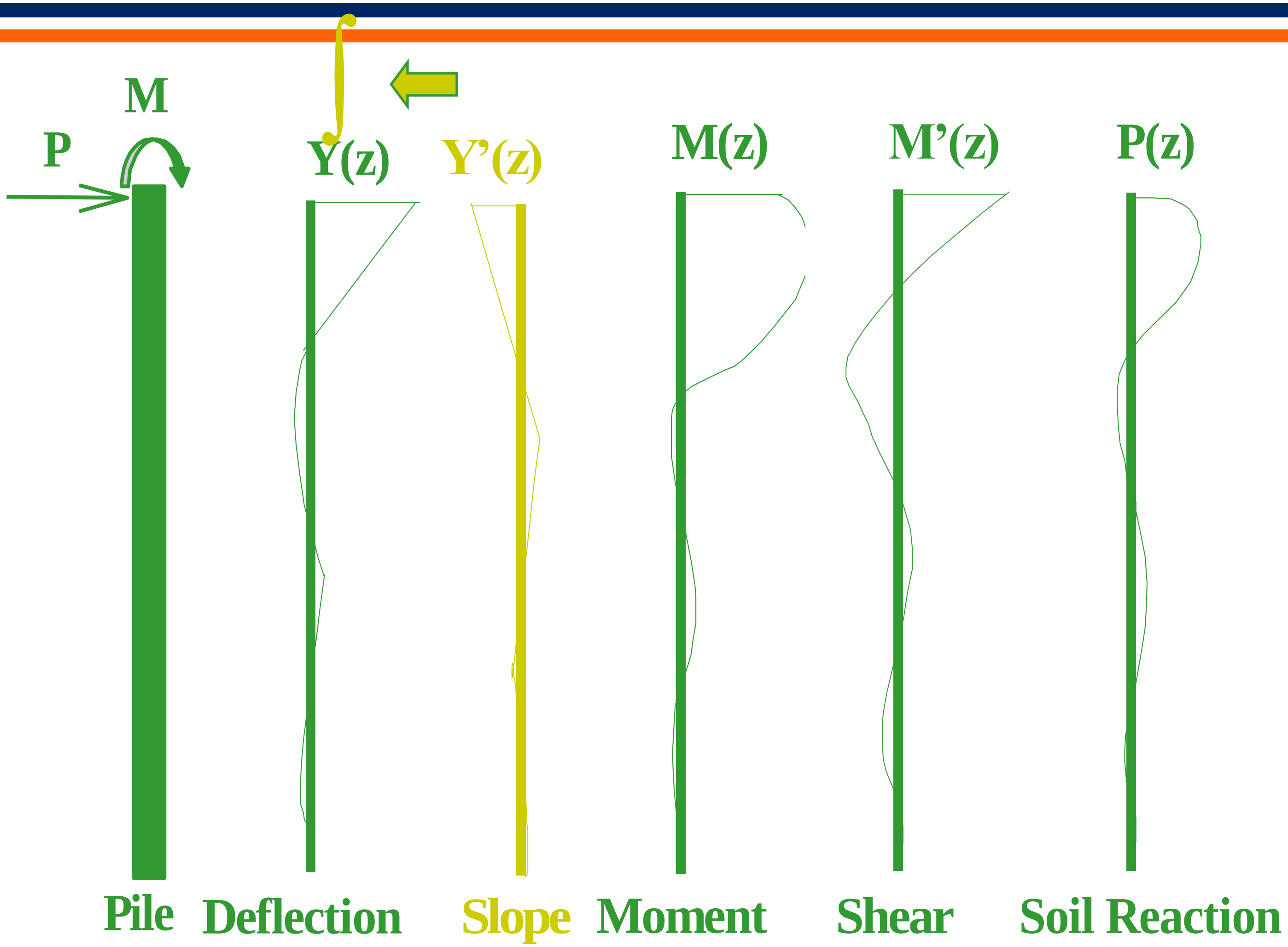
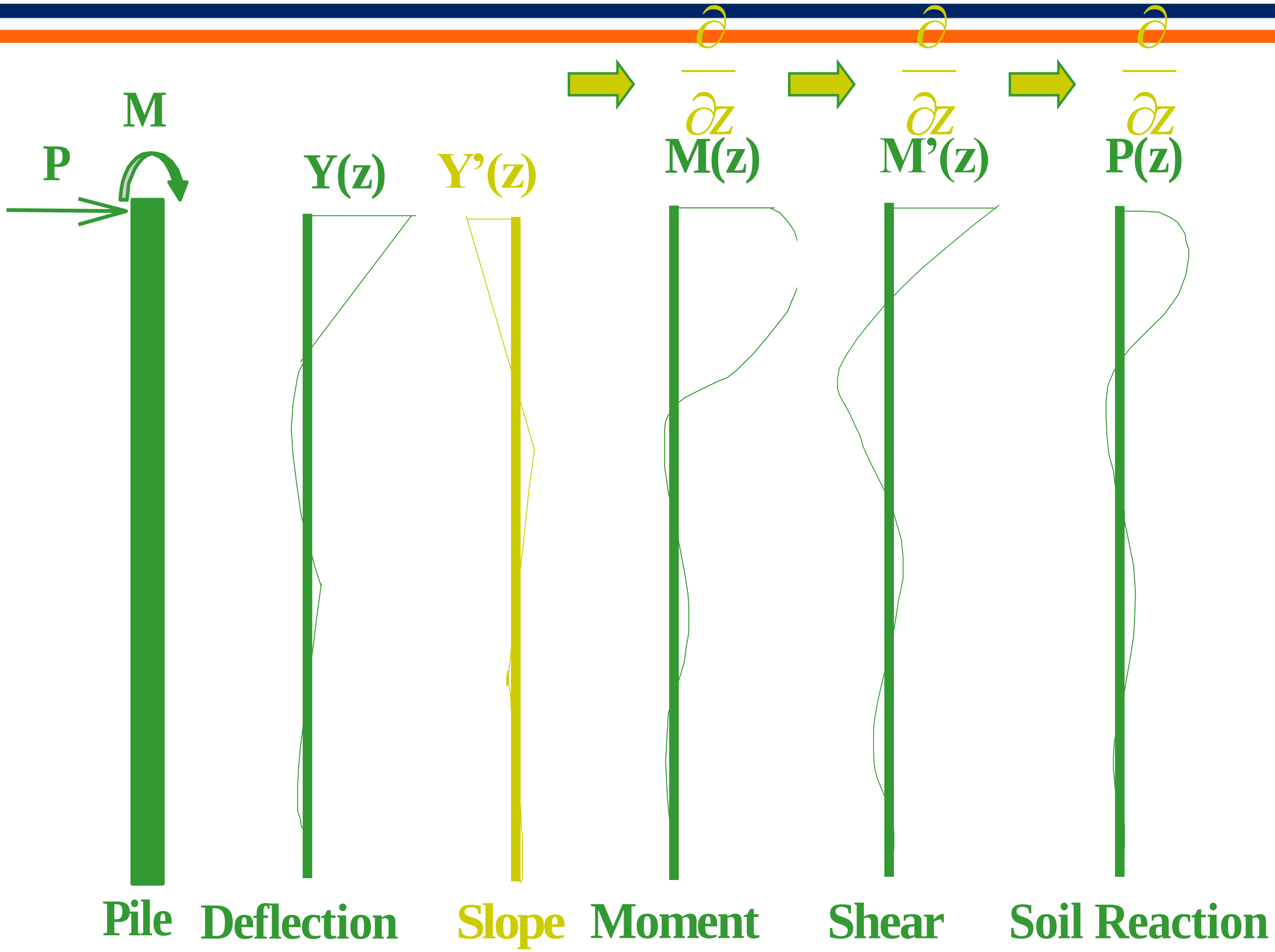
Slope Inclinometer → Slope vs. Depth



