Transportation Research Board 2016 Webinar
Sponsored by Committee AFF50 – Seismic Design & Performance of Bridges

Soil-Foundation-Structure Interaction Webinar

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Outline

- Overview of Seismic Design Principles
- Design Example 1 – Pile-founded Bridge
- Design Example 2 – Drilled Shaft-founded Bridge

Scope: Ordinary bridges, not large, signature bridges, nor seismically isolated bridges

Workshop Learning Objectives

- List the steps necessary to develop foundation spring values
- Describe the effects of foundation flexibility on the push-over displacement check
- List several methods of approximating deep-foundation spring stiffnesses

Reference Materials

- AASHTO Guide Specifications for LRFD Seismic Bridge Design (GS)
- AASHTO LRFD Bridge Design Specifications (LS)
- NHI Course 130093A (3-Day) Displacement-Based LFRD Seismic Analysis and Design of Bridges
- NHI Course 130093 (5-Day) LFRD Seismic Analysis and Design of Bridges
- Associated Design Examples FHWA-NHI-14-039
- NHI Course 132094 and 132094A LRFD Seismic Analysis and Design of Transportation Geotechnical Features

Seismic Design Overview

Topics Covered:

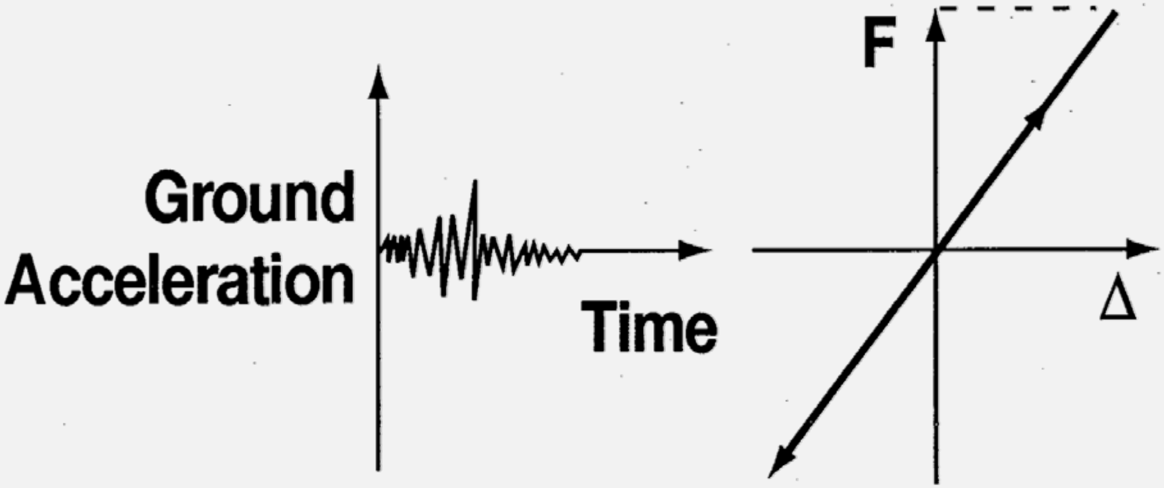
- Basic objectives in seismic design
- Emphasis on displacement-based design
- Effects of foundation flexibility
- Design steps involved

Two Themes or “Subplots” of the Webinar

1. Designs are based on “Capacity Design” principles

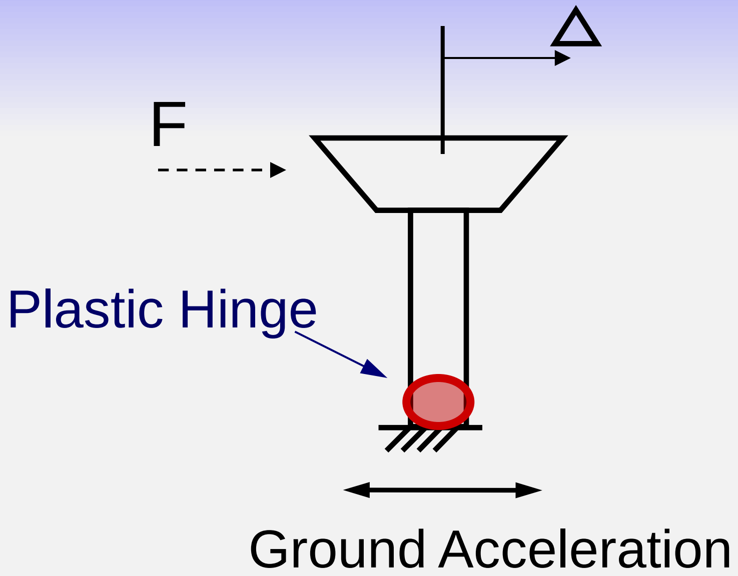
2. Analysis uses equivalent linearization techniques to predict response

We Permit Earthquakes to Damage Bridges



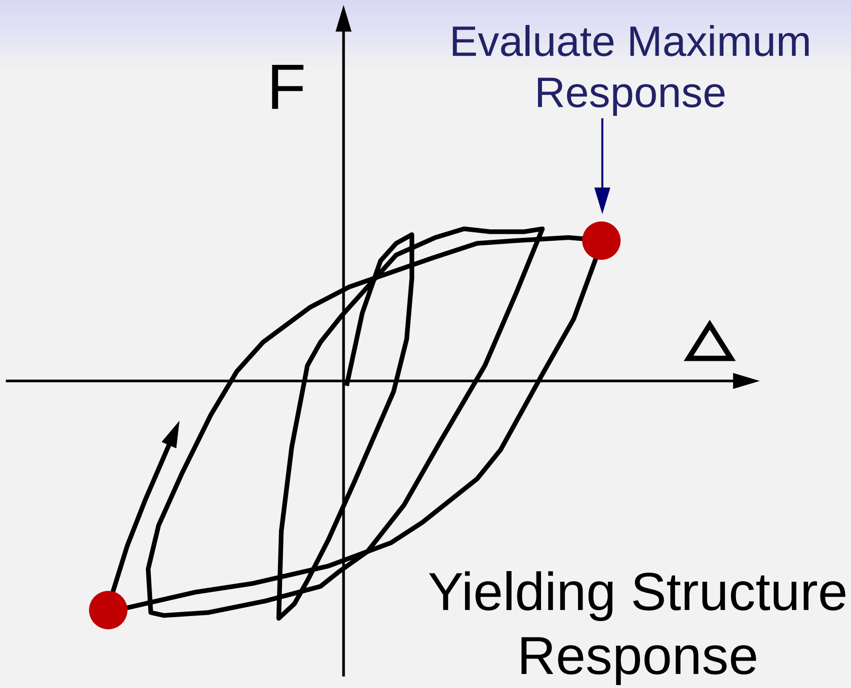
The forces induced if the structure is to remain undamaged can be too large to deal with, thus uneconomical

We Make Bridges Damage-Tolerant



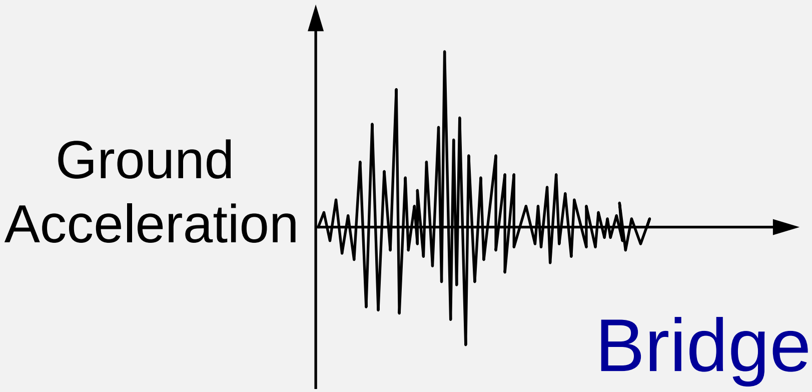
Plastic Hinge

Ground Acceleration



Evaluate Maximum Response

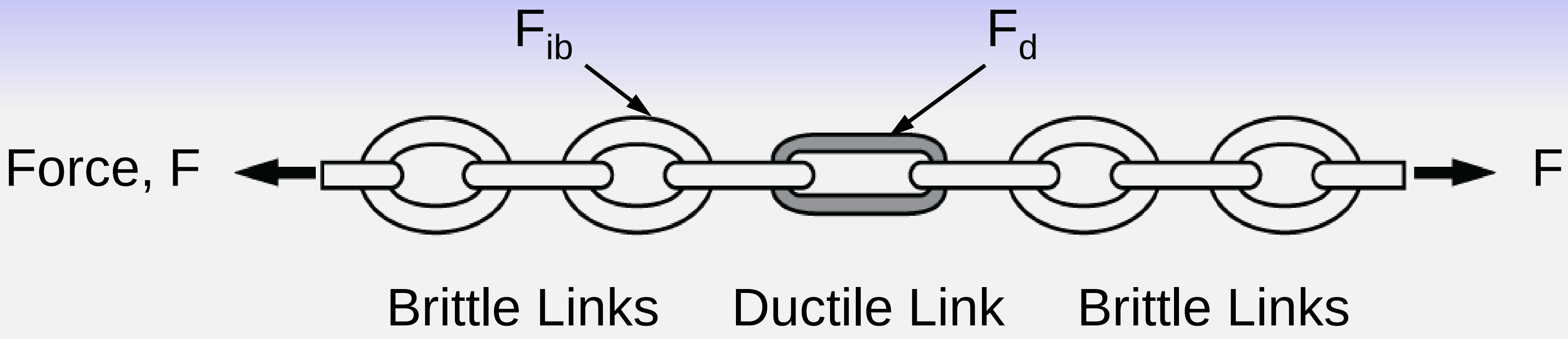
Yielding Structure Response



Ground Acceleration

Bridges can be built to perform in a ductile manner

Chain Analogy - Capacity Protection



F_{ib}

F_d

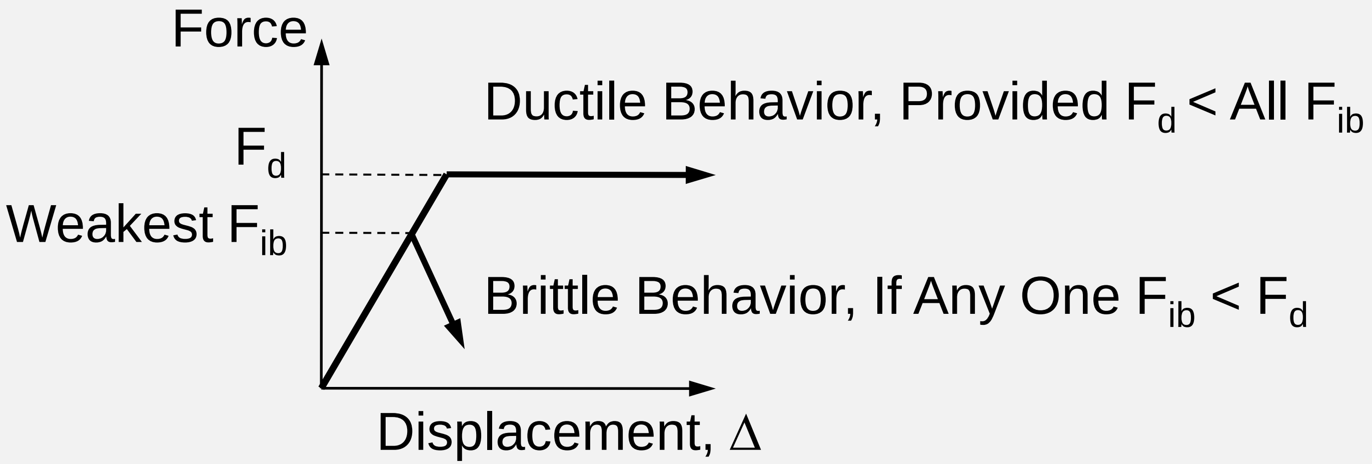
Force, F

F

Brittle Links

Ductile Link

Brittle Links



Force

F_d

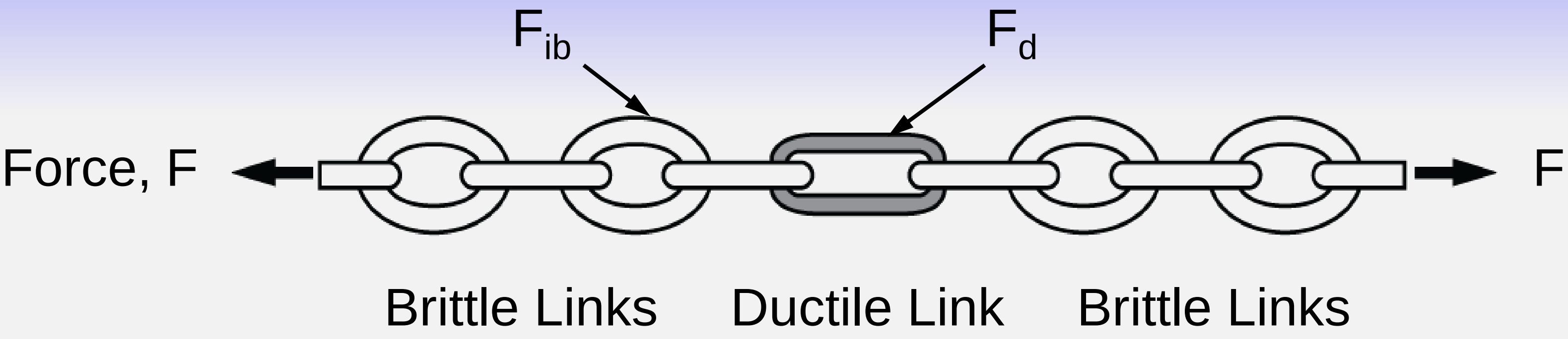
Weakest F_{ib}

Ductile Behavior, Provided $F_d <$ All F_{ib}

Brittle Behavior, If Any One $F_{ib} < F_d$

Displacement, Δ

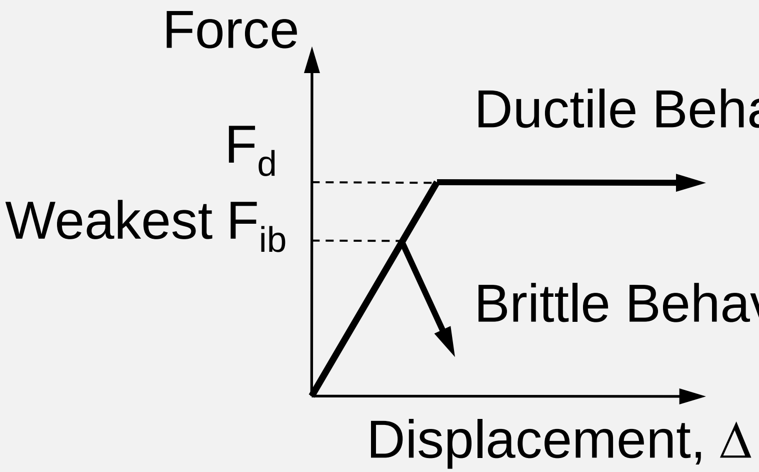
Chain Analogy - Capacity Protection



F_{ib} F_d

Force, F F

Brittle Links Ductile Link Brittle Links



Force

F_d

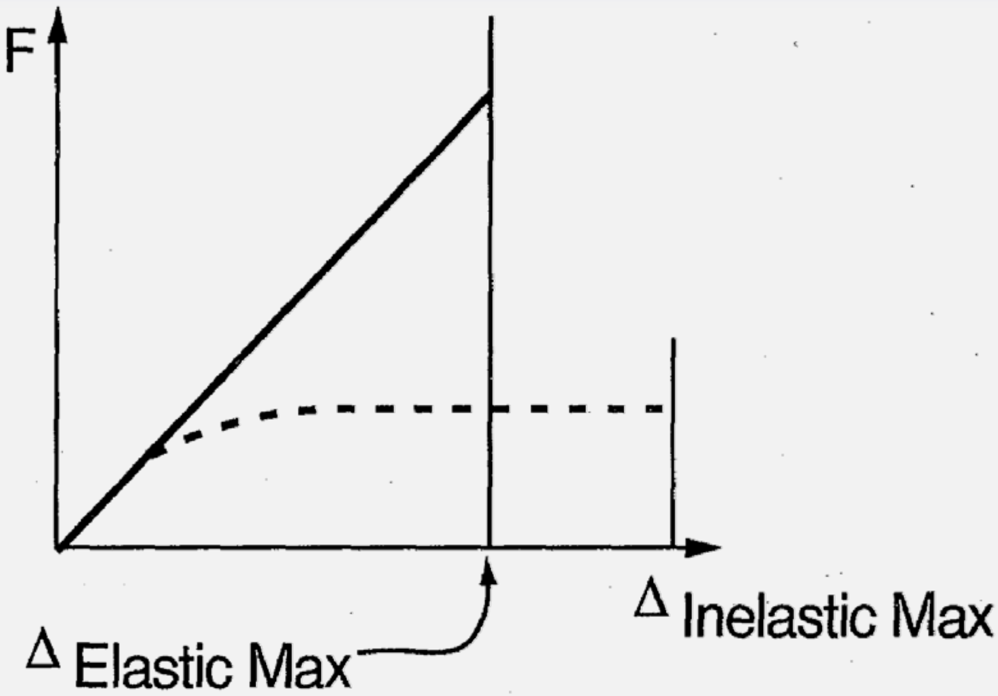
Weakest F_{ib}

Ductile Behavior, Provided $F_d < \text{All } F_{ib}$

Brittle Behavior, If Any One $F_{ib} < F_d$

Displacement, Δ

We Analyze Bridges Elastically



Can use linear elastic analysis to predict nonlinear displacements!

Inelastic to Elastic Response

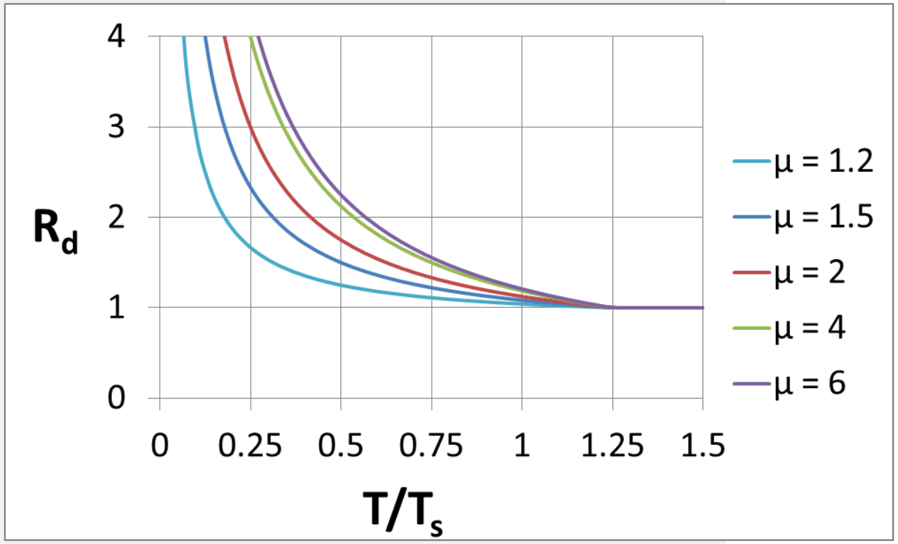
Two common methods:

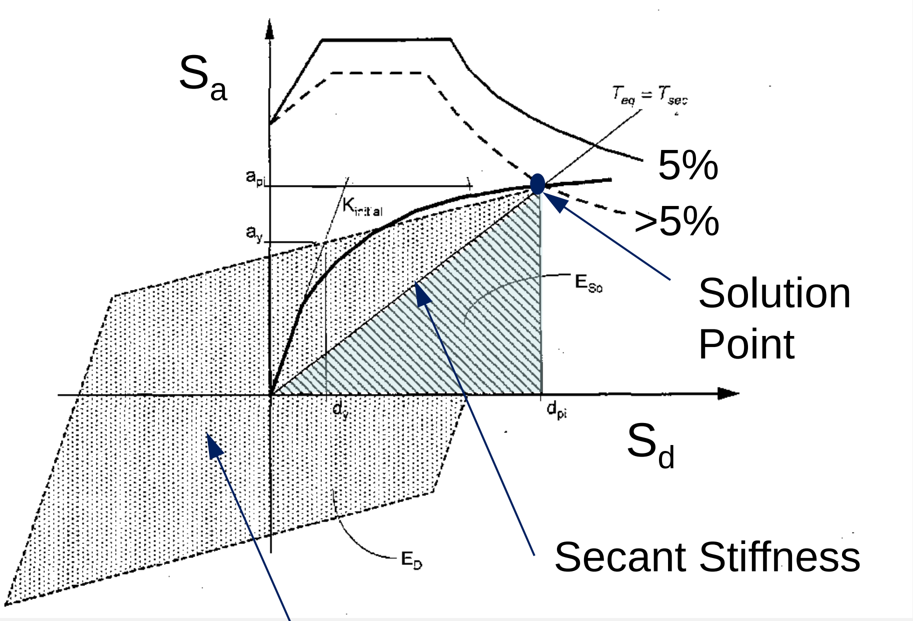
“Coefficient” Method

(AASHTO – LS and GS)

Substitute Structure Method

(Capacity Spectrum - Isolation)





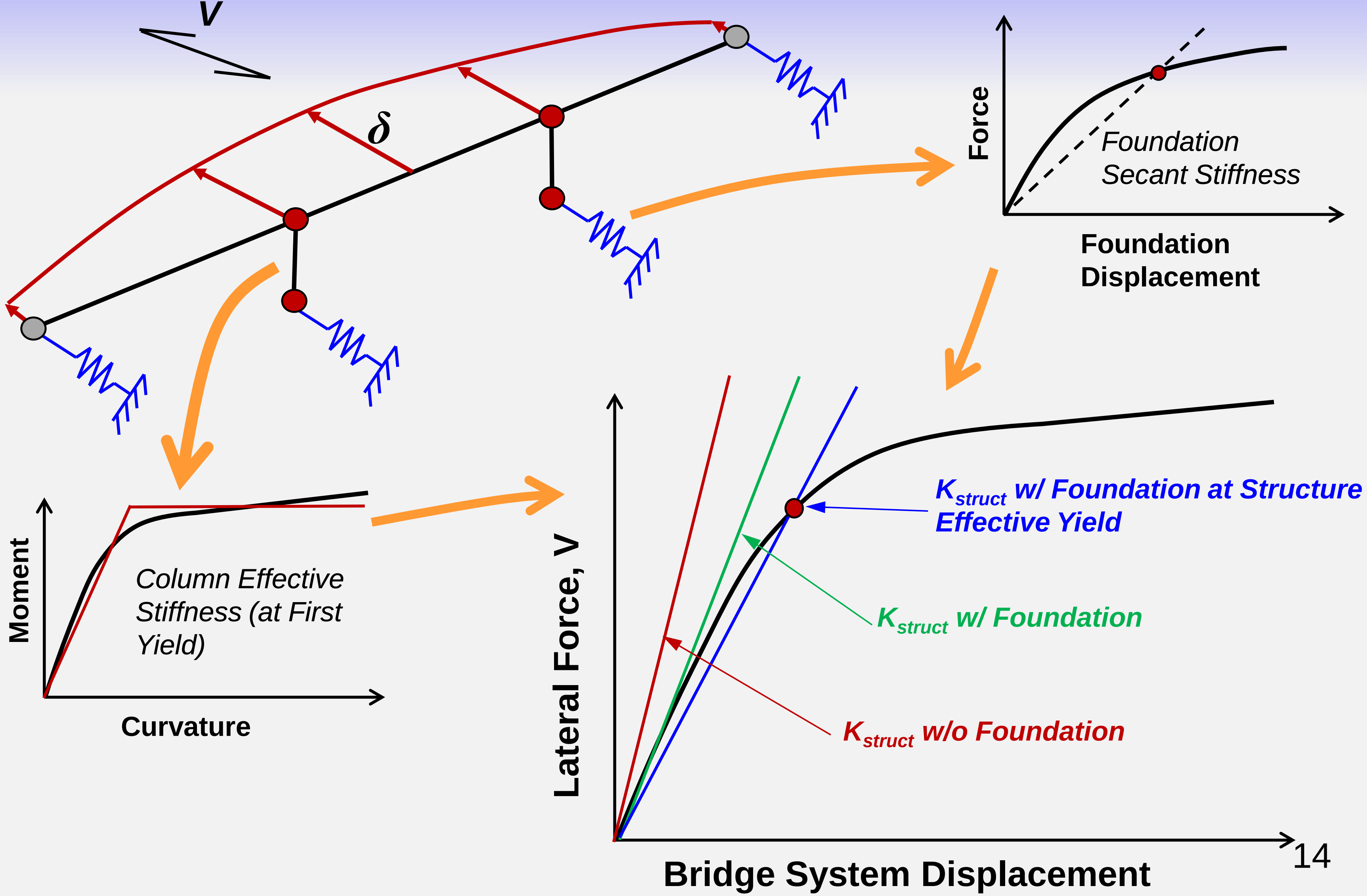
T = Fundamental Period of System
T_s = “Corner” of Response Spectrum