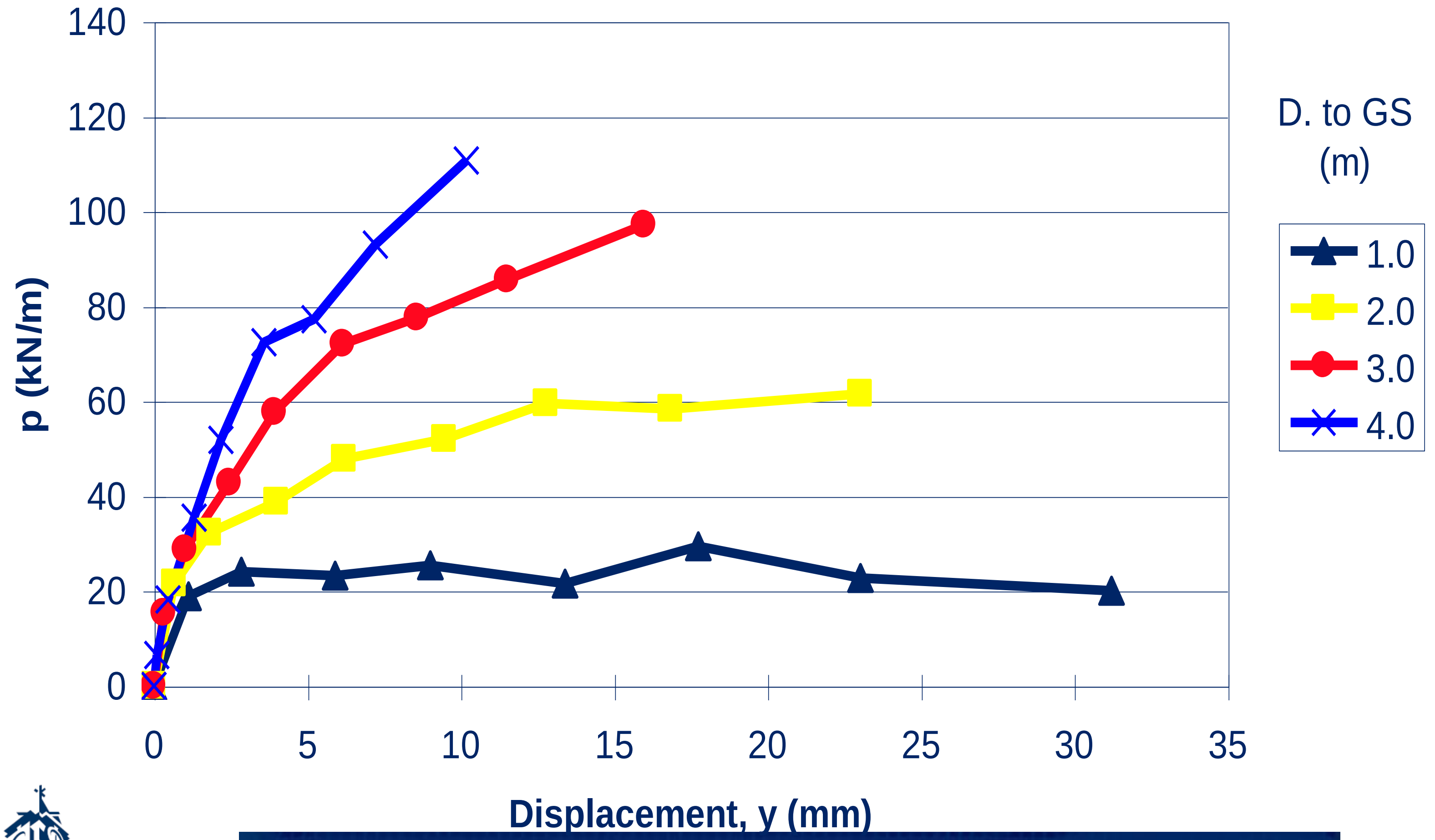
One Integral to Deflection



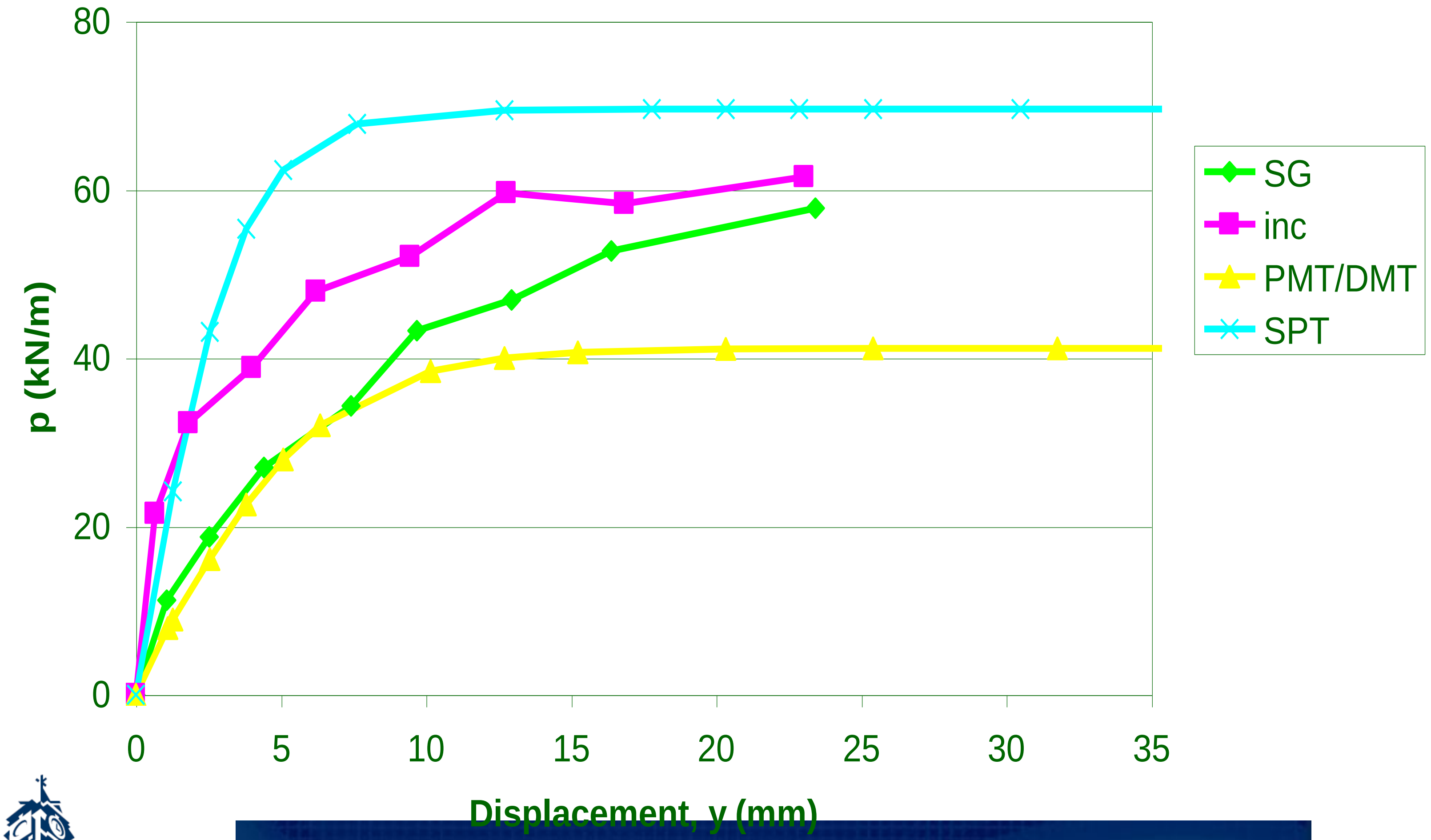
Three Derivatives to Load



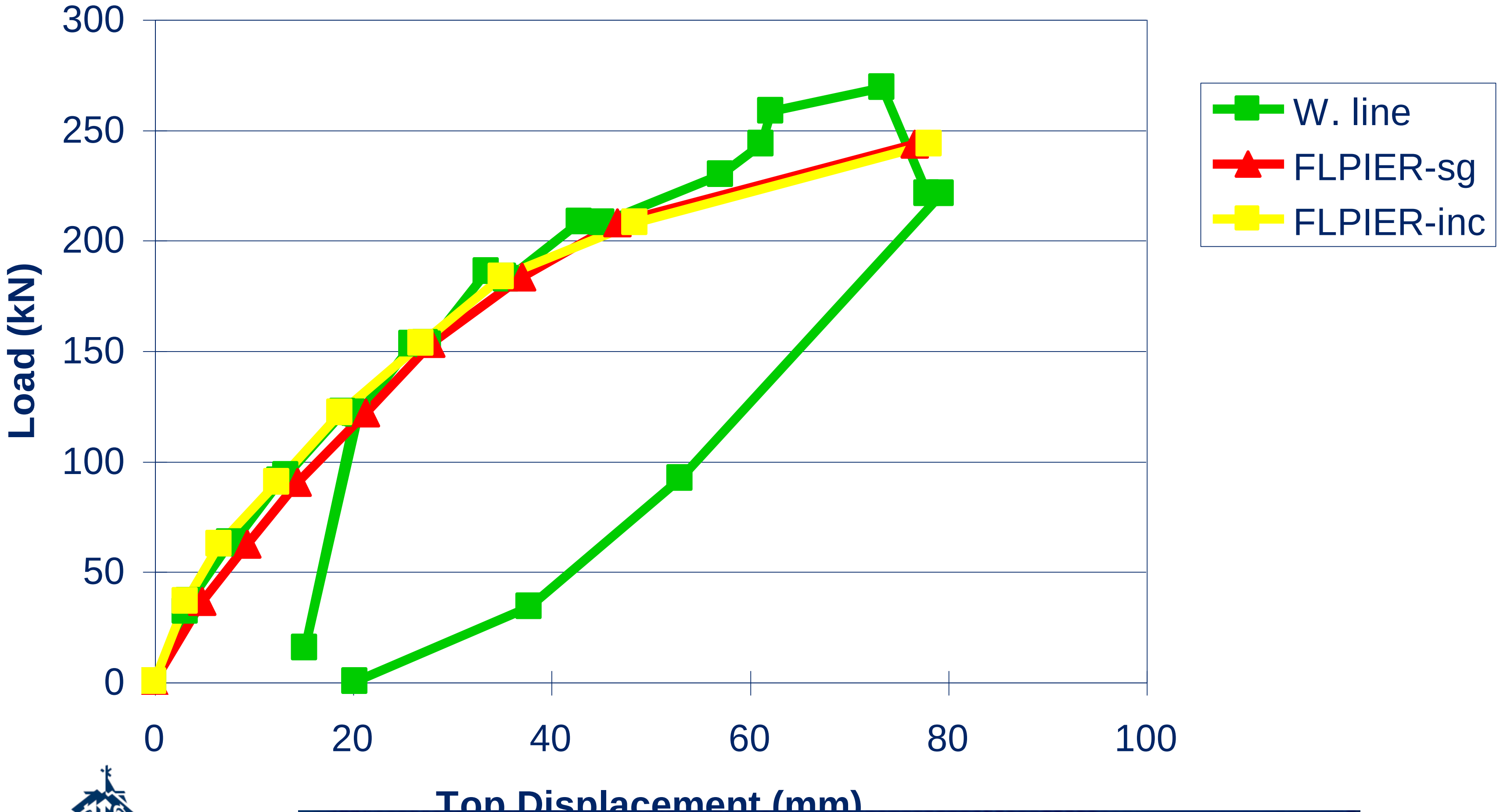
P-y Curves from Slope Inclinometer



Comparison of P-y Curves



Prediction of Pile Top Deflection



P-y Curves Available in FB-Pier

- Standard
  - Sand
    - O’Neill