Area gives effective damping – based on hysteretic behavior

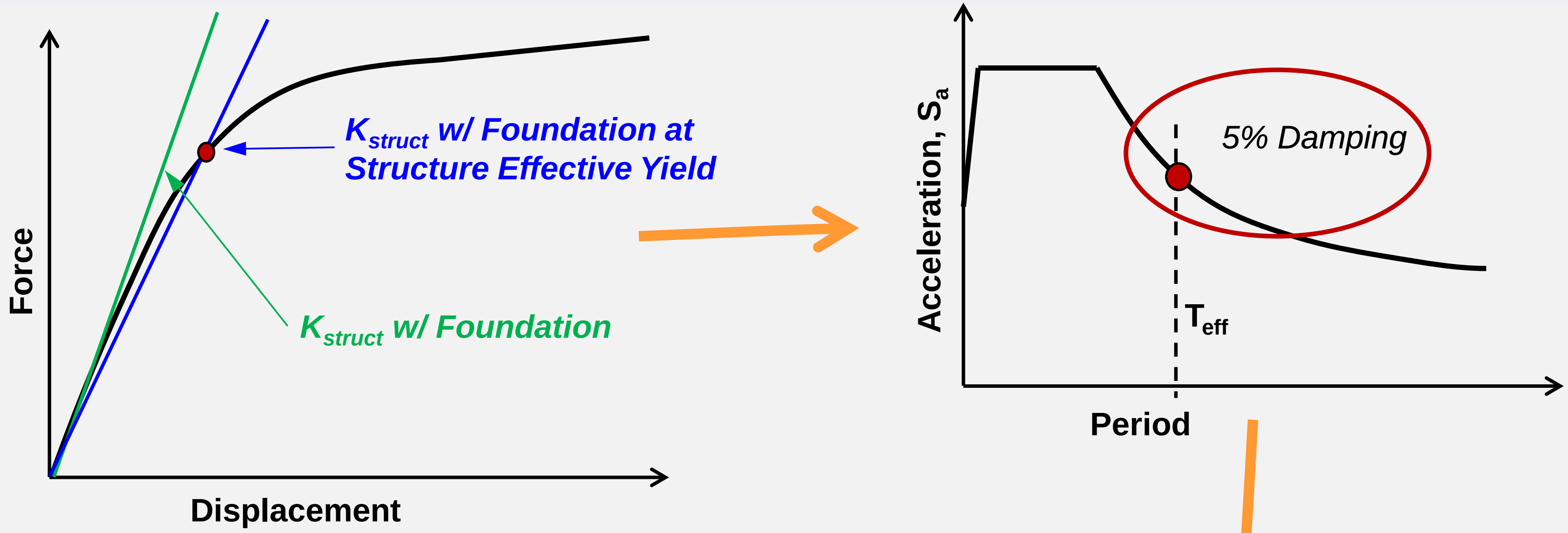
Basic Steps of Seismic Design

Step	Basic Steps for Seismic Design
1	Determine Seismic Input
2	Establish Design Procedures
3	Identify the Earthquake Resisting System and Global Design Strategy
4	Perform Demand Analysis
5	Design and Check Earthquake Resisting Elements (Ductile or Other)
6	Capacity Protect the Remaining Elements

Foundation “K”s vs Structural “K”s



Foundation “K”s vs Structural “K”s

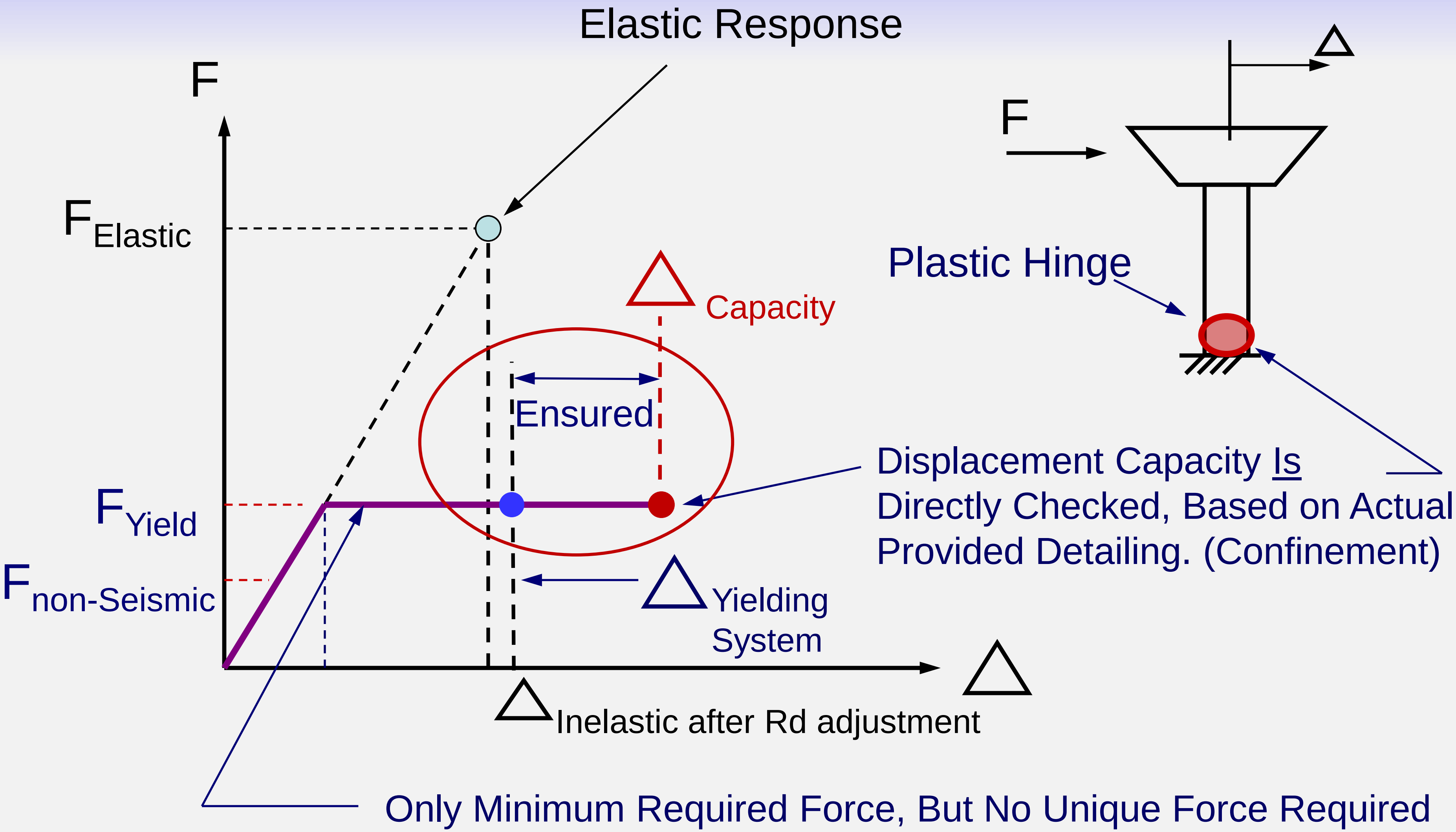


Elastic Δ_e of structure using multi-mode spectral analysis

Expected Inelastic Displacement Demand

$$\boxed{\Delta_D = R_d \Delta_e}$$

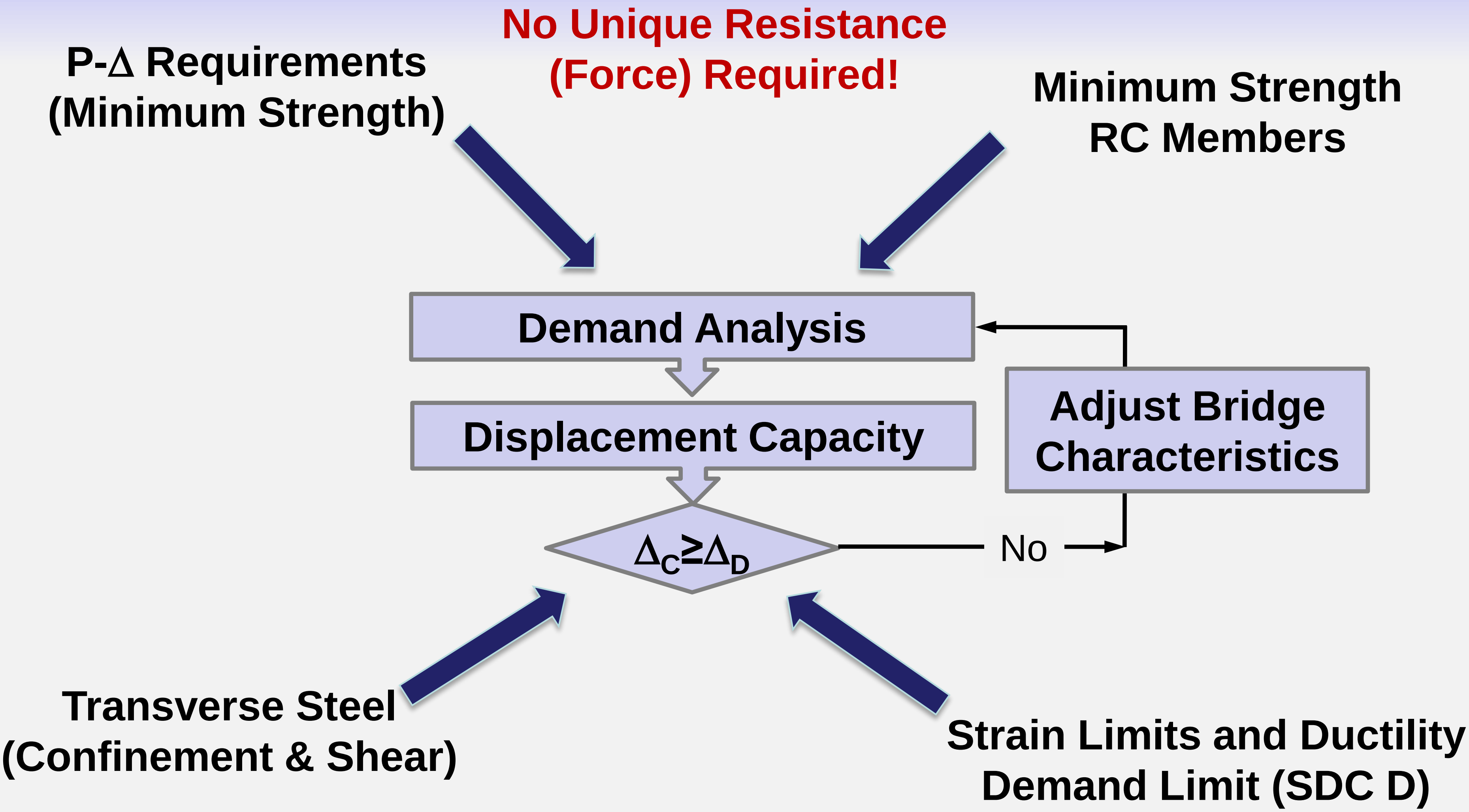
Displacement-Based Method (DBM)



Displacement Capacity Is Directly Checked, Based on Actual Provided Detailing. (Confinement)

Only Minimum Required Force, But No Unique Force Required

Ductile Design Activity - DBM



No Unique Resistance (Force) Required!

P-Δ Requirements (Minimum Strength)

Minimum Strength RC Members

Demand Analysis

Displacement Capacity

$\Delta_C \geq \Delta_D$

No

Adjust Bridge Characteristics

Transverse Steel (Confinement & Shear)

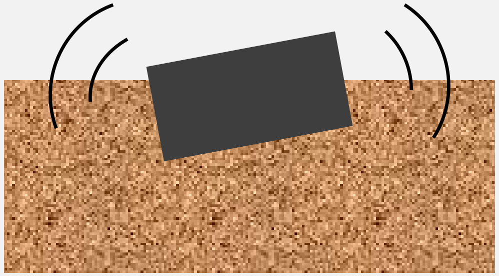
Strain Limits and Ductility Demand Limit (SDC D)

Soil-Foundation-Structure Interaction

- Inertial Response (structure ‘loads’ soil)

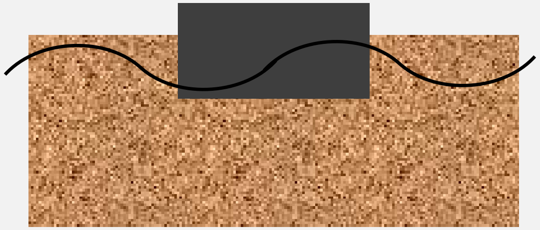
  Soil and structure respond dynamically due to their mass and the flexibility of the soil around foundation

  (Most often included form of SFSI and focus of this webinar)



- Kinematic Response (soil ‘loads’ structure)

  Presence and rigidity of foundation alters the free-field motion of soil



Foundation Modeling Aspects

- Masses
  - Structural inertial forces usually dominant
  - Inertia of soil and foundation is usually small and neglected
- Damping
  - Difficult to properly account for radiation and material damping of foundation systems
  - Material damping is strain dependent
  - Additional (>5%) damping is typically and conservatively neglected
- Therefore usually only include stiffness effects!

Foundation Modeling

- Little in LS about modeling (Appendix A10)
- GS more specific (Could be used with LS)
  - Method I – modeling: simple-to-none
  - Method II – detailed guidance

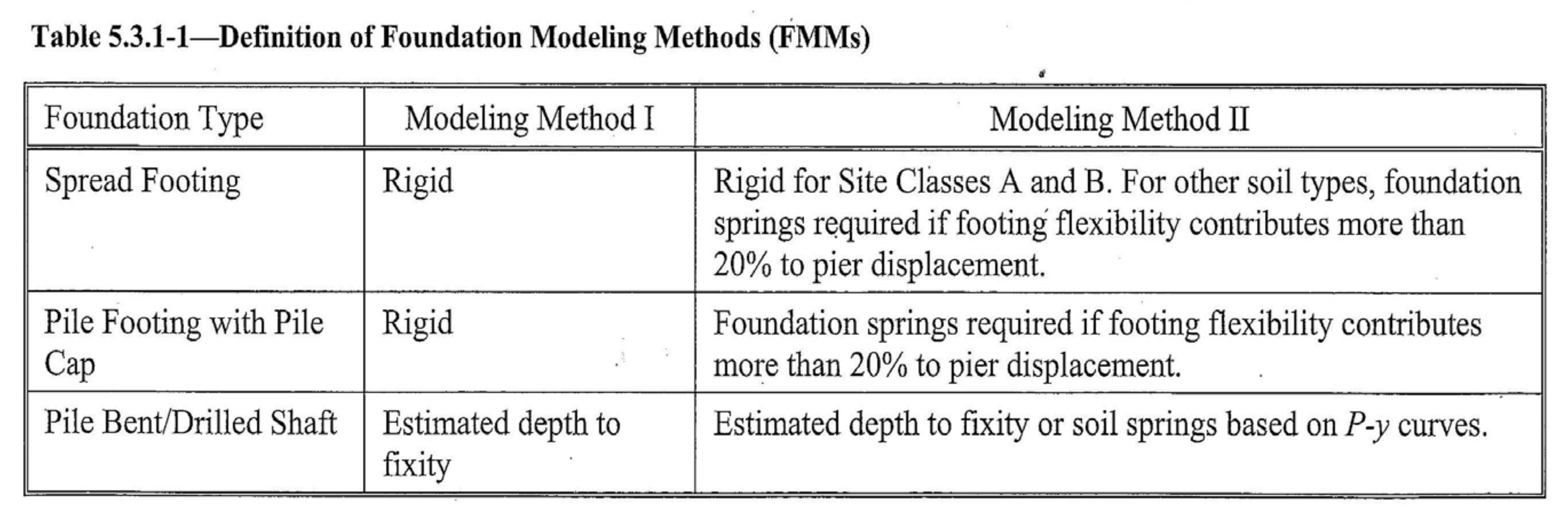


Table 5.3.1-1—Definition of Foundation Modeling Methods (FMMs)

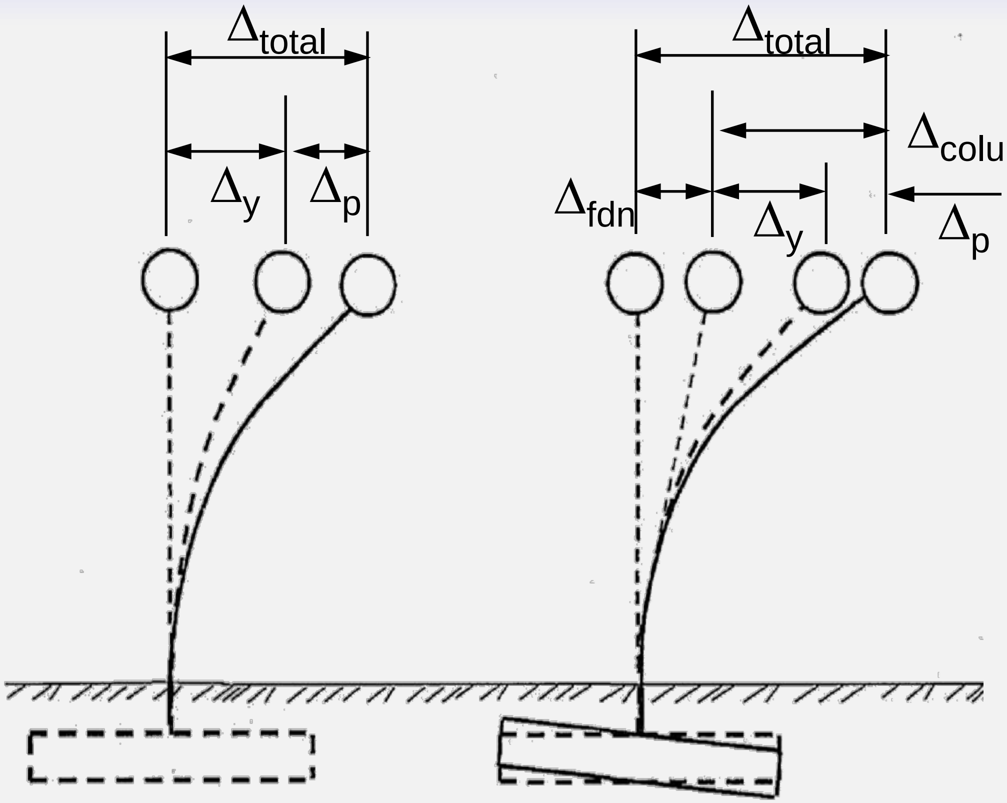
Foundation Type	Modeling Method I	Modeling Method II
Spread Footing	Rigid	Rigid for Site Classes A and B. For other soil types, foundation springs required if footing flexibility contributes more than 20% to pier displacement.
Pile Footing with Pile Cap	Rigid	Foundation springs required if footing flexibility contributes more than 20% to pier displacement.
Pile Bent/Drilled Shaft	Estimated depth to fixity	Estimated depth to fixity or soil springs based on *P*-*y* curves.

Considering Foundation Effects

- Generally, demand model and assessment (pushover) models should be consistent (i.e. either both include flexibility or both ignore flexibility)
- If demand model includes foundation flexibility:
  - OK to check without foundation considered, if all foundation effects are included with the plastic deformations (quick and dirty method)
  - Do not include foundation effects as an increase in yield – unconservative!

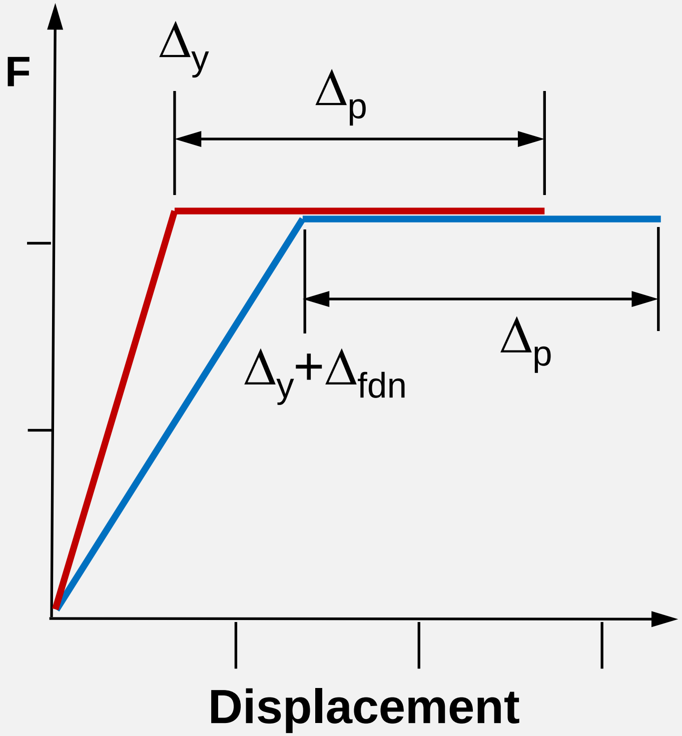
Foundation Effects

Flexibility of adjacent members increases apparent yield point, but does not change the plastic component



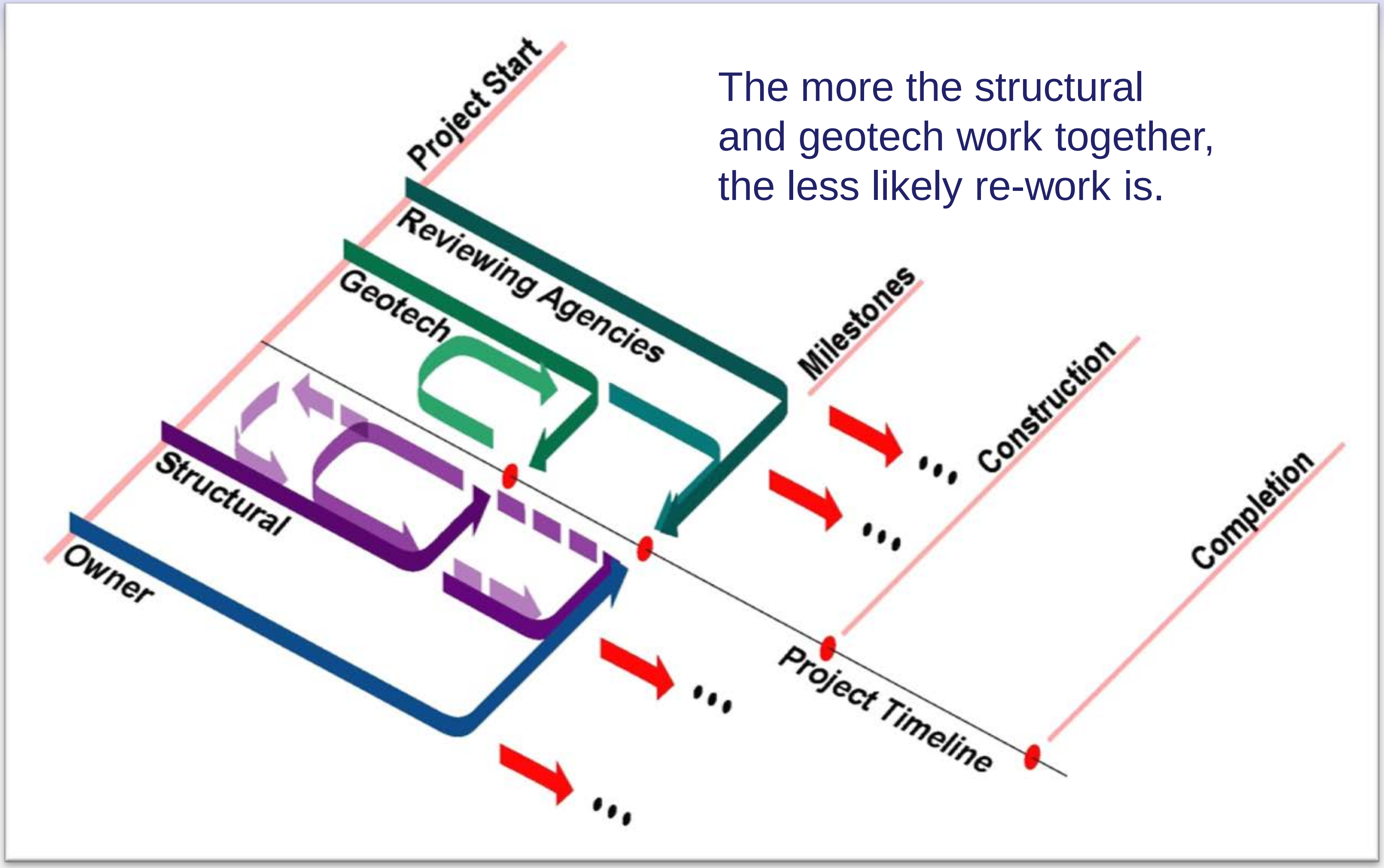
Fixed Base

Foundation Flexibility Included



Effect of Foundation Flexibility on Structure Displacement Capacity

Structural / Geotech Collaboration

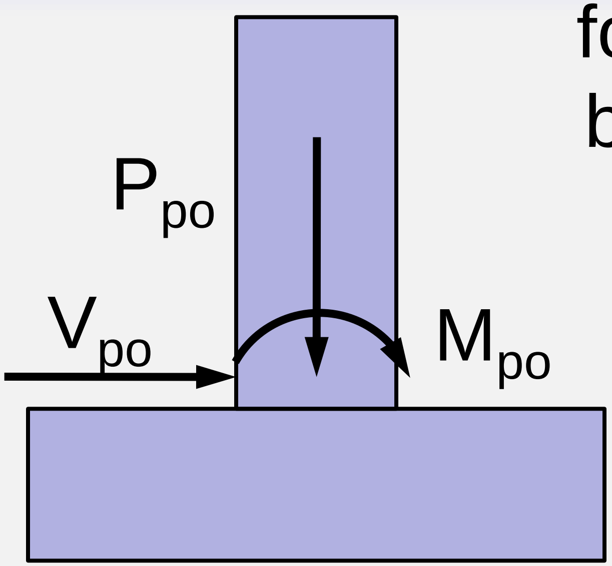


The more the structural and geotech work together, the less likely re-work is.

Capacity-Protected Elements

Example:
Spread
Footing

Use the maximum forces that can be transmitted to element



Plastic overstrength forces

Design and detail to remain “elastic”.

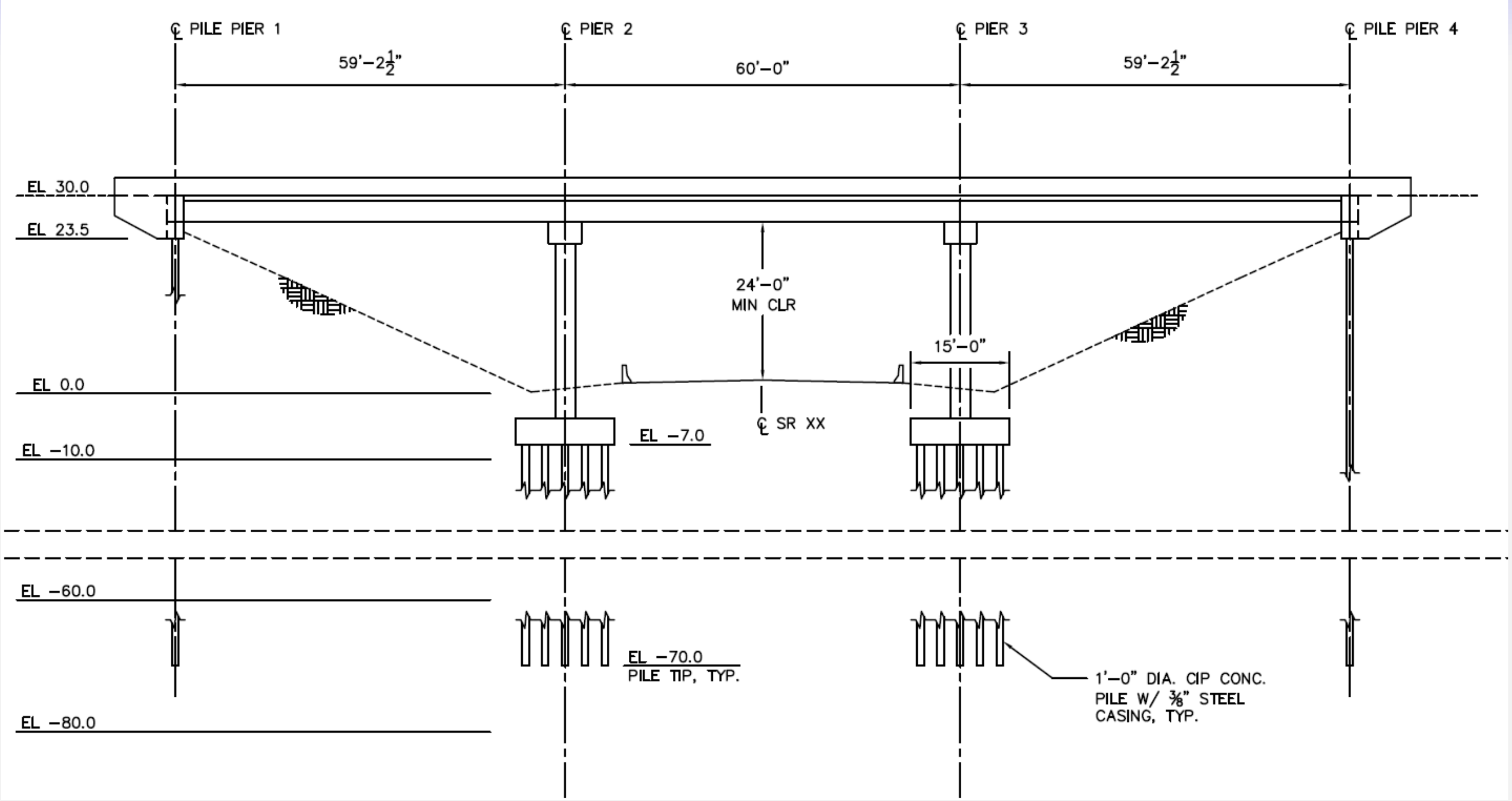
Resistance factors (ϕ) along with nominal or expected properties are used depending on desired conservatism.

Design Example No. 1

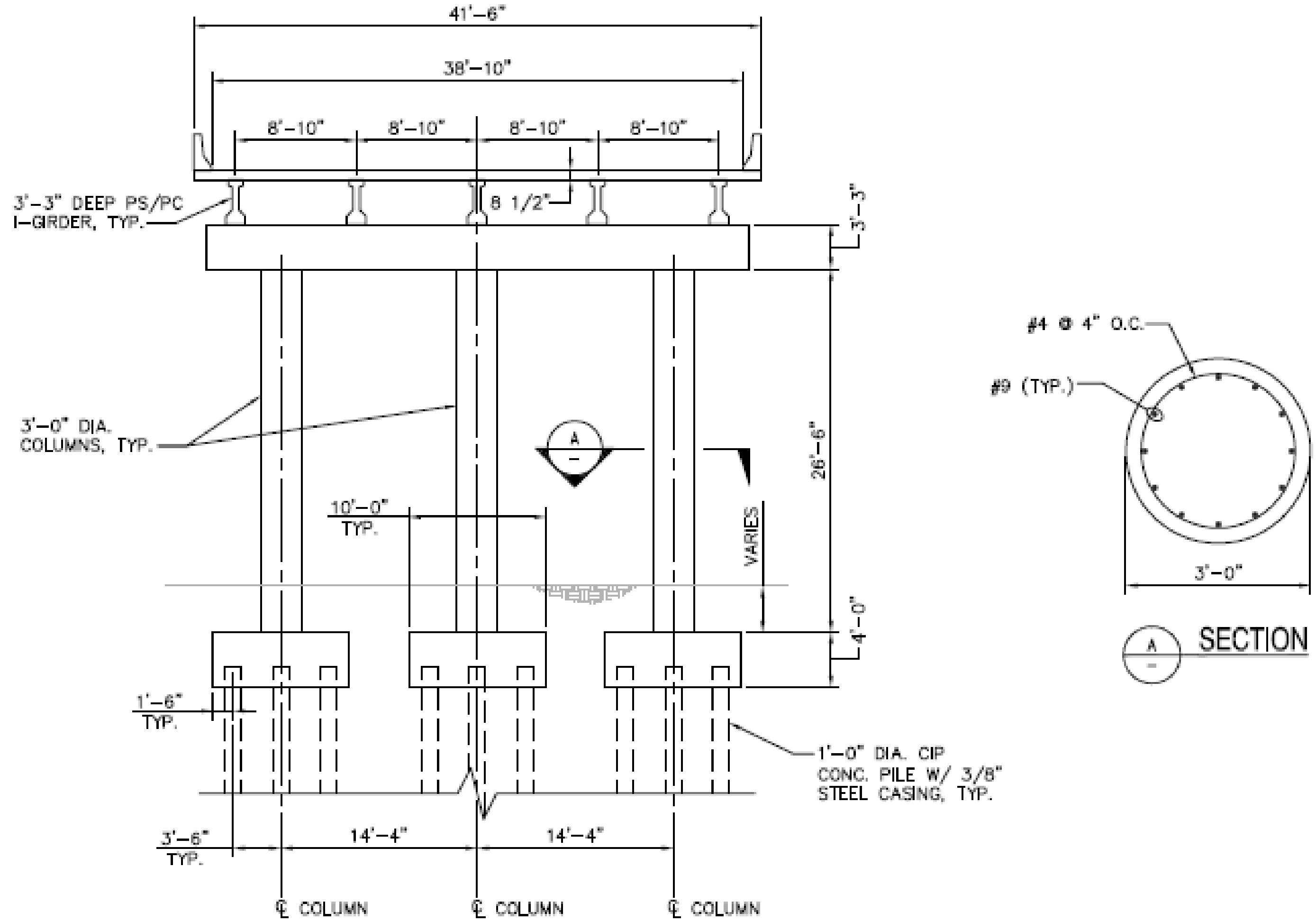
Topics Covered:

- *Guide Specifications for LRFD Seismic Bridge Design*
- Pile group and pile cap stiffness
- Structural modeling
- Displacement checks
- Capacity protection of pile group foundations

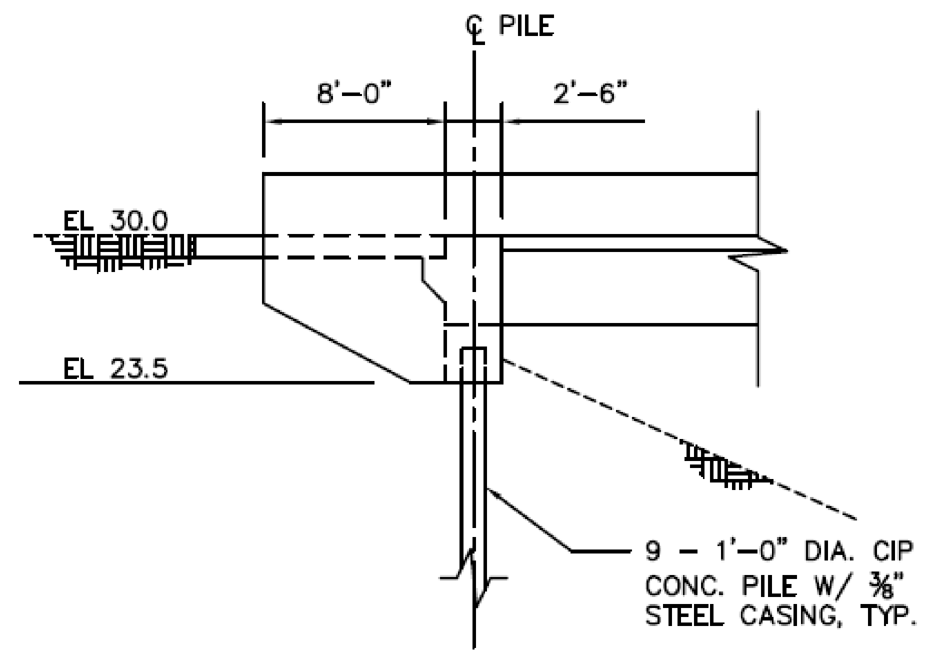
Design Example No. 1 - Elevation



Design Example No. 1 - Sections



Design Example No. 1 - Abutments



Design Example No. 1 - Data

- Location – New Madrid, MO
- Zip Code 63873, Lat: 36.555 Long: - 89.618
- *Guide Specifications for LRFD Seismic Bridge Design* (GS)
- Operational Classification – “Other” (although not in SGS)
- SD1 = 0.83 g
- Site Class D
- Seismic Design Category D
- Multi-column Piers
- No skew or curve

Basic Steps of Seismic Design

Step	Basic Steps for Seismic Design
1	Determine Seismic Input
2	Establish Design Procedures
3	Identify the Earthquake Resisting System and Global Design Strategy
4	Perform Demand Analysis
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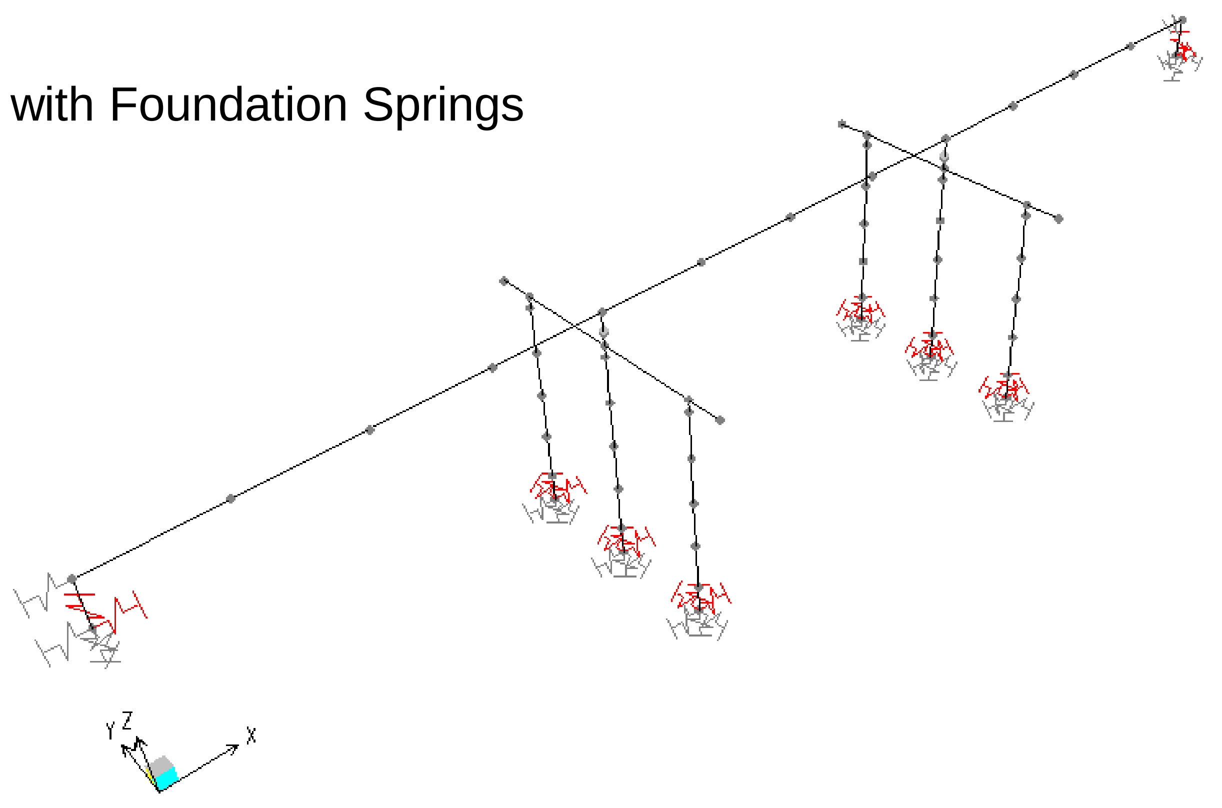
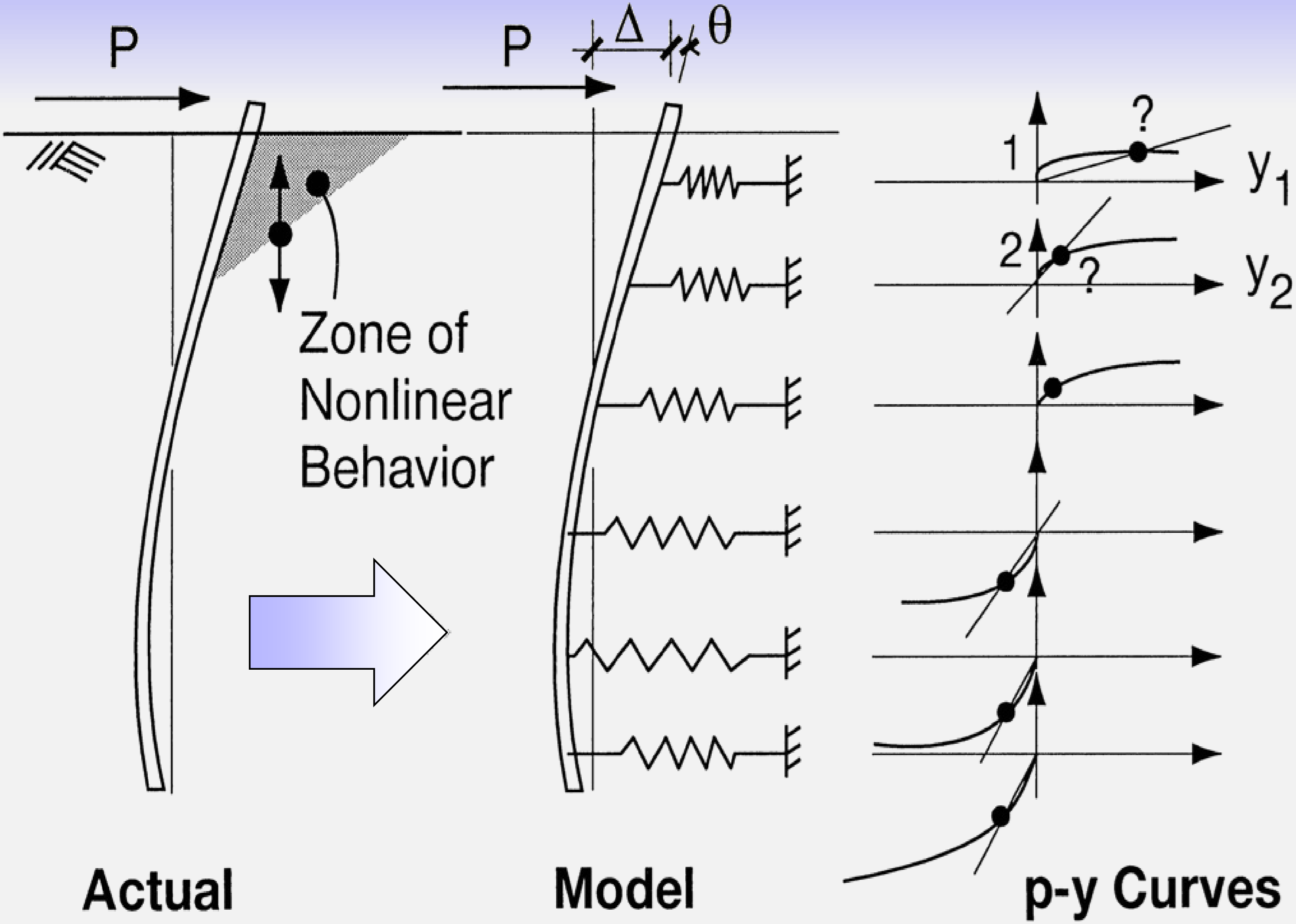
6	Capacity Protect the Remaining Elements

Structural Model

Spine Model with Foundation Springs



Nonlinear Lateral Behavior of Piles



Development of Pier Springs

LPILE results. Stiffnesses for various shear values.

Axial Load to piles = 27.9 kips/pile

Pile Type: 12" Diameter CIP with steel casing

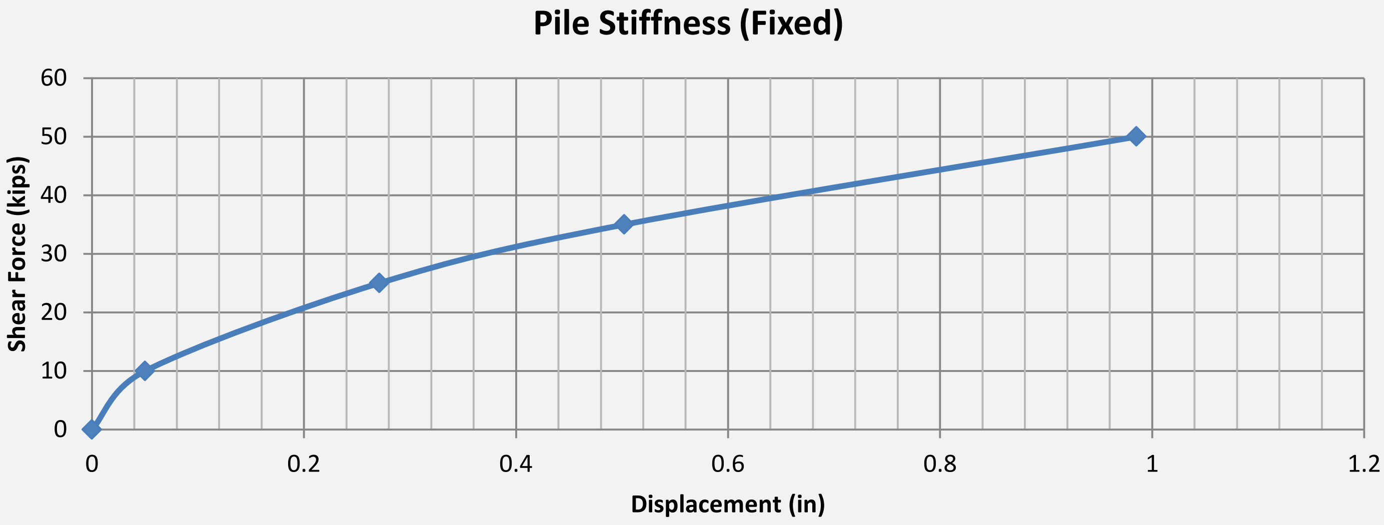
Number of Piles 14

Spaced at 3'-0" center to center Long.

Spaced at 3'-6" center to center Trans.