    - Reese, Cox, & Koop
  - Clay
    - O’Neill
    - Matlock Soft Clay Below Water Table
    - Reese Stiff Clay Below Water Table
    - Reese & Welch Stiff Clay Above Water Table

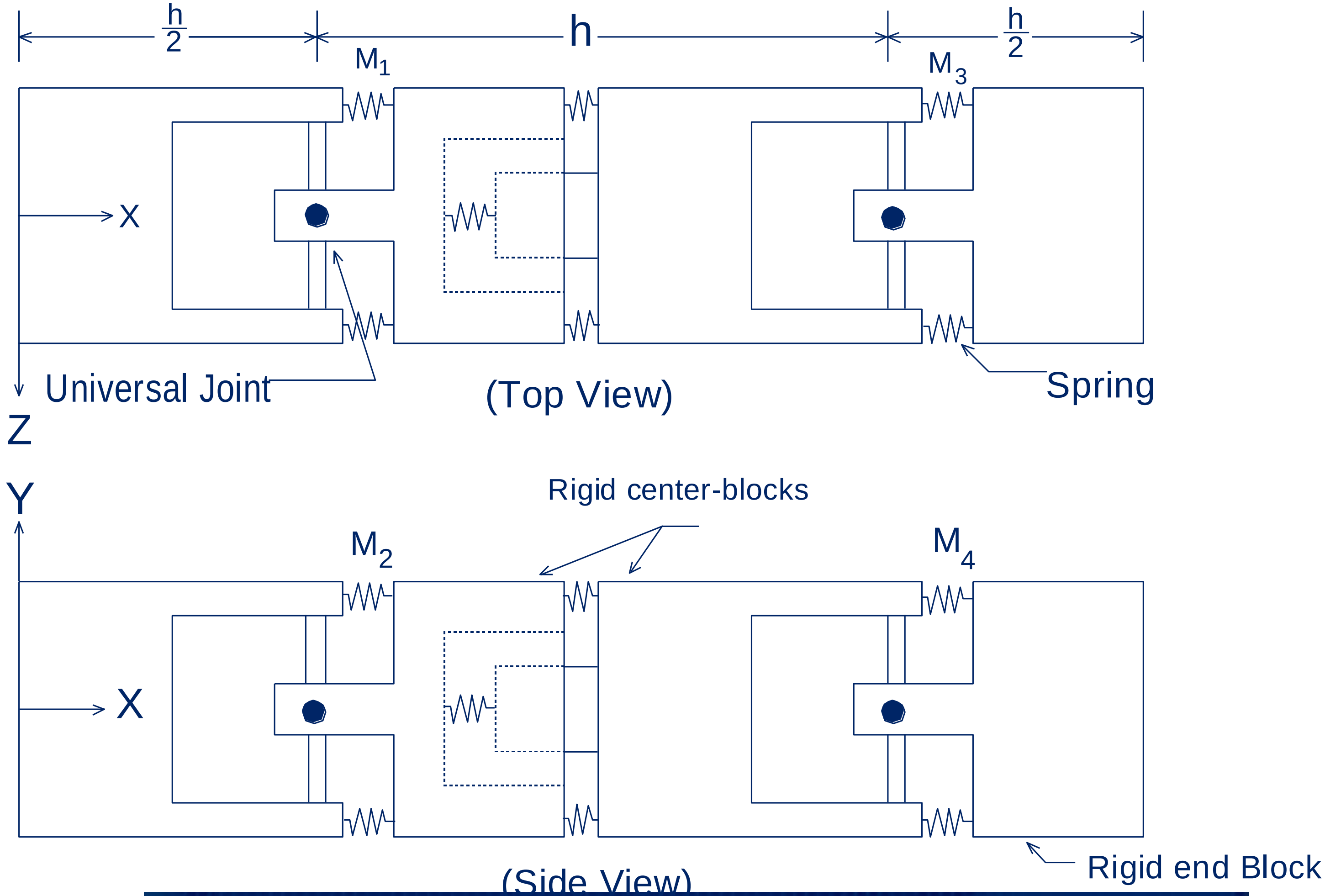
P-y Curves Available in FB-Pier

- User Defined
  - – Pressuremeter
  - – Dilatometer
  - – Instrumentation
    - Strain Gages
    - Slope Inclinometer

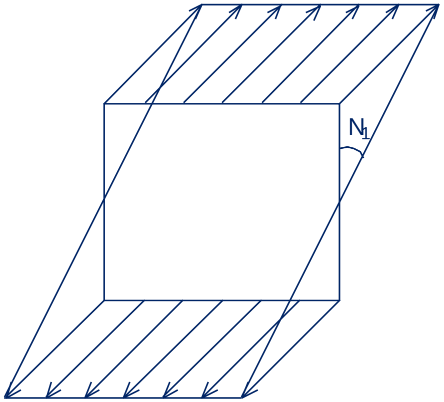
Session Outline

- Introduce FB-MultiPier Software
- Identify and Discuss Soil-Pile Interaction Models
  - Precast & Cast Insitu Axial T-Z & Q-Z Models
  - Torsional T-θ Models
  - Lateral P-Y Models
  - Nonlinear Pile Structural Models
- FB-MultiPier Input and Output
  - Example #1 Single Pile