Deflection Fixed Top

Shear	Deflection
0 kips	0 in
10 kips	0.05 in
25 kips	0.271 in
35 kips	0.502 in
50 kips	0.985 in



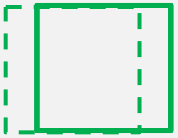
Development of Pier Springs

Axial Stiffness of Pile		
12" CIP pile Steel Encased		
Area =	190	in^2
E =	4372	ksi
Length =	63	ft
Alpha Modifier =	2	Skin Friction
K =	550	kips/in
Ktot =	7.70E+03	kips/in

Pile Group effects AASHTO LRFD Table 10.7.2.4-1			
Spacing	Row 1	Row 2	Row 3+
3B	0.7	0.5	0.35
3.5	0.78	0.59	0.44
5B	1	0.85	0.7

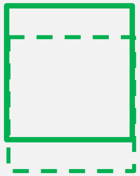
Requires Iteration with Structural Model

Longitudinal Stiffness of Pile	
Longitudinal Elastic Deflection	**0.36 in**
Pile Longitudinal Axis Stiffness	**80.15 kips/in**
Group Longitudinal Axis Stiffness	**513 kips/in**
Including Pile Cap	**555 kips/in**



Longitudinal Pile Cap Passive Stiffness	
4	ft = Cap Height
4.35	= Kp (Passive Pressure)
115	pcf = Soil Unit Weight
10	ft = Cap Width
40	kips = Plastic Soil Resistance
0.02	= Fw for Medium Dense Sand
0.96	in = Yield Deflection
41.7	kips/in = Stiffness at Elastic Deflection

Transverse Stiffness of Pile	
Transverse Elastic Deflection	**0.47 in**
Pile Transverse Axis Stiffness	**71.64 kips/in**
Group Transverse Axis Stiffness	**603 kips/in**
Including Pile Cap	**665 kips/in**



Transverse Pile Cap Passive Stiffness	
4	ft = Cap Height
4.35	= Kp (Passive Pressure)
115	pcf = Soil Unit Weight
15	ft = Cap Width
60	kips = Plastic Soil Resistance
0.02	= Fw for Medium Dense Sand
0.96	in = Yield Deflection
62.5	kips/in = Stiffness at Elastic Deflection

Development of Pier Springs

Rotational Stiffness

5 rows @ 3' of 3 piles @ 3.5' centers
(no pile under column, 14 total)

About Long Axis	9.70E+06	k-in/rad
About Trans Axis	2.14E+07	k-in/rad

Rotational Stiffness about Vertical Axis

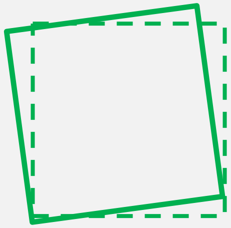
Longitudinal stiffness of a single pile (kips/in)
Transverse Dimension to locate pile (ft)

56.10 3.5	**56.10** 0	**56.10** 3.5
40.07 3.5	**40.07** 0	**40.07** 3.5
28.05 3.5		**28.05** 3.5
28.05 3.5	**28.05** 0	**28.05** 3.5
28.05 3.5	**28.05** 0	**28.05** 3.5

K (Y^2) (Kip-ft/rad)

57.27	**0.00**	**57.27**
40.91	**0.00**	**40.91**
28.64		**28.64**
28.64	**0.00**	**28.64**
28.64	**0.00**	**28.64**

SUM: 368.17 Kip-ft/rad



Transverse stiffness of a single pile (kips/in)
Longitudinal Dimension to locate pile (ft)

55.52 6	**42.09** 6	**31.34** 6
55.52 3	**42.09** 3	**31.34** 3
55.52 0		**31.34** 0
55.52 3	**42.09** 3	**31.34** 3
55.52 6	**42.09** 6	**31.34** 6

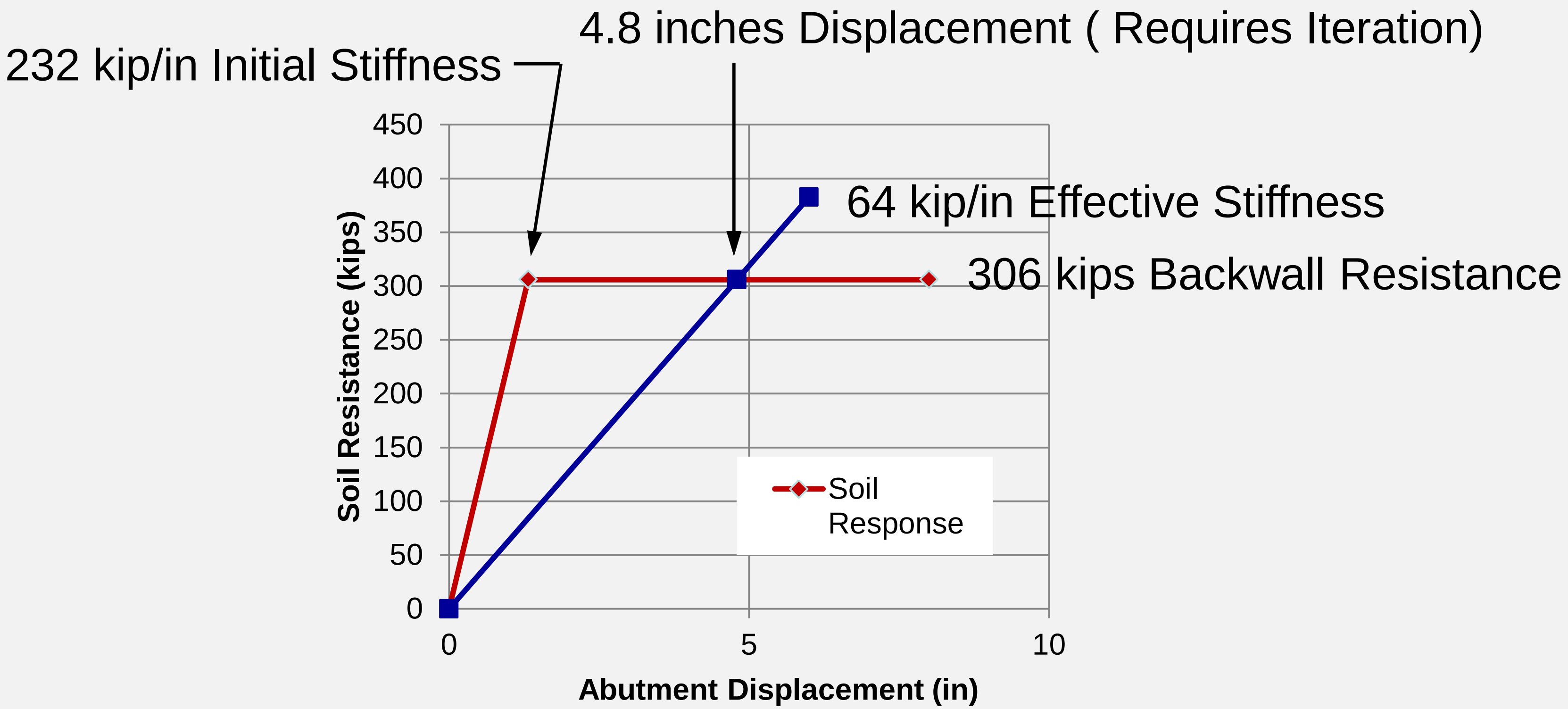
K (Y^2) (Kip-ft/rad)

166.57	**126.27**	**94.03**
41.64	**31.57**	**23.51**
0.00		**0.00**
41.64	**31.57**	**23.51**
166.57	**126.27**	**94.03**

SUM: 967.16 Kip-ft/rad

Combined SUM:	**1335.33**	**Kip-ft/rad**
	16023.98	**Kip-in/rad**

Abutment Stiffness - Longitudinal



4.8 inches Displacement (Requires Iteration)

232 kip/in Initial Stiffness

64 kip/in Effective Stiffness

306 kips Backwall Resistance

Model Results

Model Results – Longitudinal Direction

Mode	T	C_a	$(\%\text{mass} \times C_a)^2$
[---]	[seconds]	[g]	[---]
1	0.6287	1.328	0.000
2	0.5606	1.509	1.342
3 to 20	< 0.44	1.888	0.189
		Total:	1.53

$\sqrt{\sum(\%mass \times C_a)^2}$ =	1.24
W =	2,601 kips
V =	3,218 kips
Vmodel =	3,225 kips
% difference =	-0.2

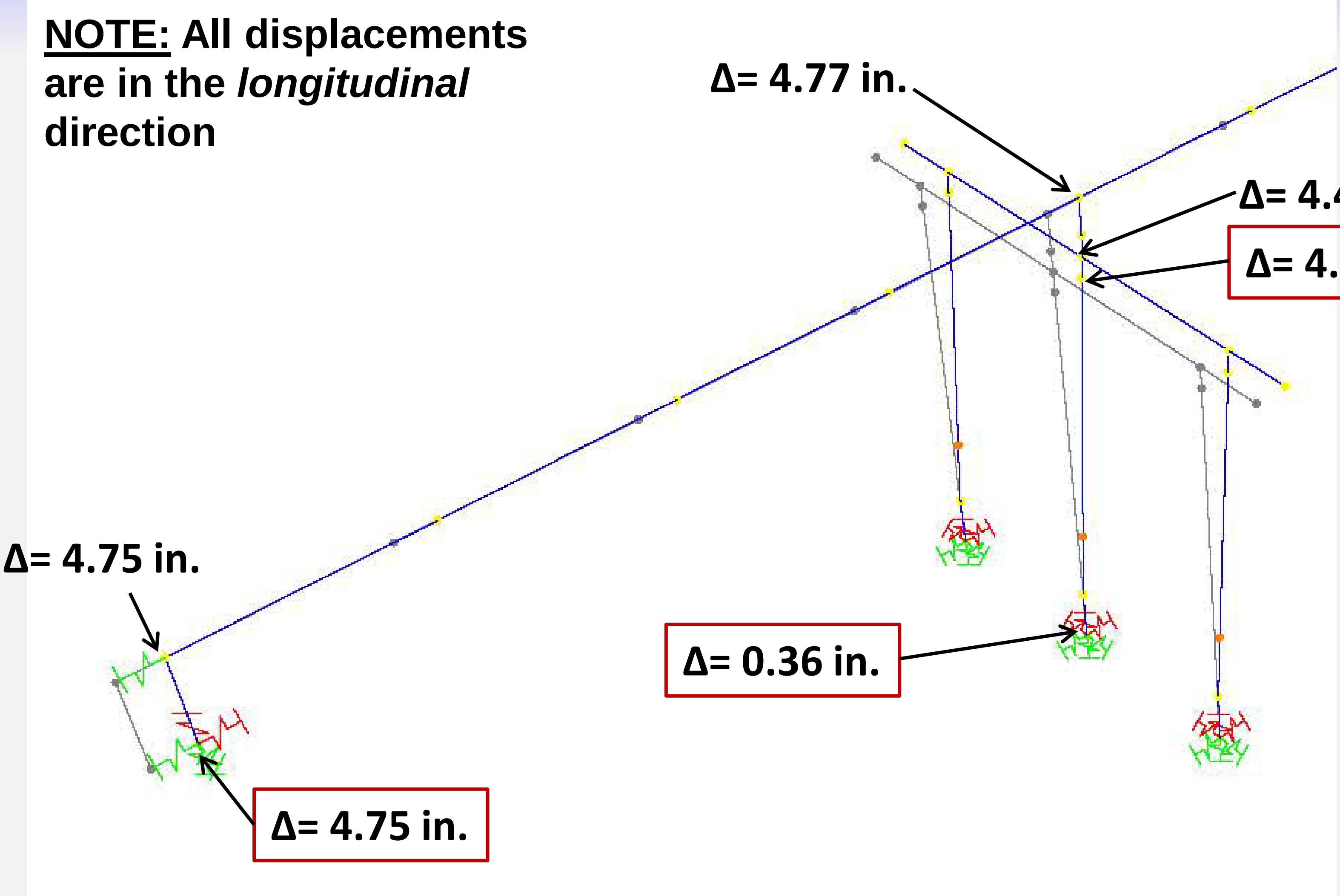
Model Results – Response Spectrum Displacements

Pier	Joint	Longitudinal EQ		Transverse EQ	
		X	Y	Y	X
[---]	[---]	[inches]	[inches]	[inches]	[inches]
2	521	4.04	0.00	5.69	0.00
3	531	4.04	0.00	5.69	0.00

Load Case 1: 100% EQ LONGITUDINAL + 30% EQ TRANSVERSE
Load Case 2: 30% EQ LONGITUDINAL + 100% EQ TRANSVERSE

Longitudinal Displaced Shape

<u>NOTE:</u> All displacements are in the *longitudinal* direction



Δ= 4.77 in.

Δ= 4.40 in.

Δ= 4.04 in.

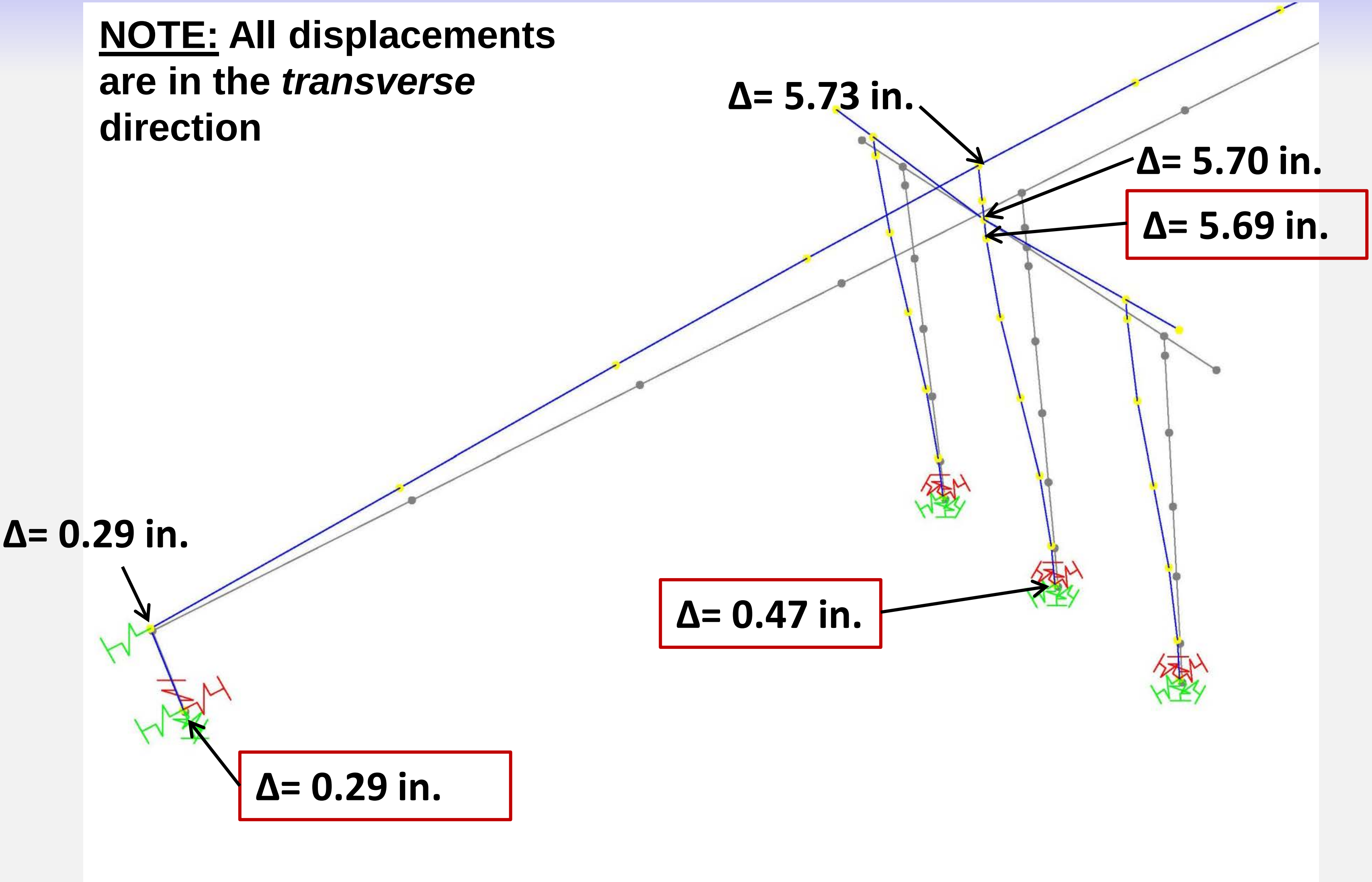
Δ= 4.75 in.

Δ= 0.36 in.

Δ= 4.75 in.

Transverse Displaced Shape

<u>NOTE:</u> All displacements are in the *transverse* direction



Δ= 5.73 in.

Δ= 5.70 in.

Δ= 5.69 in.

Δ= 0.29 in.

Δ= 0.47 in.

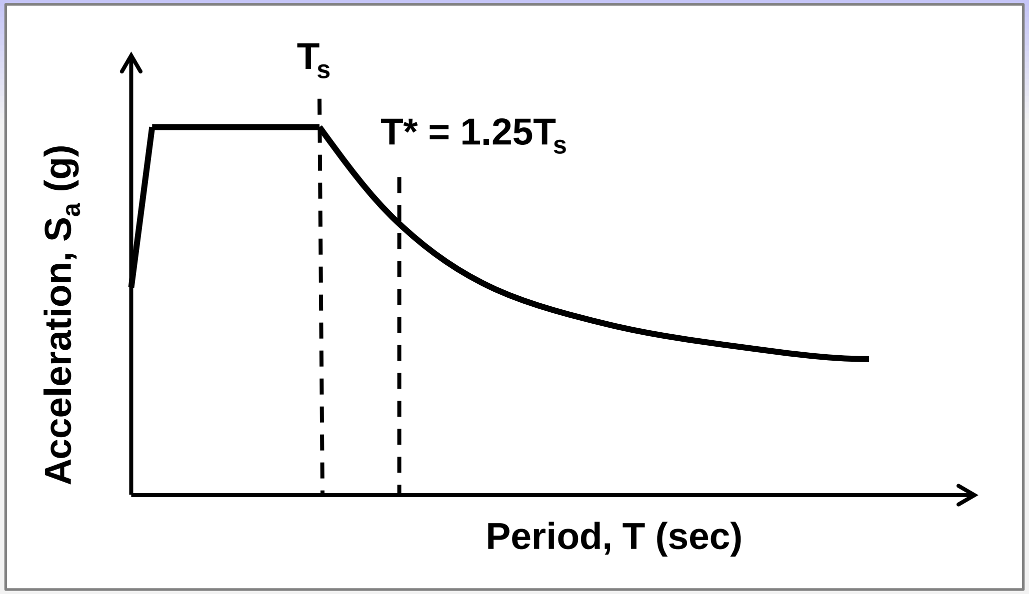
Δ= 0.29 in.

Displacement Magnification

$$R_d = \left(1 - \frac{1}{\mu_D}\right) \times \frac{T^*}{T} + \frac{1}{\mu_D}$$

$$T_s = \frac{S_{D1}}{S_{DS}} = \frac{0.831g}{1.888g} = 0.44s$$

$$T^* = 1.25 \times 0.44s = 0.55s$$



Longitudinal Direction

$$T = 0.561s$$

$$\frac{T^*}{T} = \frac{0.55\ s}{0.561\ s} = 0.98 < 1.0$$

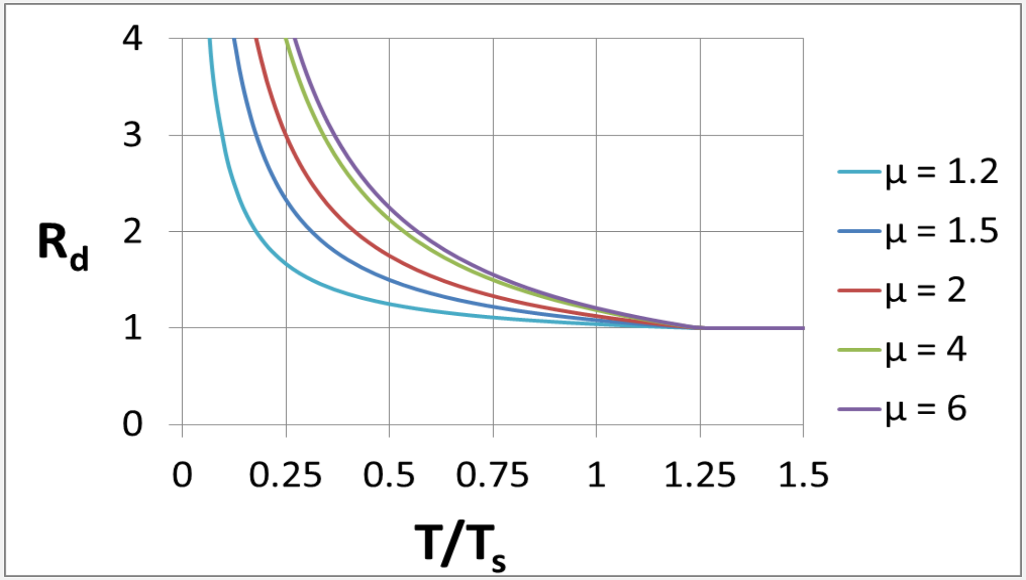
Displacement magnification is not required

Transverse Direction

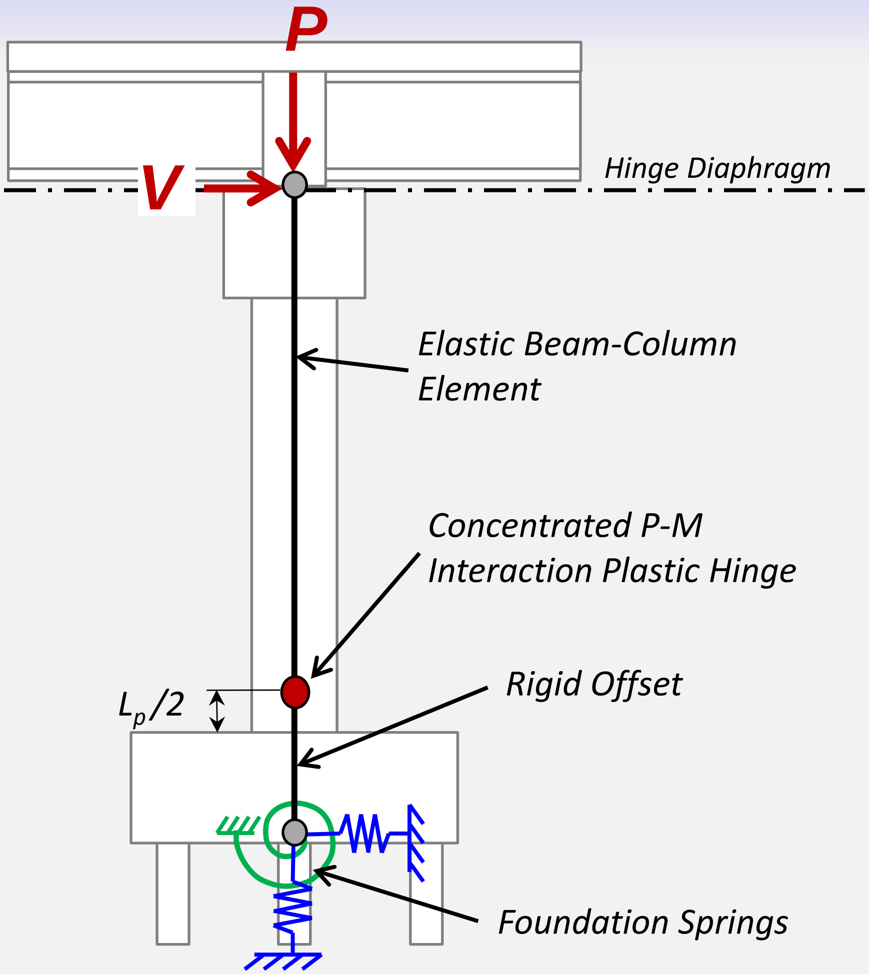
$$T = 0.629s$$

$$\frac{T^*}{T} = \frac{0.55\ s}{0.629\ s} = 0.87 < 1.0$$

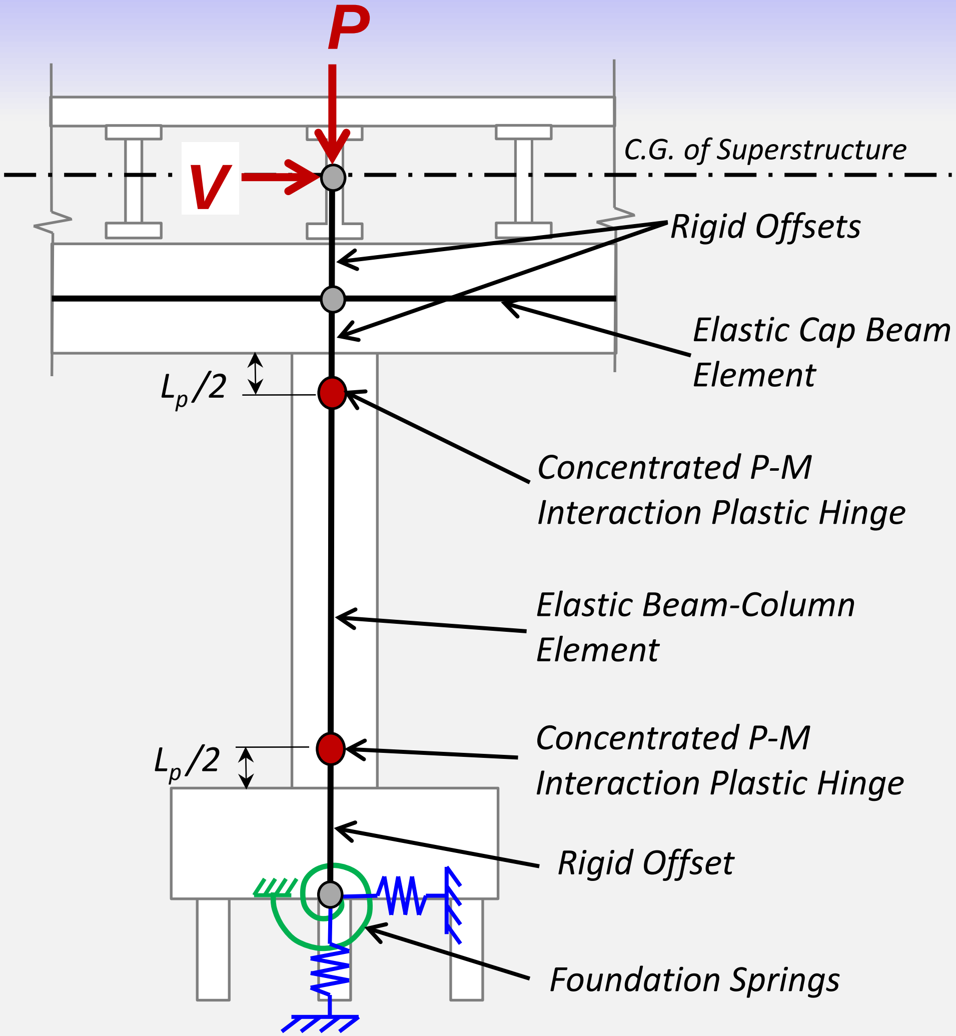
Displacement magnification is not required



Pushover Analysis Models

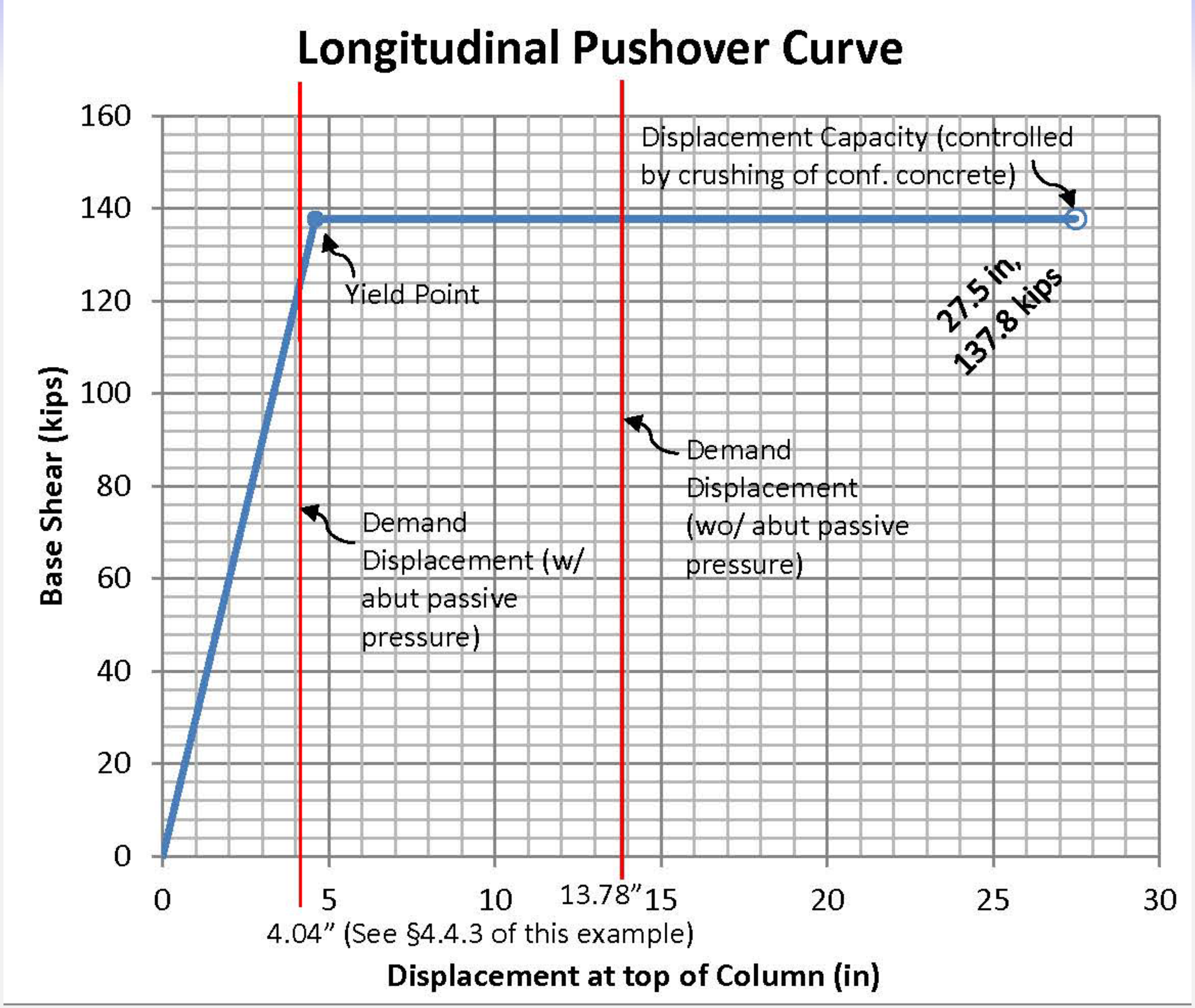


Longitudinal

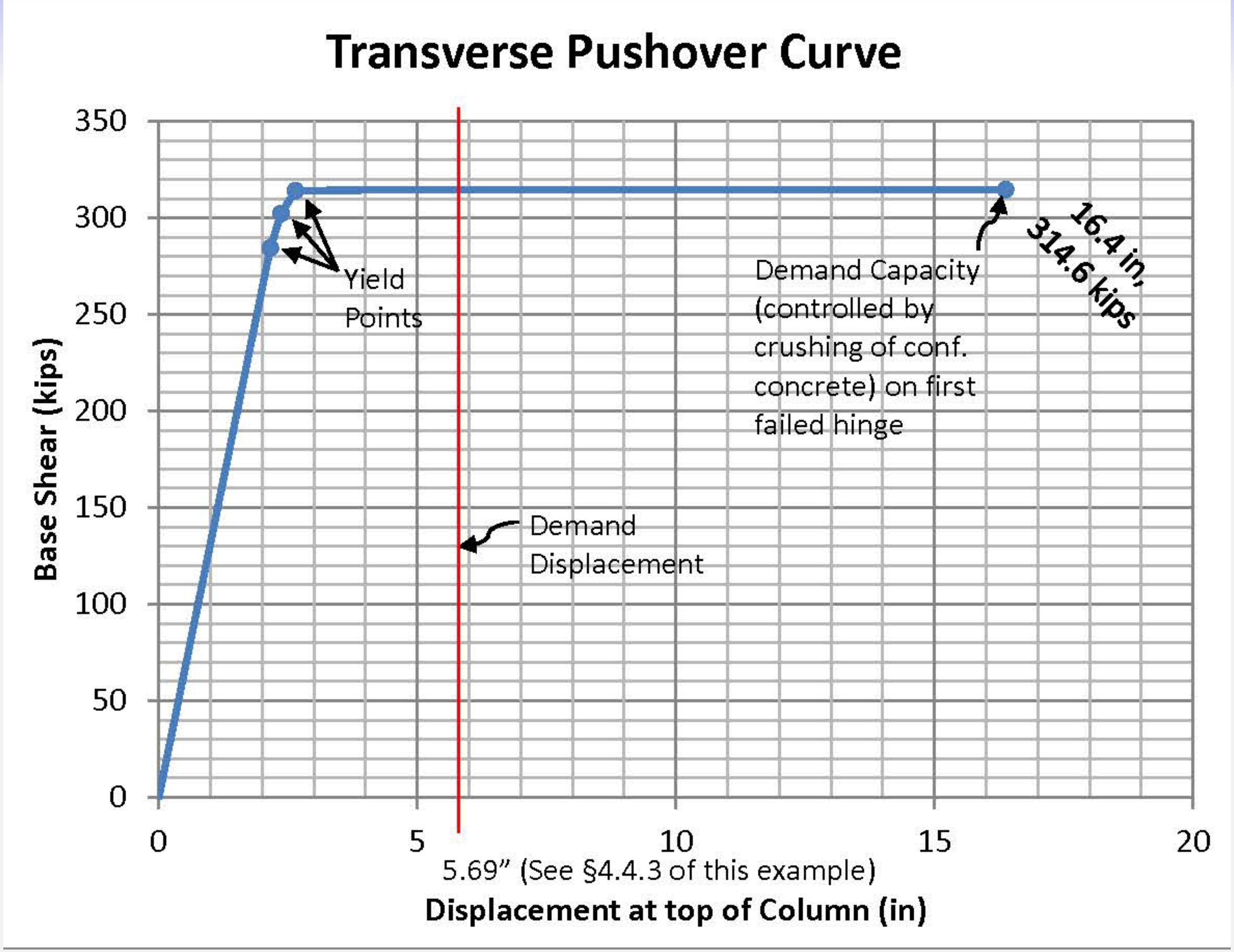


Transverse

Pier Pushover Longitudinal Direction

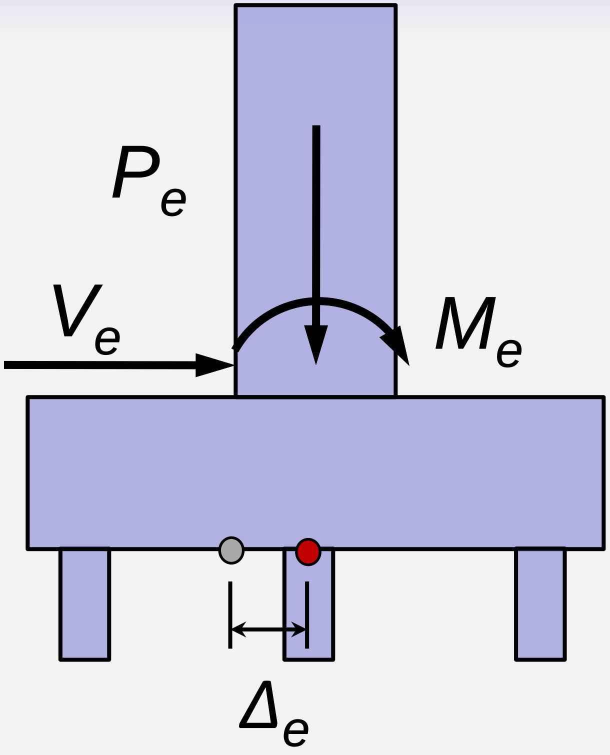


Pier Pushover Transverse Direction



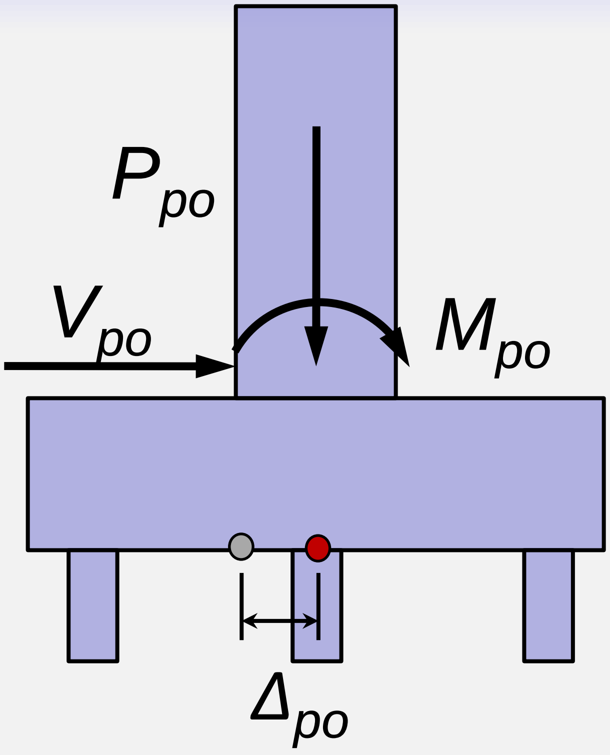
Elastic and Plastic Overstrength Forces

Elastic Forces



P_e = 469.3 kip
V_e = 272.4 kip
M_e = 3,355 kip-ft
Δ_e = 0.47 in.

Plastic Overstrength Forces



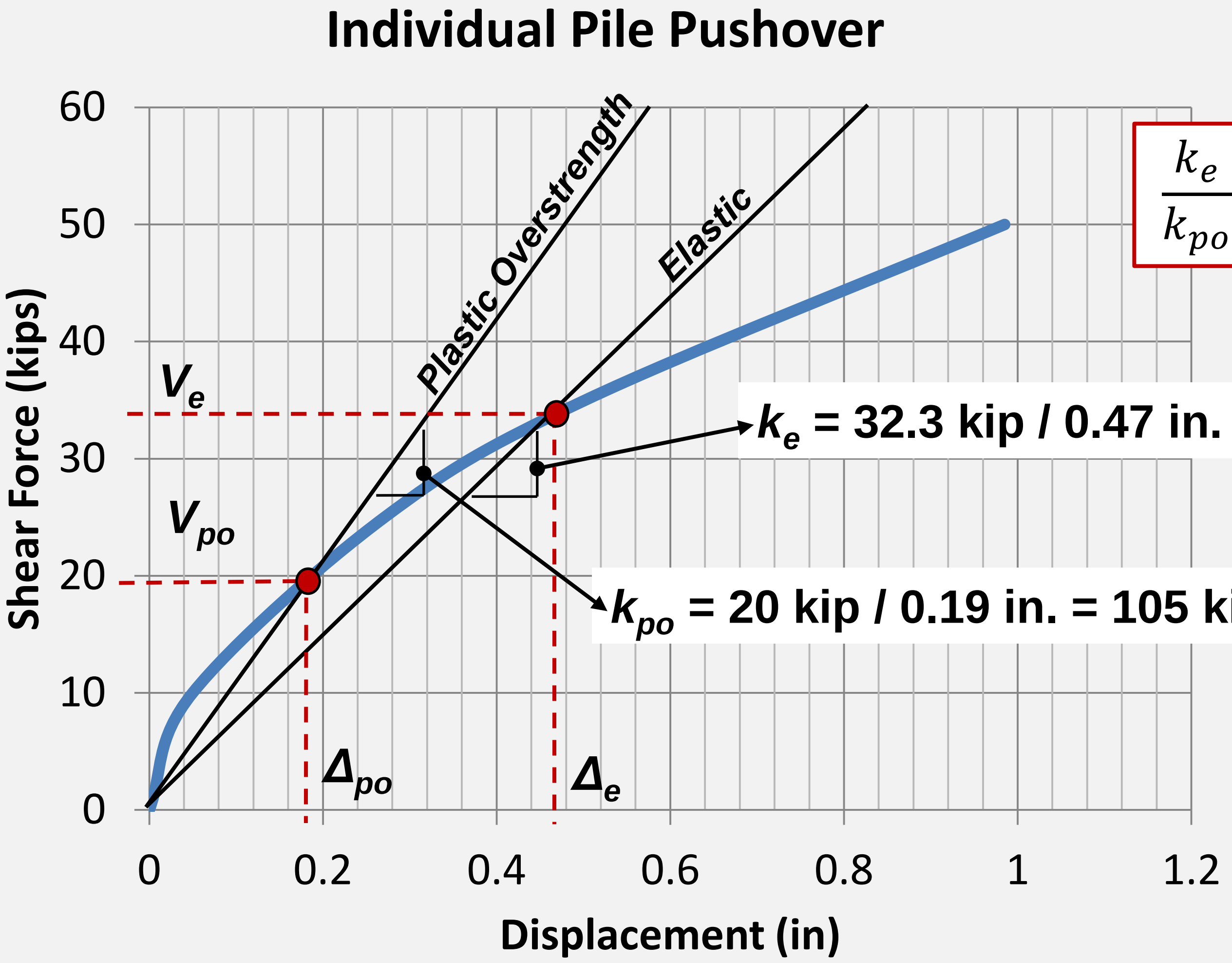
P_{po} = 471 kip
V_{po} = 124.6 kip
M_{po} = 1,663 kip-ft
Δ_{po} = 0.19 in.

NOTES:

(1) Forces are taken at the bottom of the exterior column under +ΔP transverse loading.
(2) Plastic forces are taken from the pier capacity protection design forces
(3) $\Delta_{po} = V_{po} / K_{trans}$

Elastic and Plastic Overstrength Forces

Take the horizontal translation of the pile cap under elastic and overstrength forces and apply to an individual pile pushover (without group effects)



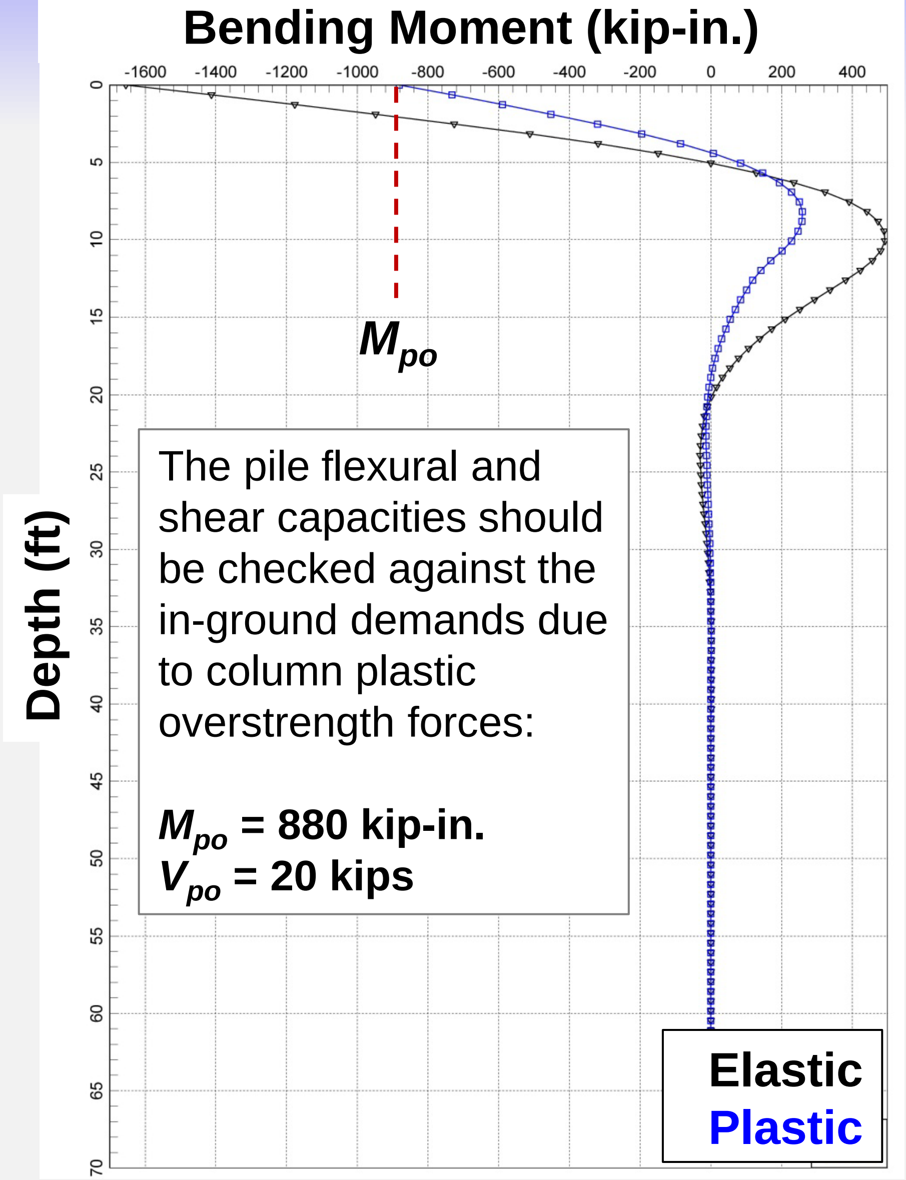
$$\frac{k_e}{k_{po}} = \frac{68.7\ k/in}{105\ k/in} = \mathbf{0.65}$$

k_e = 32.3 kip / 0.47 in. = 68.7 kip/in.

k_{po} = 20 kip / 0.19 in. = 105 kip/in.

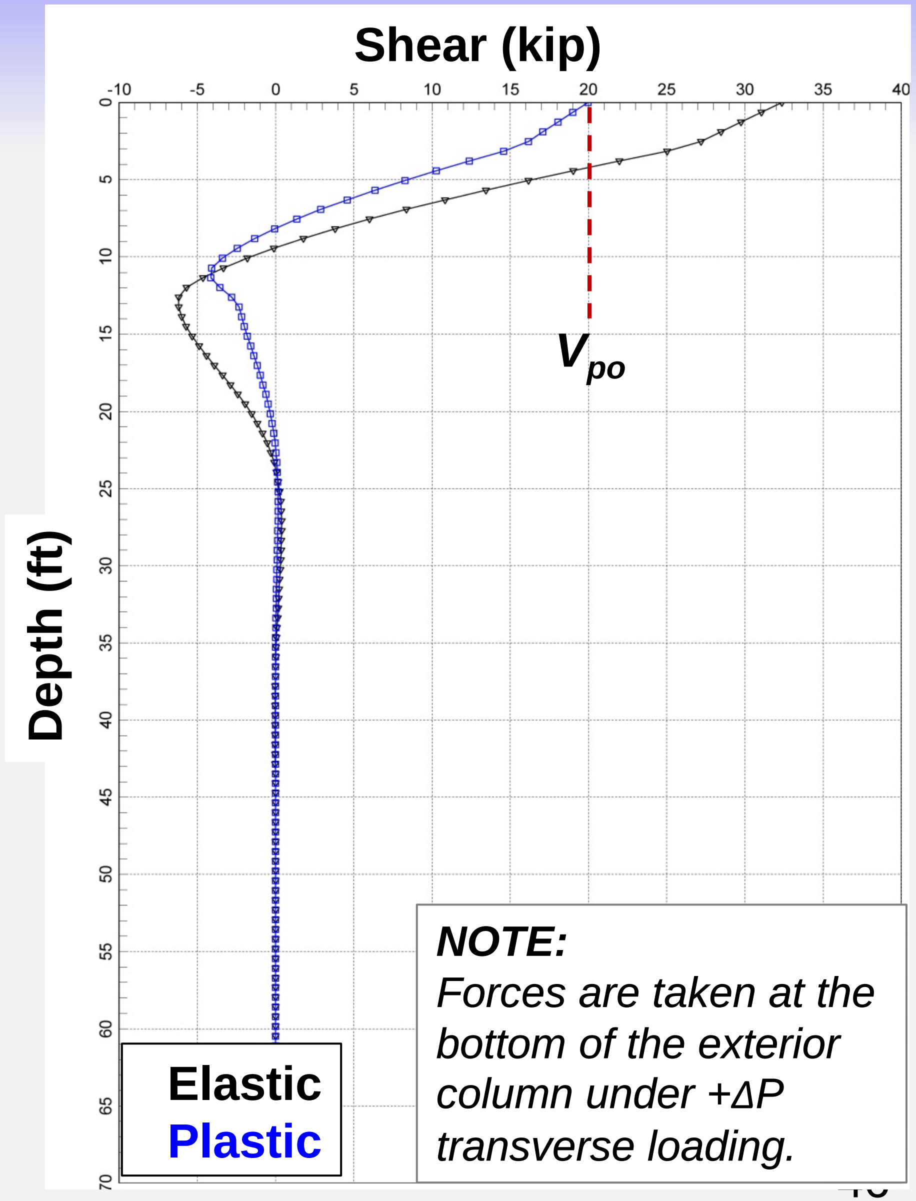
NOTE:
Forces are taken at the bottom of the exterior column under +ΔP transverse loading.

Elastic and Plastic Overstrength Forces



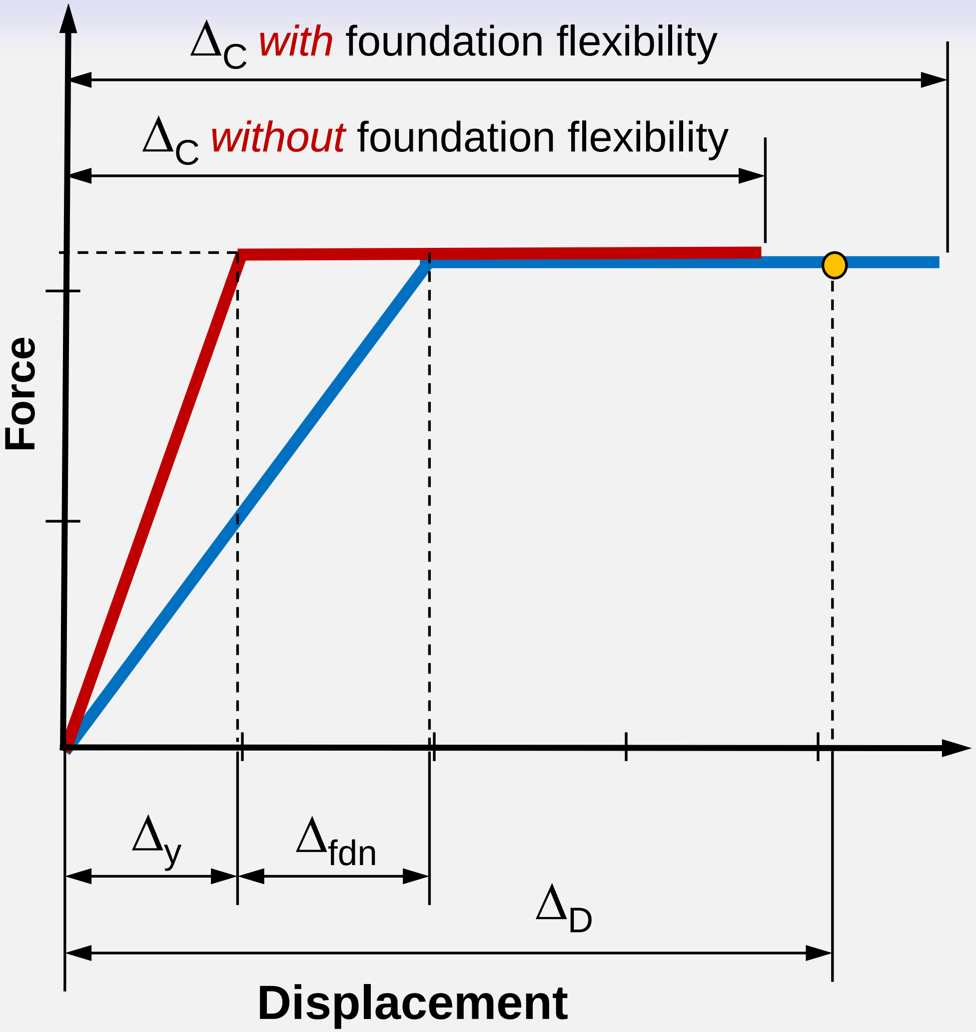
The pile flexural and shear capacities should be checked against the in-ground demands due to column plastic overstrength forces:

M_{po} **= 880 kip-in.**
V_{po} **= 20 kips**



NOTE:
Forces are taken at the bottom of the exterior column under +ΔP transverse loading.