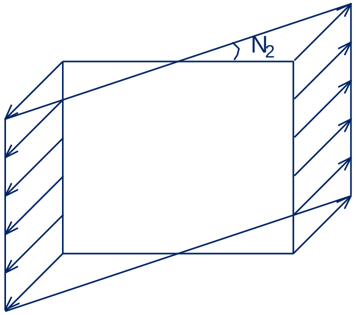
Pile Element Model



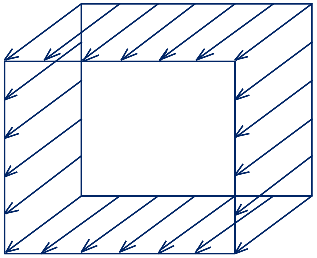
Curvature-Strain-Stress-Moment



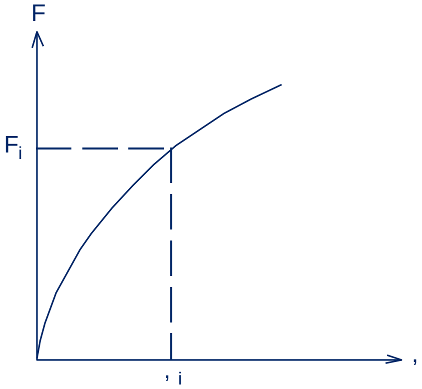
a) Strain due to
z-axis bending



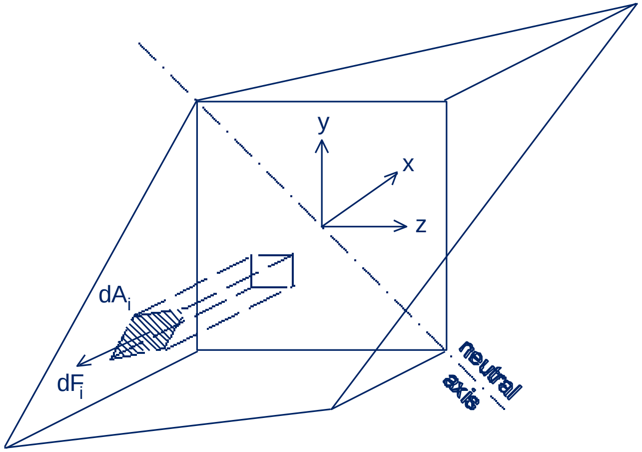
b) Strain due to
y-axis bending



c) Strain due to
axial thrust

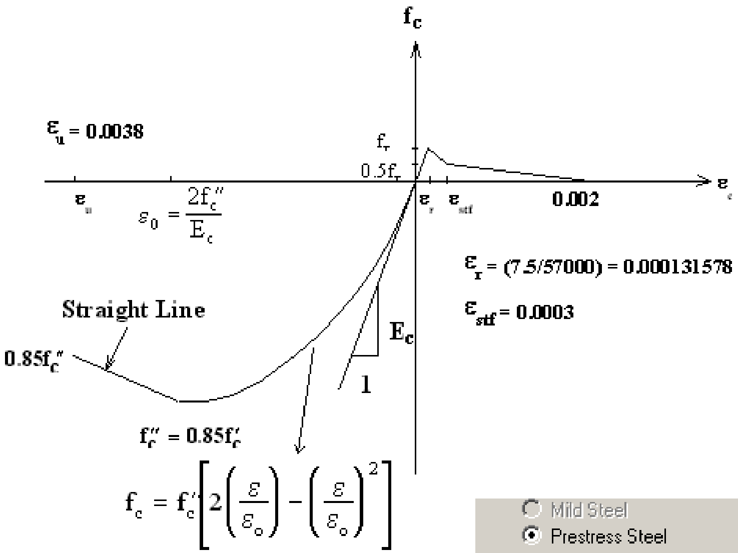


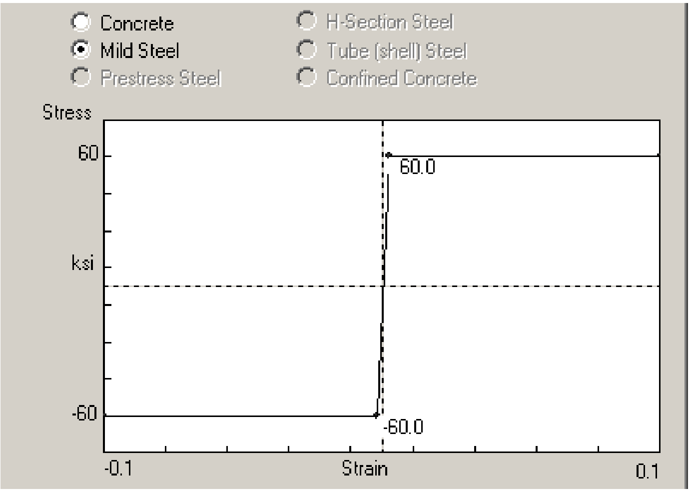
e) Stress-strain relationship

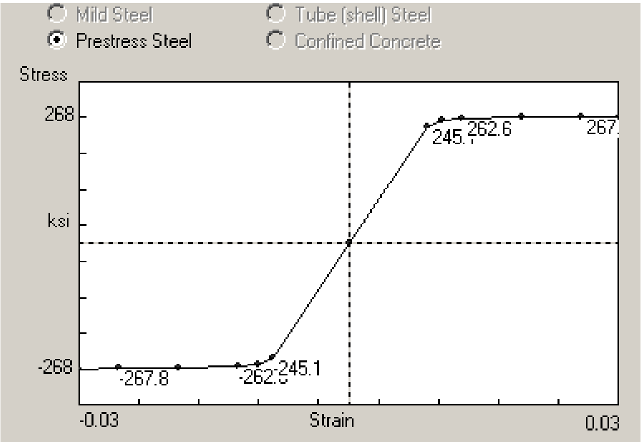


d) Combined strains

Stress-Strain Curves for Concrete & Steel




○ Concrete
● Mild Steel
○ Prestress Steel
○ H-Section Steel
○ Tube (shell) Steel
○ Confined Concrete

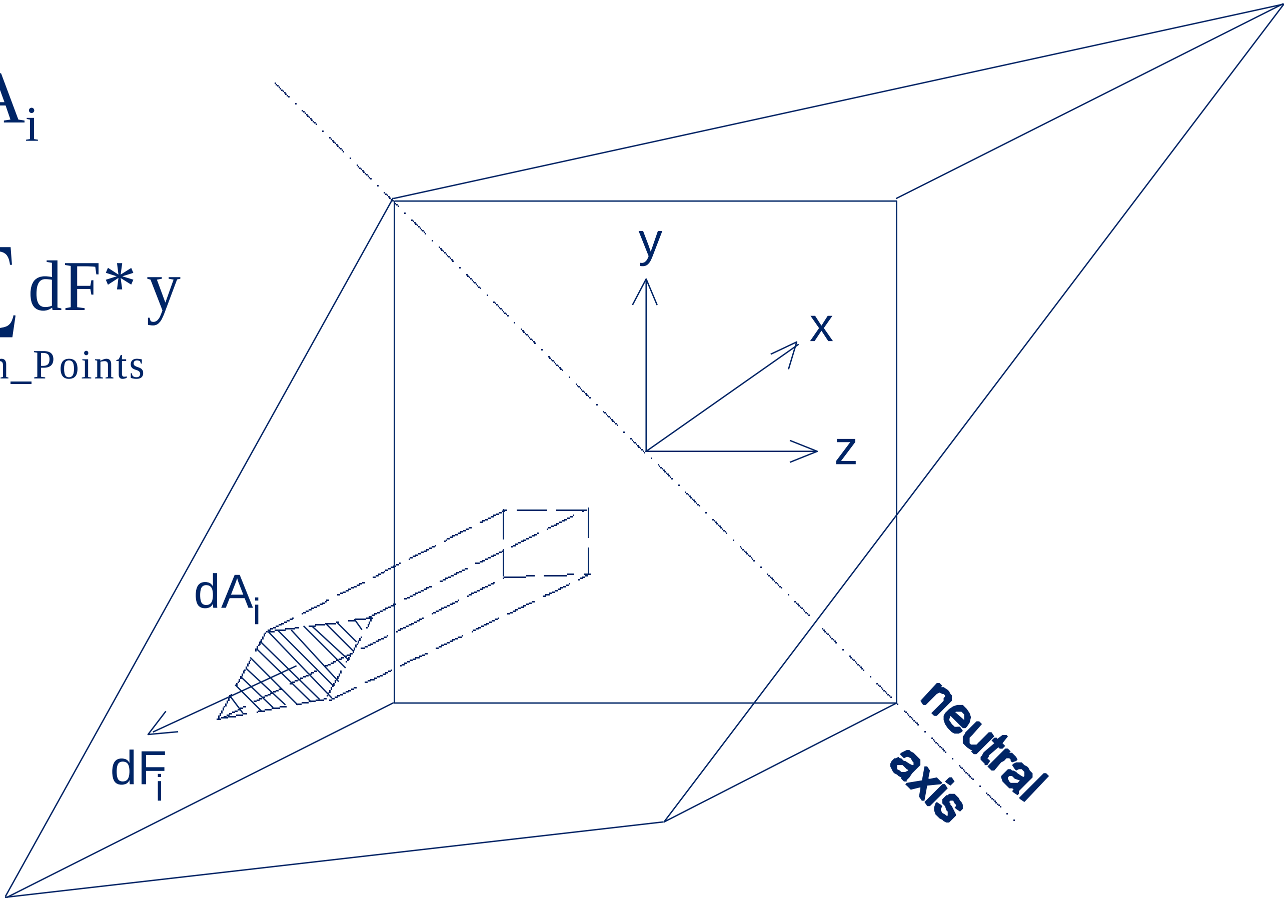

○ Mild Steel
● Prestress Steel
○ Tube (shell) Steel
○ Confined Concrete

CIVIL ENGINEERING

Strains -> Stress -> Moments

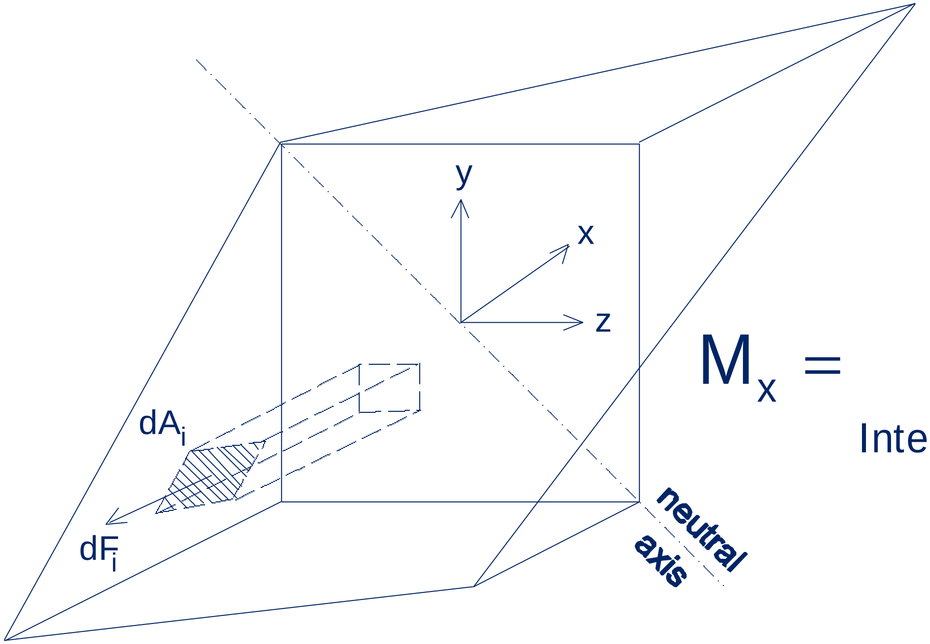