Column Ductility Checks



Ductility *without* Foundation Effects

$$\mu_D = \frac{\Delta_D}{\Delta_y}$$

Ductility *with* Foundation Effects

$$\mu_{D,fdn} = \frac{\Delta_D}{\Delta_y + \Delta_{fdn}}$$

Therefore: $\mu_{D,fdn} \leq \mu_D$

AASHTO GS Article C4.9

*"In calculating the yield displacement and plastic displacement demand, any contribution to the displacements from foundation, capbeam, or superstructure should be removed. **Inclusion of such flexibilities is unconservative**"*

Column Ductility Checks

Ductility *without* Foundation Effects

$$\mu_D = \frac{\Delta_D}{\Delta_y}$$

$$\Delta_y = 2\left(\frac{\phi_y L^2}{3}\right)$$

$$\boxed{\Delta_D = 5.69\ in}$$

	Left Column	Center Column	Right Column
Axial Load (kip)	37	254	471
ϕ_y ***(1/in.)***	0.000154	0.000150	0.000144
L ***(in.)***	159	159	159
Δ_y ***(in.)***	2.60	2.52	2.43
μ_D	**2.19**	**2.26**	**2.34**

OK < 6   GS 4.9 Multicolumn Piers SDC D

Ductility *with* Foundation Effects

$$\mu_D = \frac{\Delta_D}{\Delta_y + \Delta_{fdn}}$$

$$\Delta_y = 2\left(\frac{\phi_y L^2}{3}\right)$$

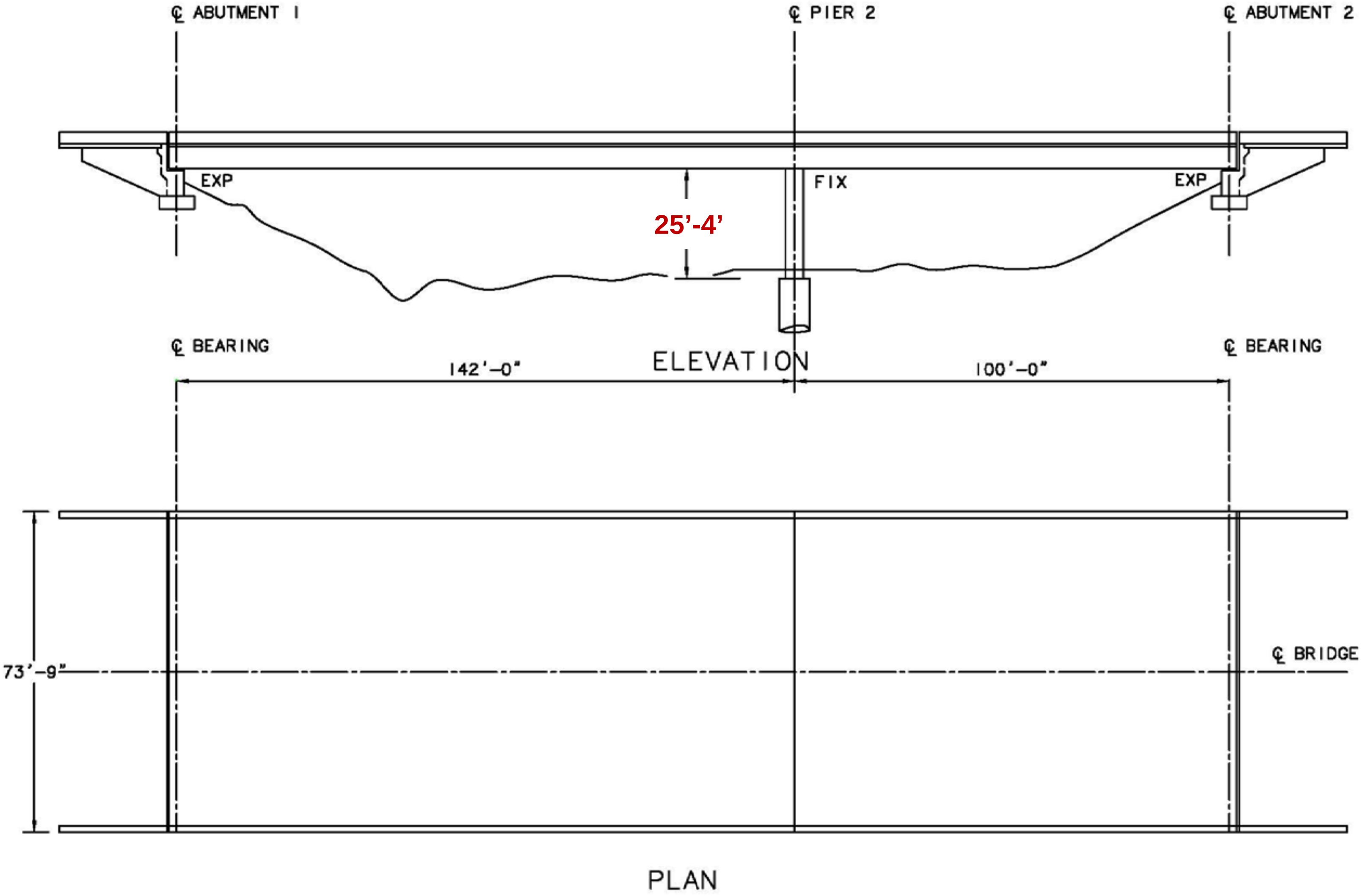
	Left Column	Center Column	Right Column
Axial Load (kip)	37	254	471
ϕ_y ***(1/in.)***	0.000154	0.000150	0.000144
L ***(in.)***	159	159	159
Δ_y ***(in.)***	2.60	2.52	2.43
Δ_{fdn} ***(in.)***	0.13	0.16	0.19
μ_D	**2.08**	**2.12**	**2.17**

Design Example No. 2

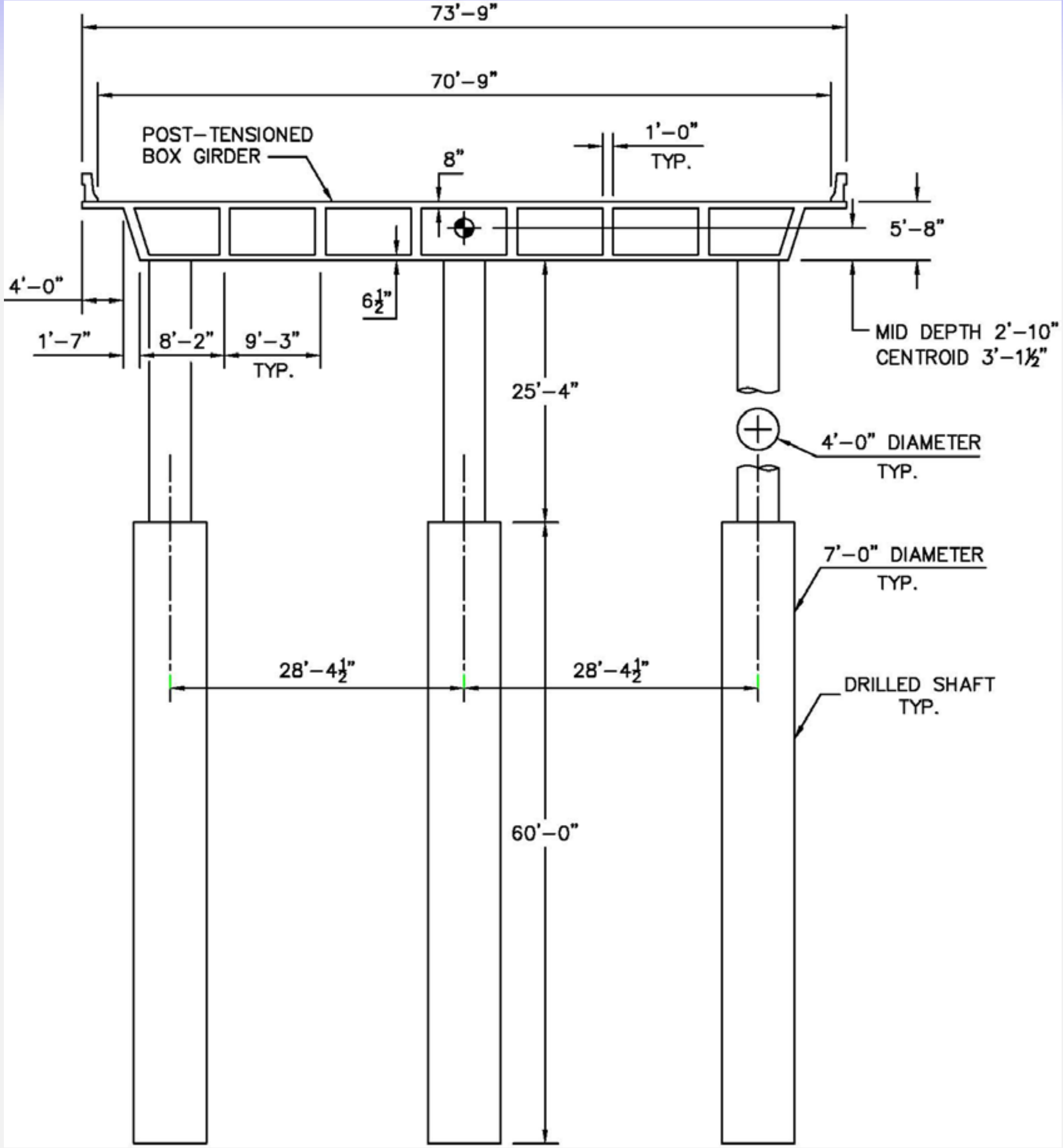
Topics Covered :

- *LRFD Bridge Design Specifications* – seismic design
- Drilled shaft stiffness
- Structural modeling
- Column design
- Capacity protection of drilled shafts

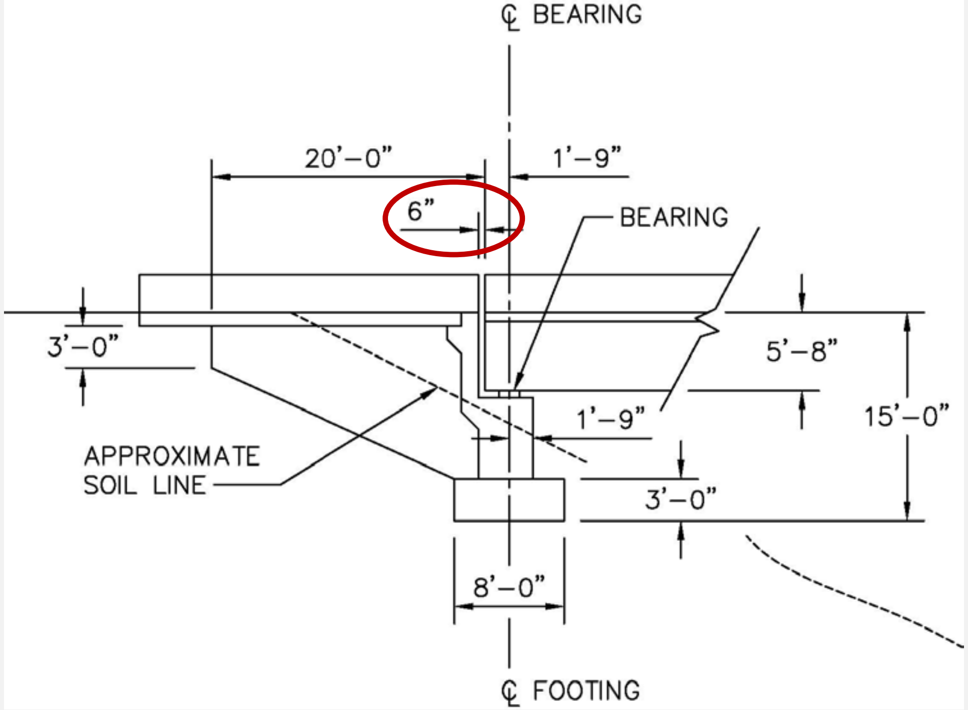
Design Example No. 2 – Elev and Plan



Design Example No. 2 – Section at Pier



Design Example No. 2 - Abutments

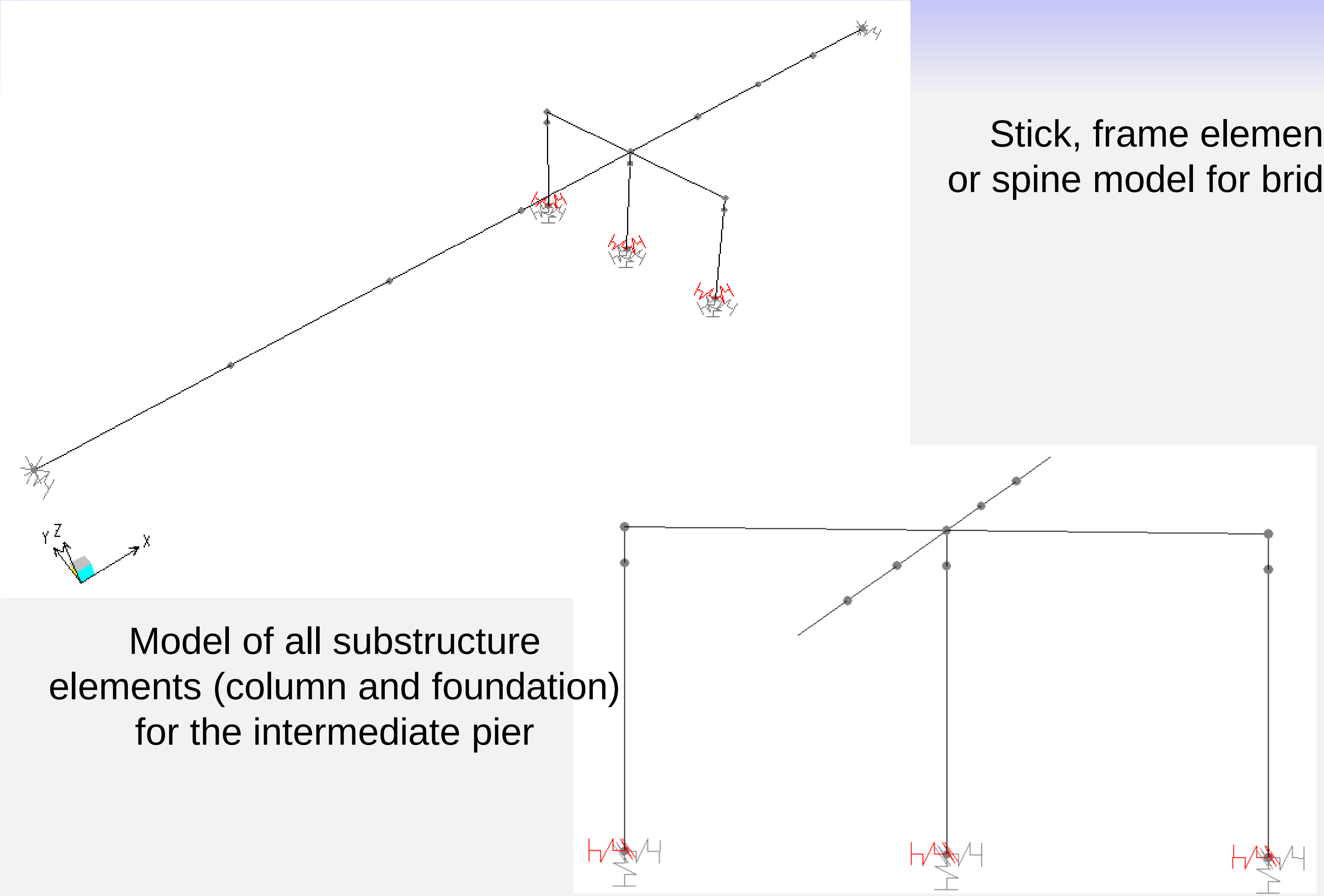


Design Example No. 2 - Data

- Location – Big Arm, MT (Flathead Lake)

  Zip Code 59910, Lat: 47.798 Long: -114.309
- LRFD *Bridge Design Specifications*
- Operational Classification – “Other”
- SD1 = 0.39 g
- Site Class D
- Seismic Zone 3
- Multi-column Bent, R=5

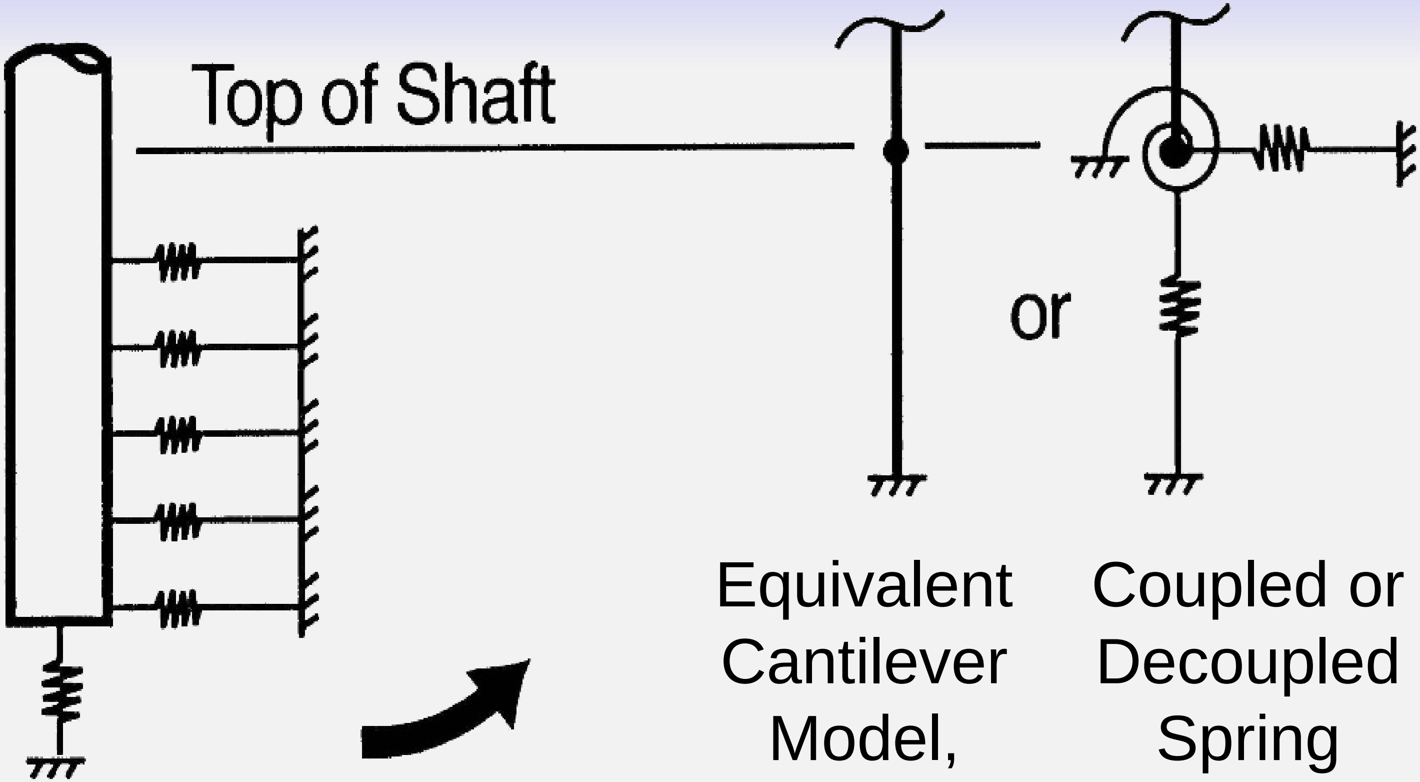
Spine Model



Stick, frame element
or spine model for bridge

Model of all substructure
elements (column and foundation)
for the intermediate pier

Modeling Deep Foundation Stiffnesses



Direct foundation spring model, P-y springs

Equivalent Cantilever Model, Depth-to-fixity

Coupled or Decoupled Spring Model

DM7 (NAVFAC Design Manual 7.02)

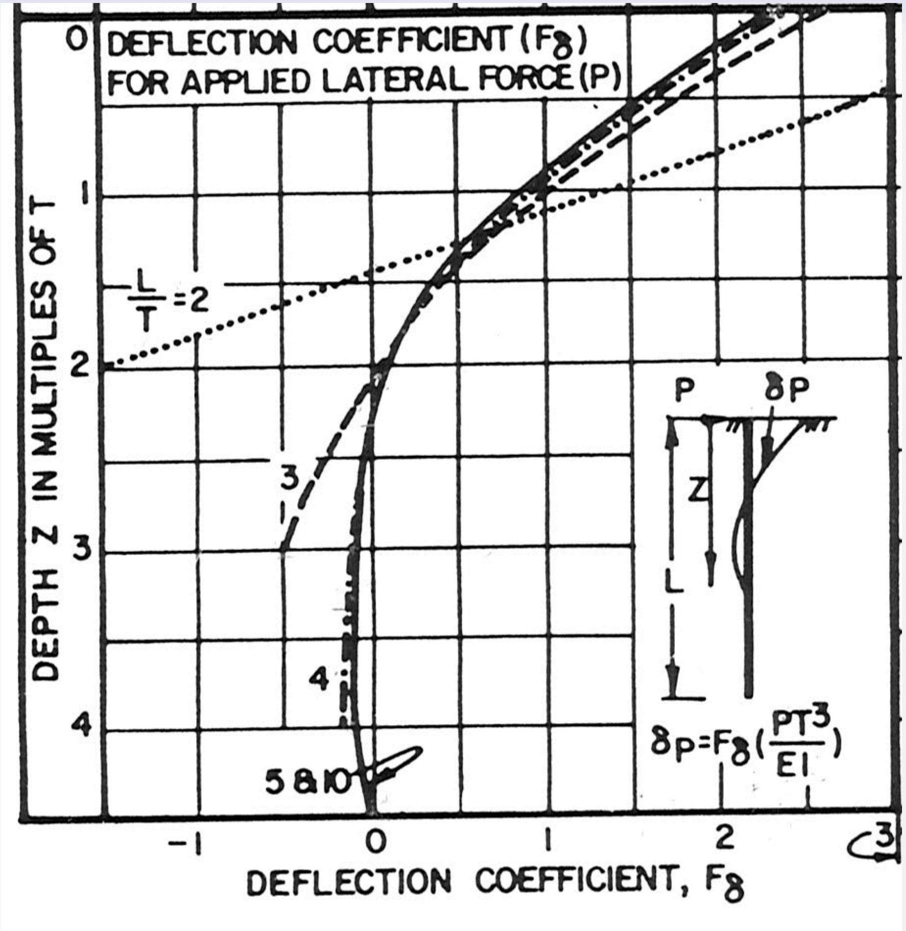
Characteristic Length

$T = (EI / n_h)^{1/5}$

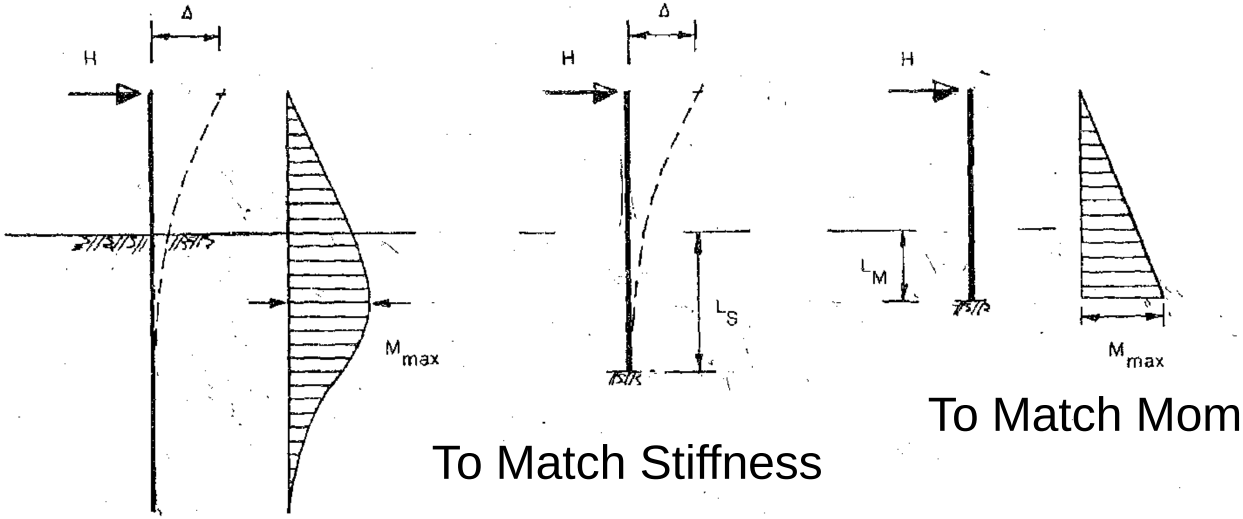
EI - Pile Flexural Stiffness
n_h – Coefficient of Lateral Subgrade Reaction (sometimes “ f ”)