$dF_i = \sigma_i * dA_i$

$$M_x = \sum_{Integration\_Points} dF * y$$

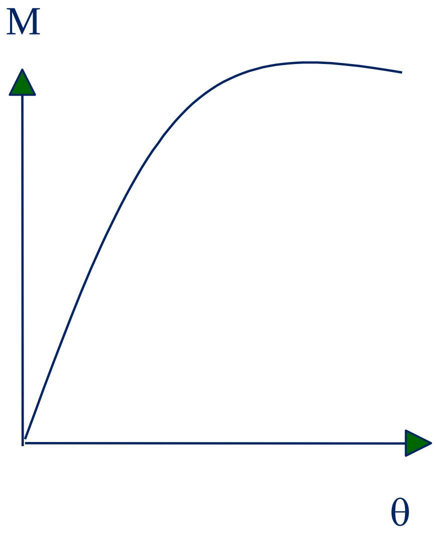


Civil Engineering

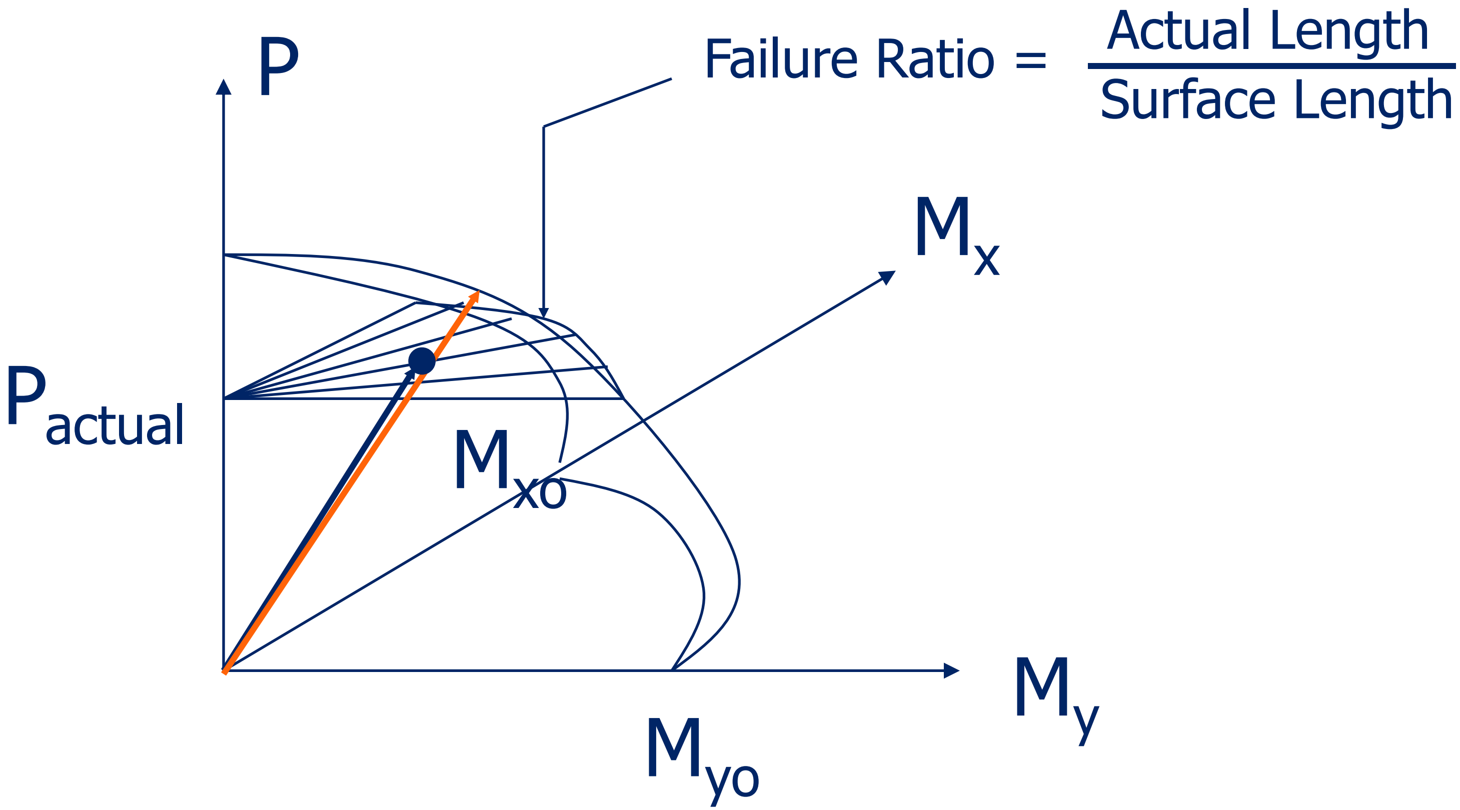
Stiffness of Cross-Section: Flexure, Axial



$$M_x = \sum_{Integration\_Points} dF^* y$$

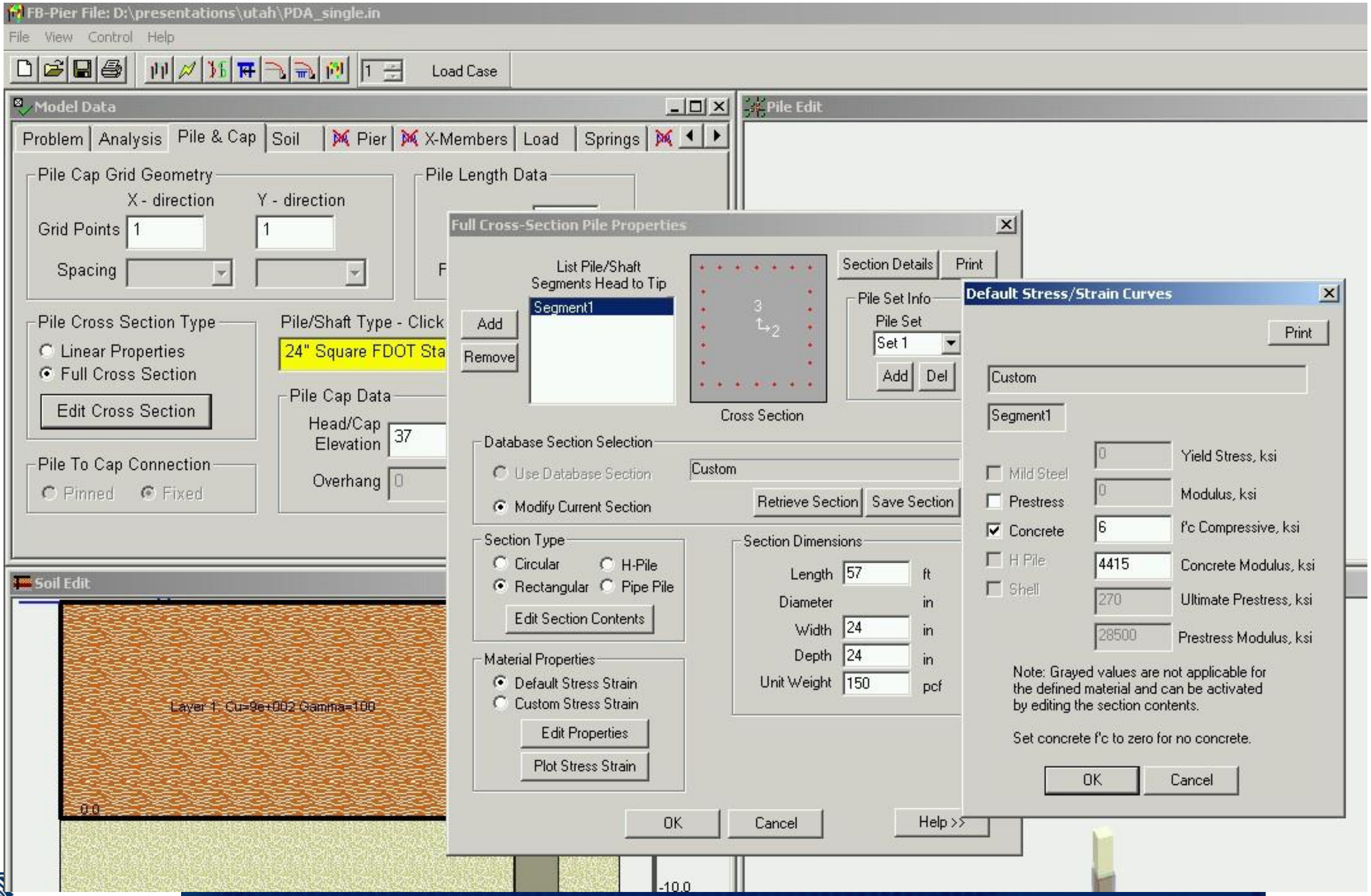


Failure Ratio Calculation



Failure Ratio = $\frac{\text{Actual Length}}{\text{Surface Length}}$

Pile Material Properties



Model Data – Pile & Cap

Pile Cap Grid Geometry

	X - direction	Y - direction
Grid Points	1	1
Spacing		

Pile Length Data

Pile Cross Section Type
- ○ Linear Properties
- ● Full Cross Section

Edit Cross Section

Pile/Shaft Type - Click: 24" Square FDOT Sta

Pile Cap Data
- Head/Cap Elevation: 37
- Overhang: 0

Pile To Cap Connection: ○ Pinned ● Fixed

Full Cross-Section Pile Properties

List Pile/Shaft Segments Head to Tip: Segment1

Add
Remove

Cross Section

Section Details
Print

Pile Set Info
- Pile Set: Set 1

Add
Del

Database Section Selection
- ○ Use Database Section
- ● Modify Current Section

Custom

Retrieve Section
Save Section

Section Type
- ○ Circular
- ○ H-Pile
- ● Rectangular
- ○ Pipe Pile

Edit Section Contents

Section Dimensions

Length	57	ft
Diameter		in
Width	24	in
Depth	24	in
Unit Weight	150	pcf

Material Properties
- ● Default Stress Strain
- ○ Custom Stress Strain

Edit Properties
Plot Stress Strain

OK
Cancel
Help >>

Default Stress/Strain Curves

Print

Custom

Segment1

☐ Mild Steel	0	Yield Stress, ksi
	0	Modulus, ksi
☐ Prestress	6	f'c Compressive, ksi
☑ Concrete	4415	Concrete Modulus, ksi
☐ H Pile	270	Ultimate Prestress, ksi
☐ Shell	28500	Prestress Modulus, ksi

Note: Grayed values are not applicable for the defined material and can be activated by editing the section contents.

Set concrete f'c to zero for no concrete.

OK
Cancel

References:

- **Robertson, P. K., Campanella, R. G., Brown, P. T., Grof, I., and Hughes, J. M., "Design of Axially and Laterally Loaded Piles Using In Situ Tests: A Case History,“ Canadian Geotechnical Journal, Vol. 22, No. 4, pp.518-527, 1985.**
- **Robertson, P. K., Davies, M. P., and Campanella, R. G., "Design of Laterally Loaded Driven Piles Using the Flat Dilatometer," Geotechnical Testing Journal, GTJODJ, Vol. 12, No. 1, pp. 30-38, March 1989.**
- **Reese, L. C., Cox, W. R. and Koop, F. D (1974). "Analysis of Laterally Loaded Piles in Sand," Paper No. OTC 2080, Proceedings, Fifth Annual Offshore Technology Conference, Houston, Texas, (GESA Report No. D-75-9).**
- **Hoit, M.I, McVay, M., Hays, C., Andrade, P. (1996). “Nonlinear Pile Foundation Analysis Using Florida Pier." *Journal of Bridge Engineering*. ASCE. Vol. 1, No. 4, pp.135-142.**
- **Randolph, M. and Wroth, C., 1978, ‟Analysis of Deformation of Vertically Loaded Piles, ASCE *Journal of Geotechnical Engineering*, Vol. 104, No. 12, pp. 1465-1488.**
- **Matlock, H., and Reese, L., 1960, ‟Generalized Solutions for Laterally Loaded Piles,″ *ASCE, Journal of Soil Mechanics and Foundations Division*, Vol. 86, No. SM5, pp. 63-91.**

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