L / T = Measure of Pile Embedment

Shear on Free Head Case



Equivalent Depth to Fixity – Extended Column



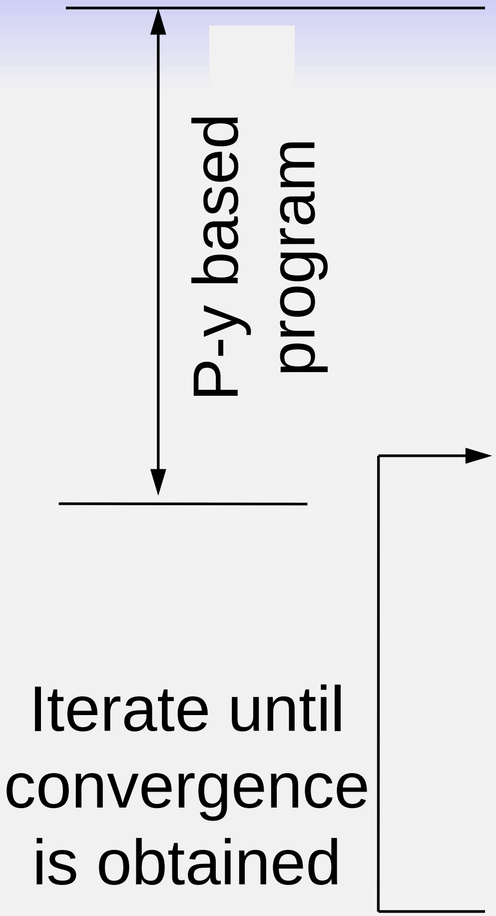
To Match Stiffness

To Match Moment

	L_S	L_M
Cohesive Soil Constant K_h	$1.4\sqrt[4]{\frac{EI}{K_h}}$	$0.44\sqrt[4]{\frac{EI}{K_h}}$
Cohesionless Soil Constant n_h	$1.8\sqrt[5]{\frac{EI}{n_h}}$	$0.78\sqrt[5]{\frac{EI}{n_h}}$

The lengths listed are derived to match the quantities listed – stiffness and moment – not points on the p-y deflected shape plot.

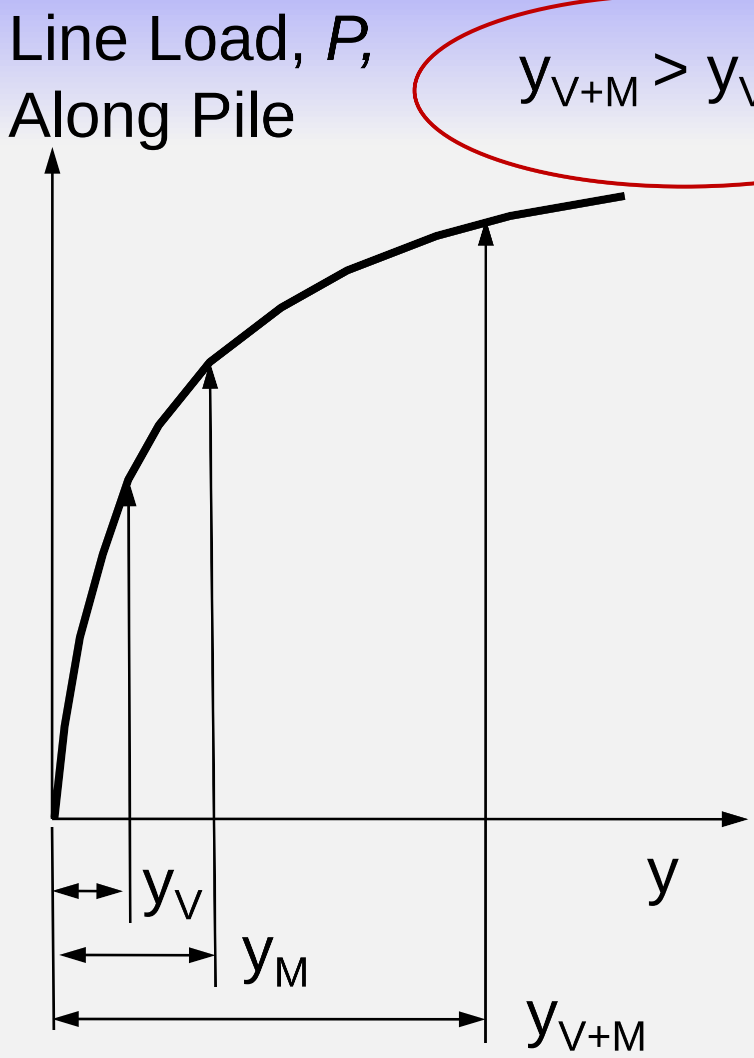
Single-Pile Lateral Stiffness Iteration

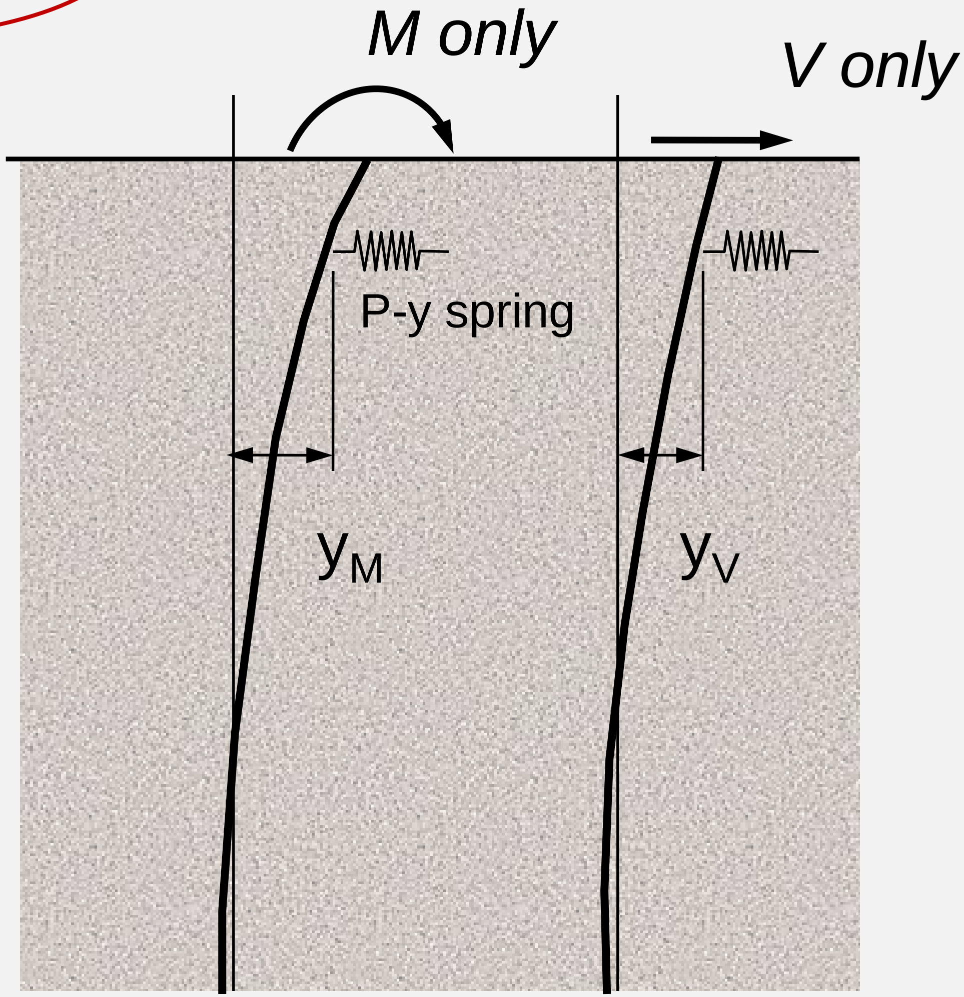


1. Model entire pile using P-y based program
2. Generate P-y curves for springs along pile [FHWA (1986) or other]
3. Load model and determine Δ and θ
4. For a given Δ and θ calculate foundation springs (uncoupled or coupled)
5. Analyze mathematical model of bridge
6. Using foundation forces from bridge model (must judge elastic vs plastic), determine new Δ and θ from P-y model

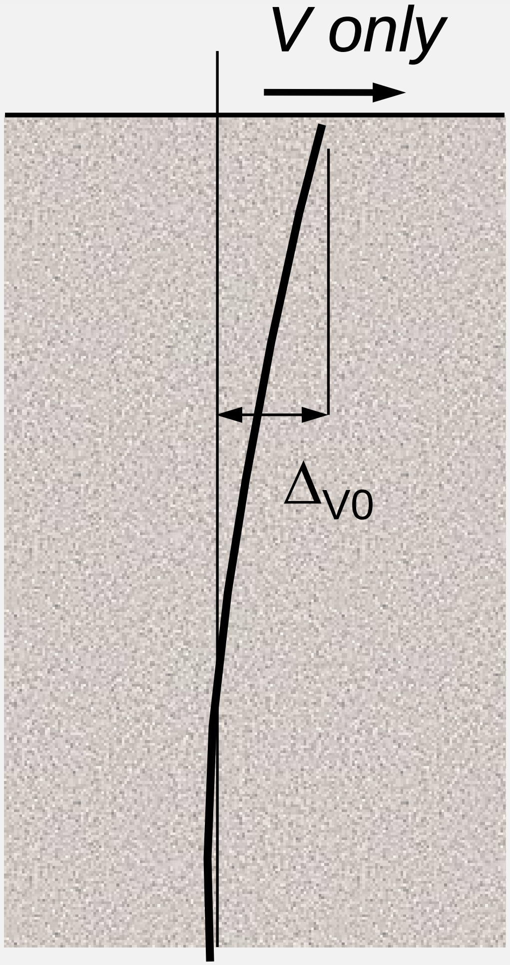
Limitation of Superposition

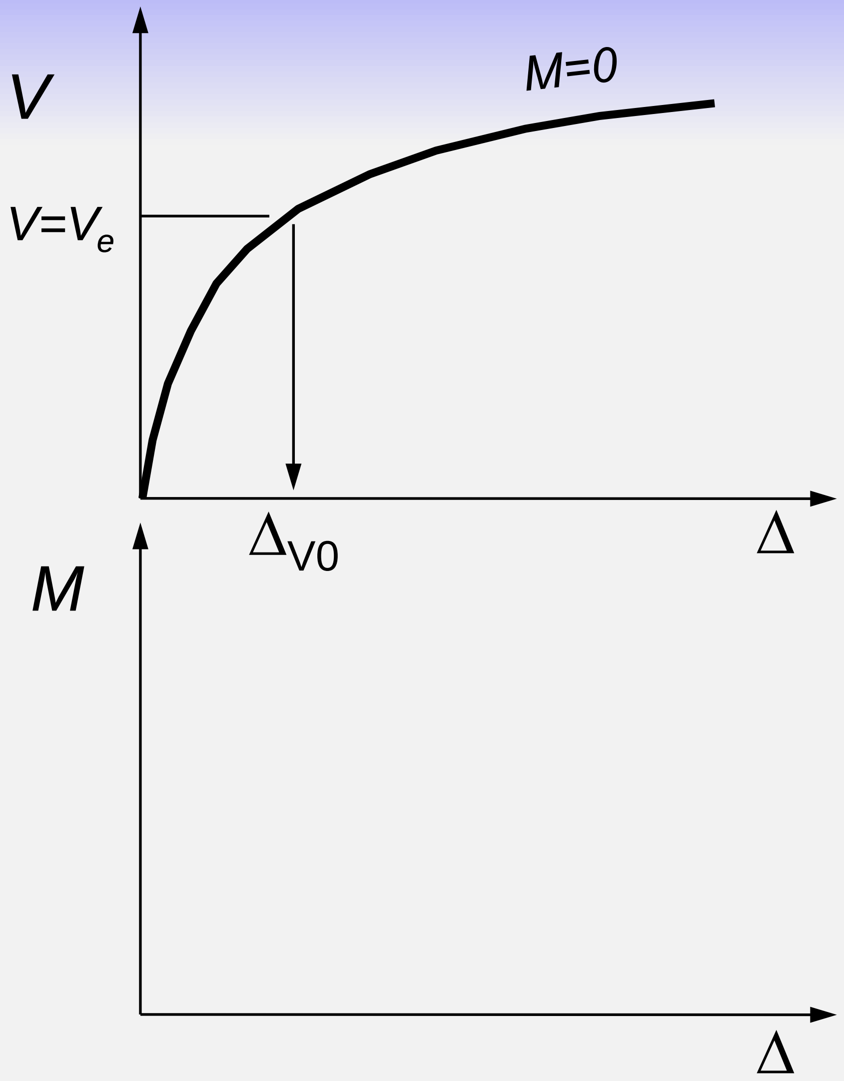
$$y_{V+M} > y_V + y_M$$



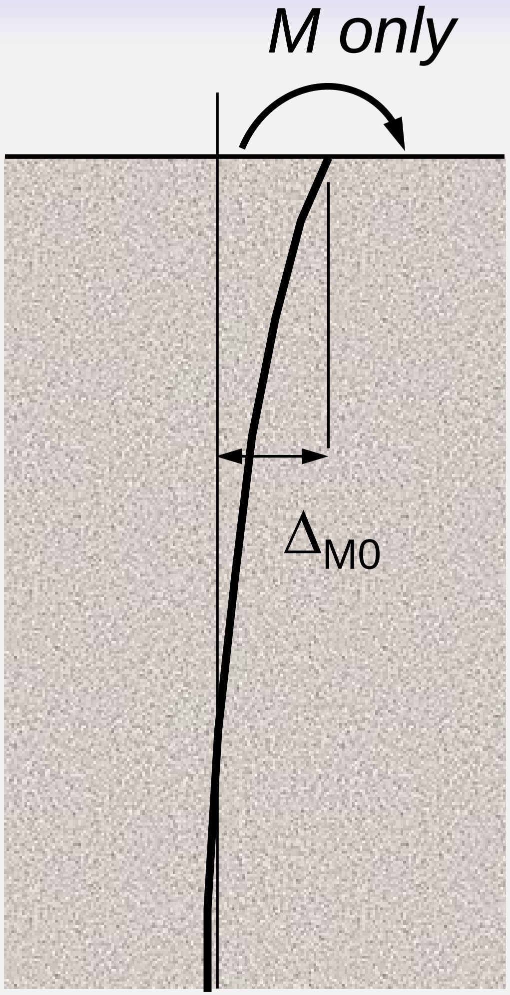


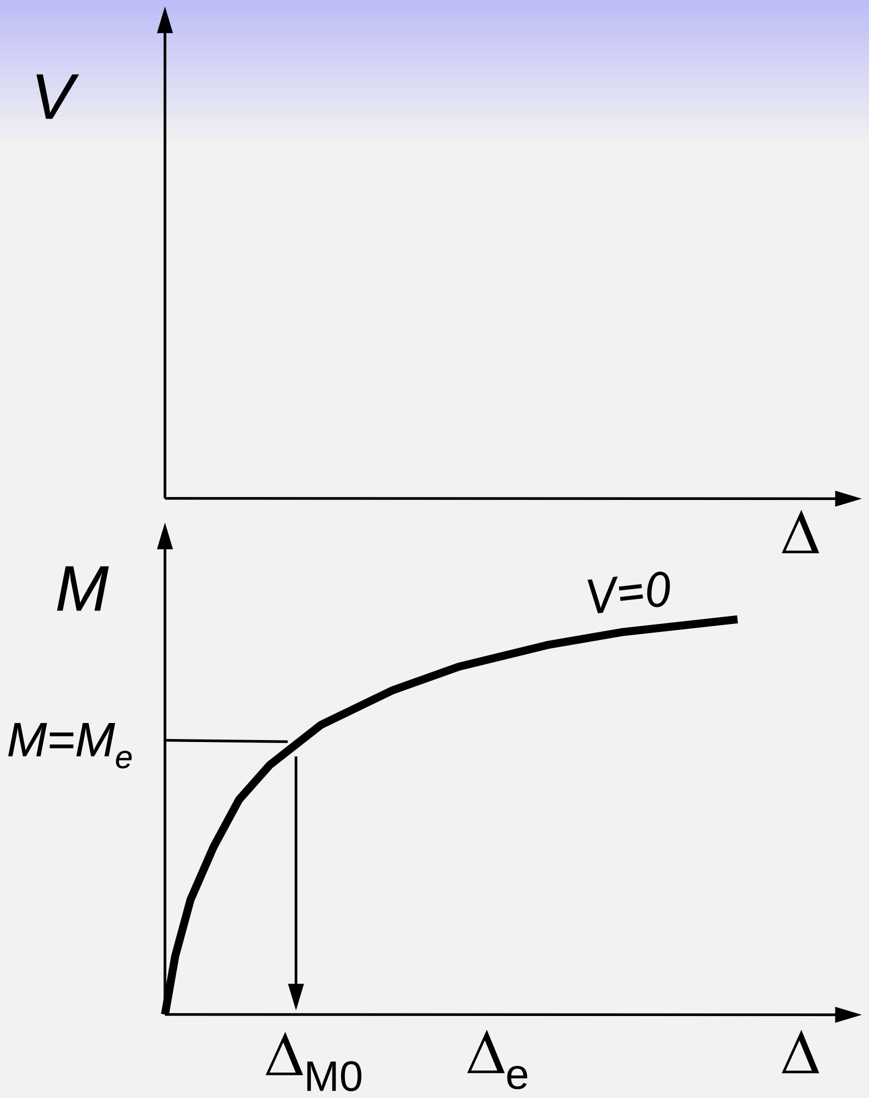
Development of Spring Stiffnesses



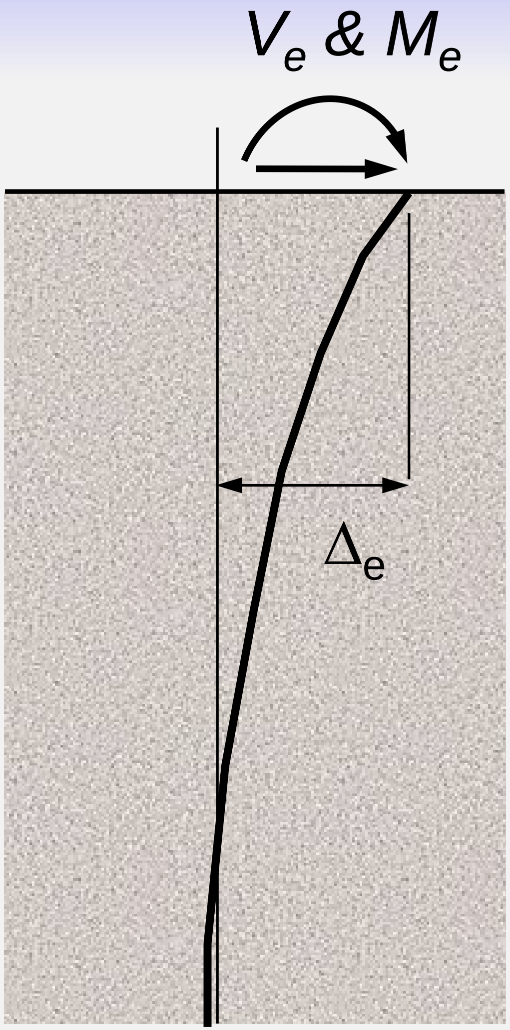


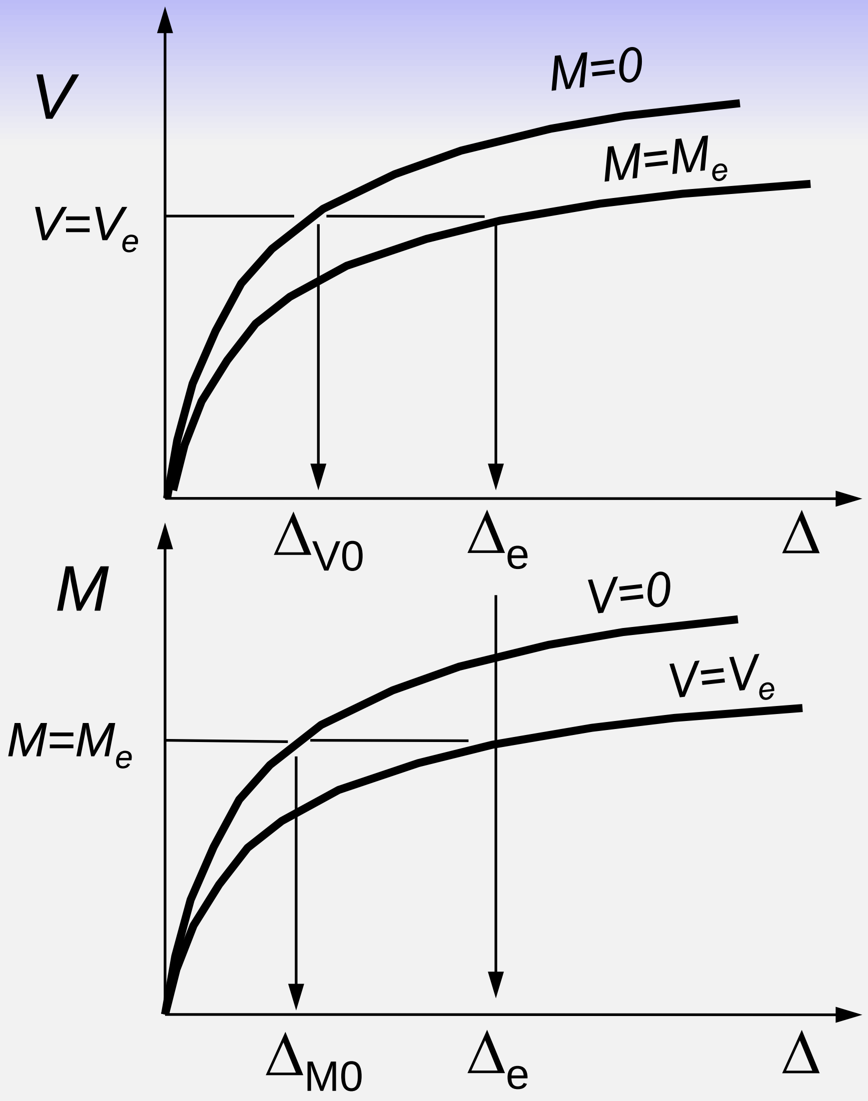
Development of Spring Stiffnesses



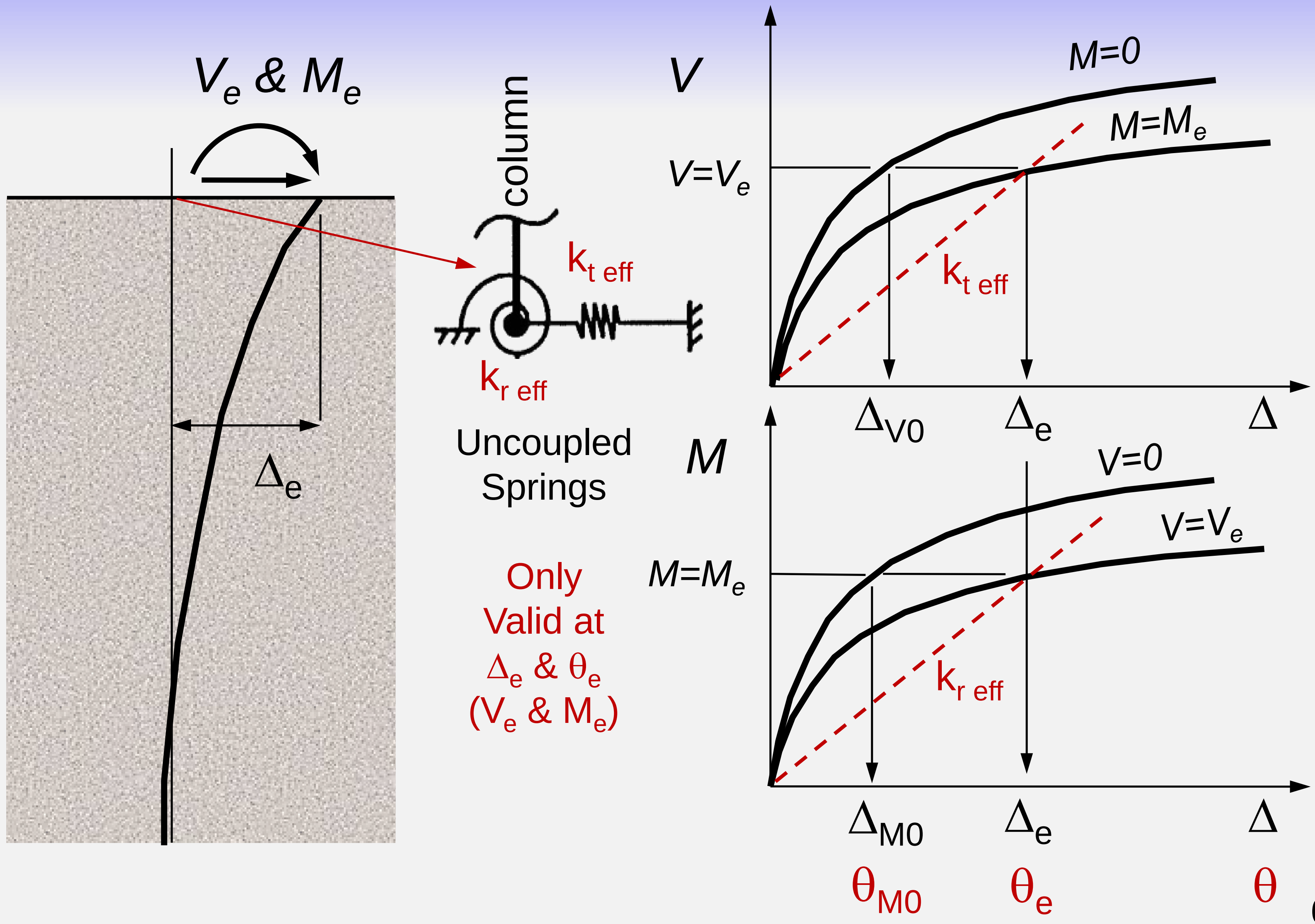


Development of Spring Stiffnesses





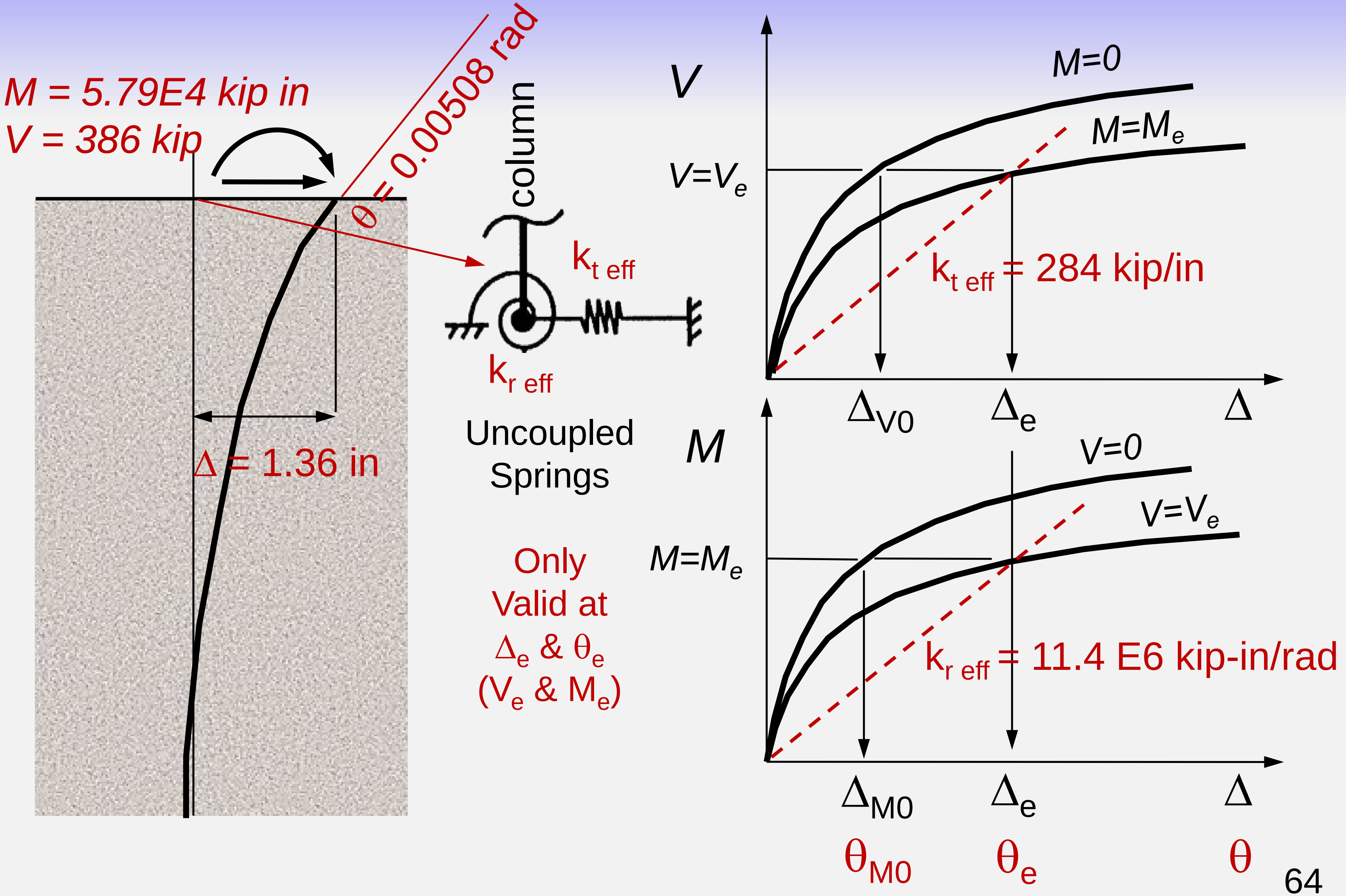
Development of Spring Stiffnesses



Uncoupled Springs

Only Valid at Δ_e & θ_e (V_e & M_e)

Example: 7-ft Drilled Shaft DE2



$M = 5.79E4$ kip in

$V = 386$ kip

$\theta = 0.00508$ rad

$\Delta = 1.36$ in

Uncoupled Springs

Only Valid at Δ_e & θ_e (V_e & M_e)

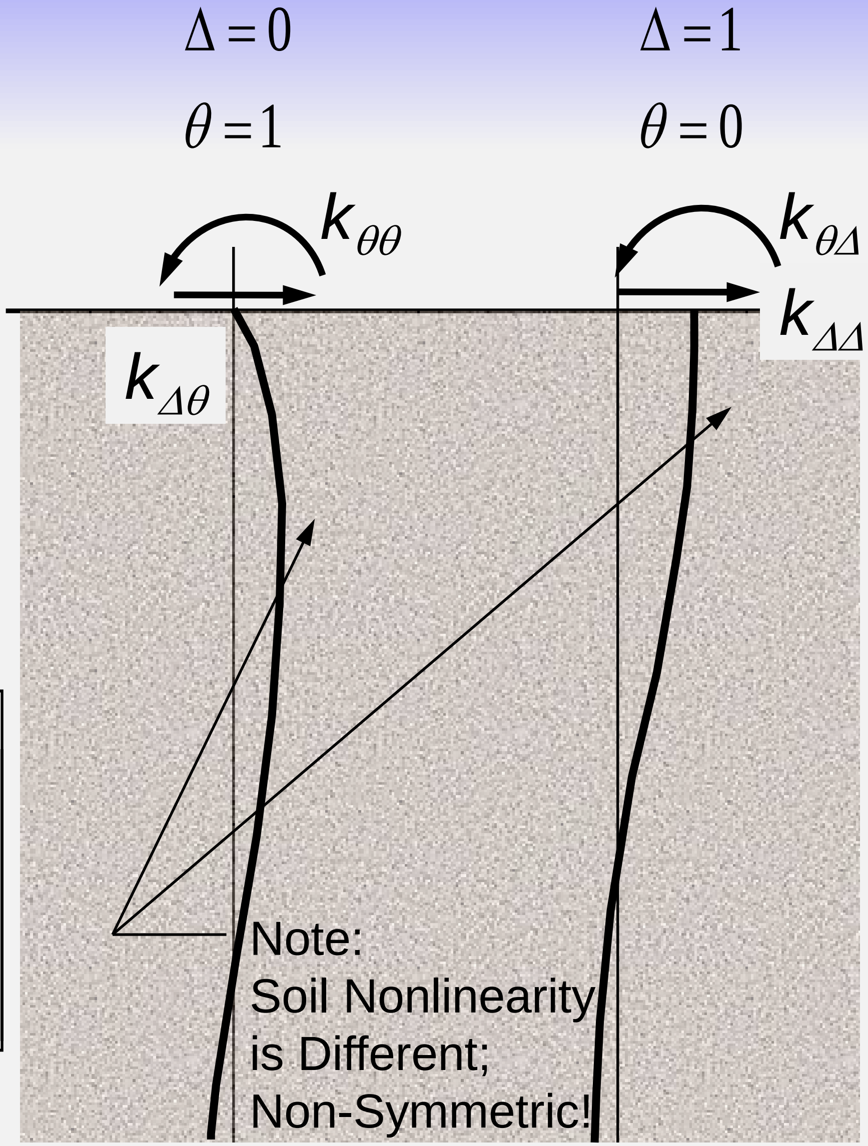
$k_{t\ eff} = 284$ kip/in

$k_{r\ eff} = 11.4$ E6 kip-in/rad

Development of Coupled Matrix Coefficients

$$\begin{array}{ccc} & \Delta=1 & \Delta=0 \\ & \theta=0 & \theta=1 \\ K_{2x2} = & k_{\Delta\Delta} & k_{\Delta\theta} \\ & k_{\theta\Delta} & k_{\theta\theta} \end{array}$$

$$K_{6x6} = \begin{bmatrix} K_{x\_2x2} & 0 & 0 & 0 \\ 0 & K_{y\_2x2} & 0 & 0 \\ 0 & 0 & K_{axial} & 0 \\ 0 & 0 & 0 & K_{torque} \end{bmatrix}$$



Note:
Soil Nonlinearity is Different;
Non-Symmetric!

Example: 7-ft Drilled Shaft DE 2

$$K_{2x2}=\begin{array}{c} \\ \\ \end{array}\begin{array}{cc} \Delta=1 & \Delta=0 \\ \theta=0 & \theta=1 \\ \Downarrow & \Downarrow \\ \end{array}$$

$$K_{2x2}=\begin{bmatrix} 1407 & -2.89E5 \\ -2.37E5 & 7.37E7 \end{bmatrix}$$

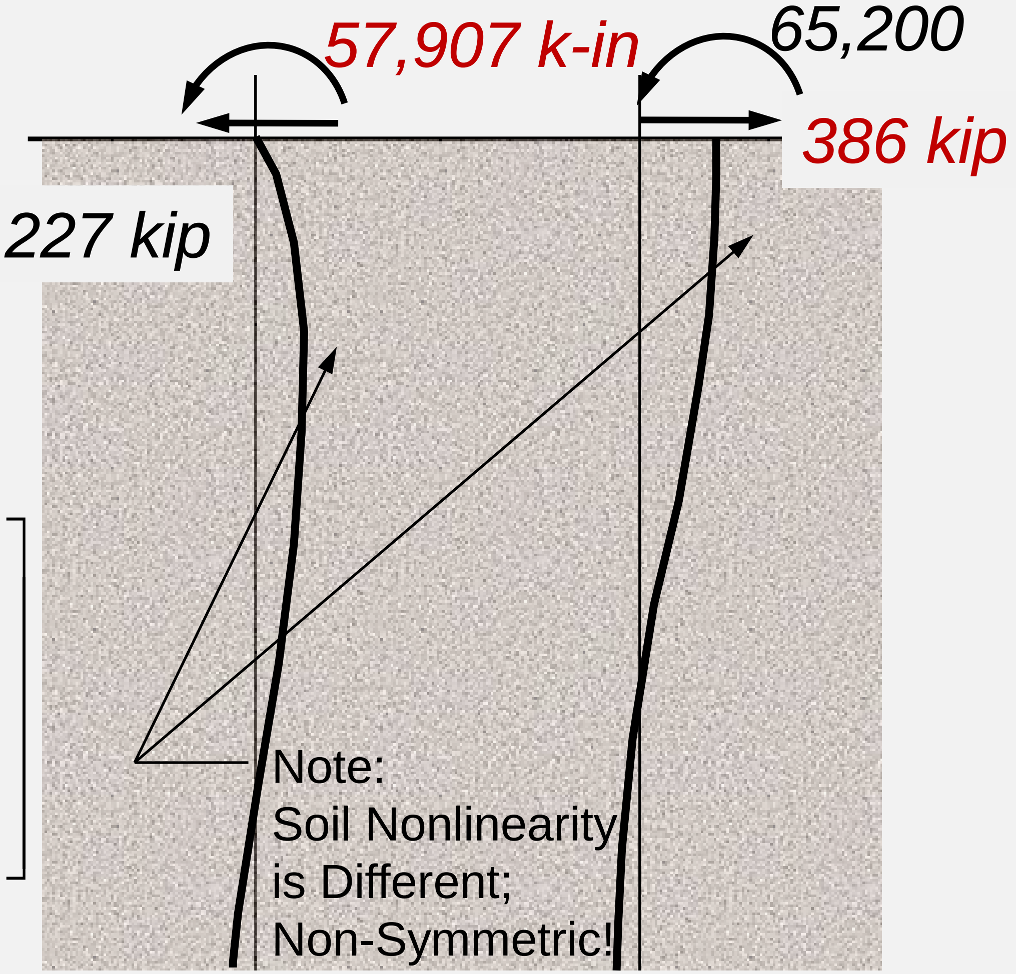
$$K_{6x6}=\begin{bmatrix} K_{x\_2x2} & 0 & 0 & 0 \\ 0 & K_{y\_2x2} & 0 & 0 \\ 0 & 0 & K_{axial} & 0 \\ 0 & 0 & 0 & K_{torque} \end{bmatrix}$$

$\Delta=0$

$\theta=0.000786$ rad

$\Delta=0.275$ in

$\theta=0$



Note:
Soil Nonlinearity is Different; Non-Symmetric!

Comparison – Uncoupled vs Coupled

Uncoupled Springs:

$V=386$ kip $\Delta=1.34$ in,

$M=57{,}907$ k-in $\theta=0.00508$ rad

Coupled Springs:

$V=386$ kip $\Delta=1.29$ in (94% of uncoupled),

$M=57{,}907$ k-in $\theta=0.00494$ rad (97% uncoupled)

Difference is due to soil nonlinearity for combined V and M

Design Example 2: Dynamic Model Results

	Longitudinal (X-axis)		Transverse (Y-axis)	
Fundamental Period:	1.33	sec	0.52	sec
Total Mass Participation:	98.9	%	99.1	%
Calculated Base Shear:	1,394	kips	3,620	kips
Model Base Shear Reaction:	1,445	kips	3,732	kips
% Difference:	-3.6	%	-3.1	%

Top of Column Displacements

Pier	Joint	Longitudinal EQ		Transverse EQ	
		X	Y	Y	X
[---]	[---]	[inches]	[inches]	[inches]	[inches]
2	4213	5.09	0.00	2.08	0.00

Displacement Magnification

Transverse Direction

$$T_S = 0.85 \cdot \text{sec}$$

$$1.25 \cdot T_S = 1.25 \cdot (0.85 \cdot \text{sec}) = 1.06 \cdot \text{sec}$$

$$T = 0.52 \cdot \text{sec} < 1.25 \cdot T_S = 1.06 \cdot \text{sec}$$

→ **Magnification is required.**

Longitudinal Direction

$$T_S = 0.85 \cdot \text{sec}$$

$$1.25 \cdot T_S = 1.25 \cdot (0.85 \cdot \text{sec}) = 1.06 \cdot \text{sec}$$

$$T = 1.33 \cdot \text{sec} > 1.25 \cdot T_S = 1.06 \cdot \text{sec}$$

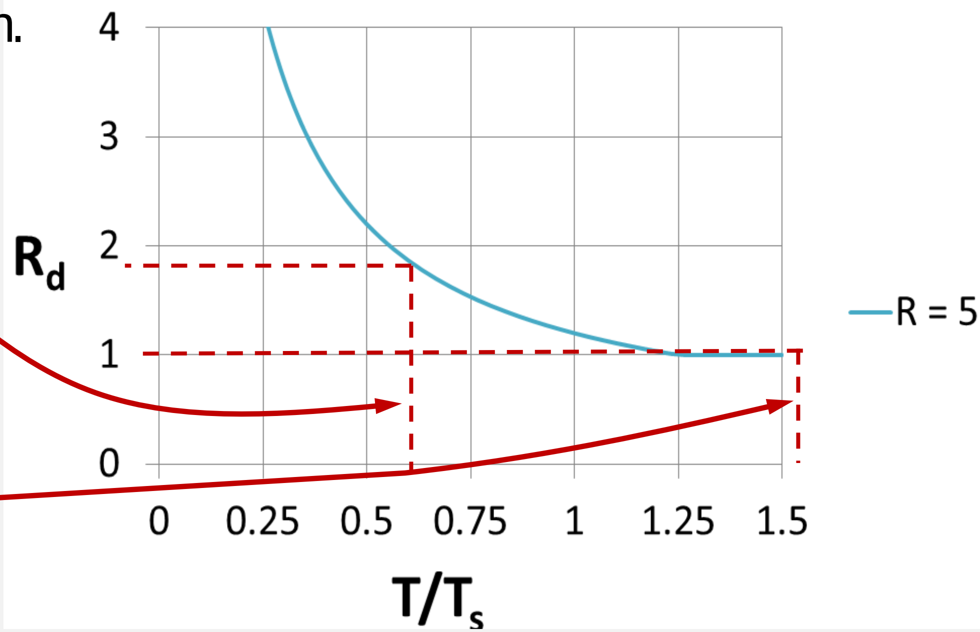
→ **Magnification is not required.**

$$R_d = \left(1 - \frac{1}{R}\right) \cdot \frac{1.25 \cdot T_S}{T} + \frac{1}{R} = \left(1 - \frac{1}{5}\right) \cdot \frac{1.06 \cdot \text{sec}}{0.52 \cdot \text{sec}} + \frac{1}{5} = 1.83$$

$$\Delta_{\text{trans}} = R_d \cdot \Delta_e = 1.83 \cdot (2.08 \cdot \text{in.}) = 3.82 \cdot \text{in.}$$

Transverse $\frac{T}{T_S} = \frac{0.52}{0.85} = 0.62$

Longitudinal $\frac{T}{T_S} = \frac{1.33}{0.85} = 1.56$



Displacement Magnification

However, the structure is nearly elastic under transverse loading, determine distribution of forces:

$$\left.\begin{aligned}
&V_{trans} \approx 3{,}732 \cdot kips \\
&V_{pier} = 3 \cdot V_{col} = 3 \cdot (220 \cdot kips) = 660 \cdot kips \\
&V_{abut} = V_{trans} - V_{pier} = 3{,}732 \cdot kips - 660 \cdot kips = 3{,}072 \cdot kips
\end{aligned}\right\} \textbf{Elastic forces from RSA}$$

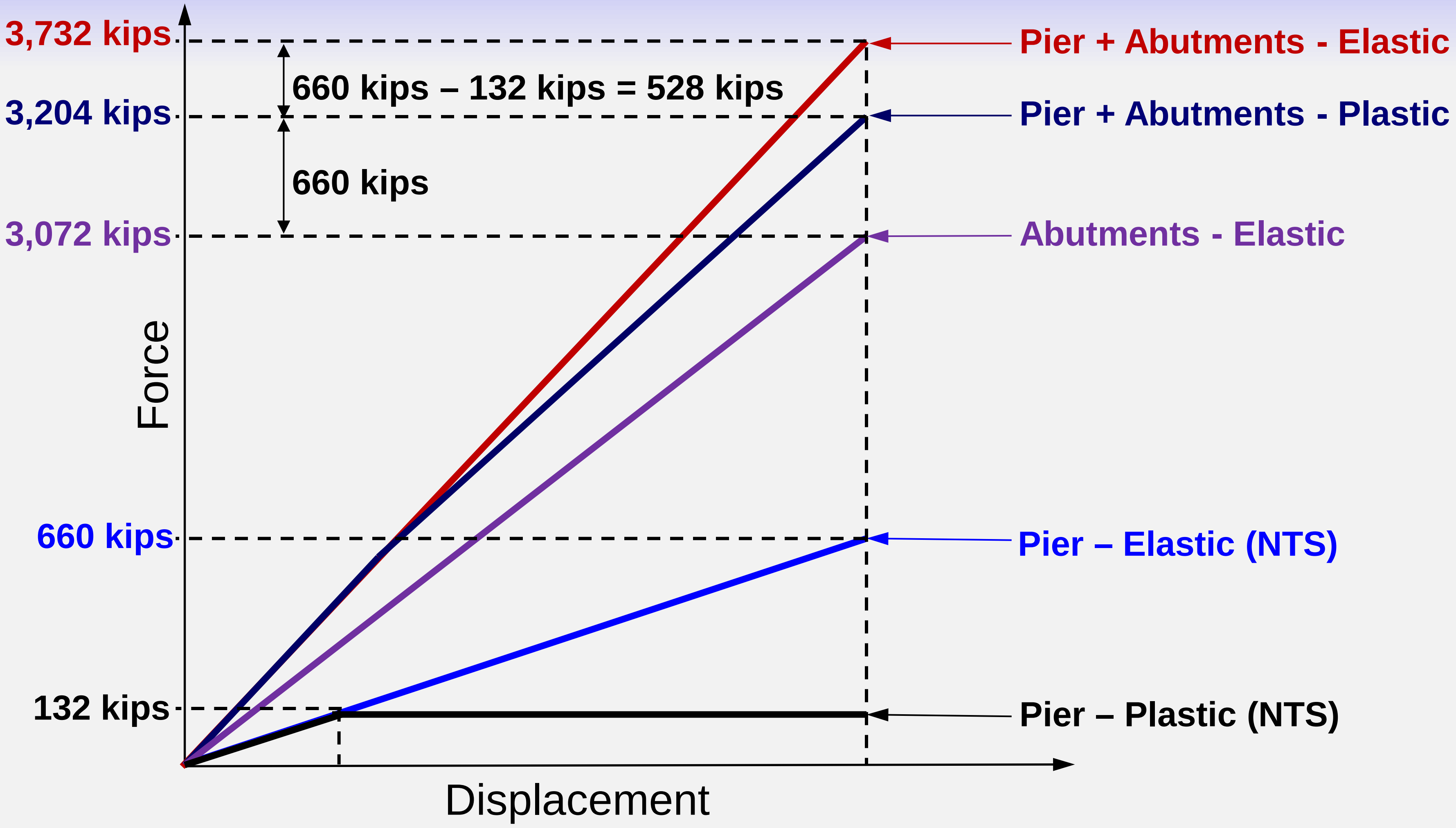
Prorate the base shear to determine the effective R value:

$$\frac{V_{trans}}{R_{eff}} = V_{abut} + \frac{V_{pier}}{R}$$

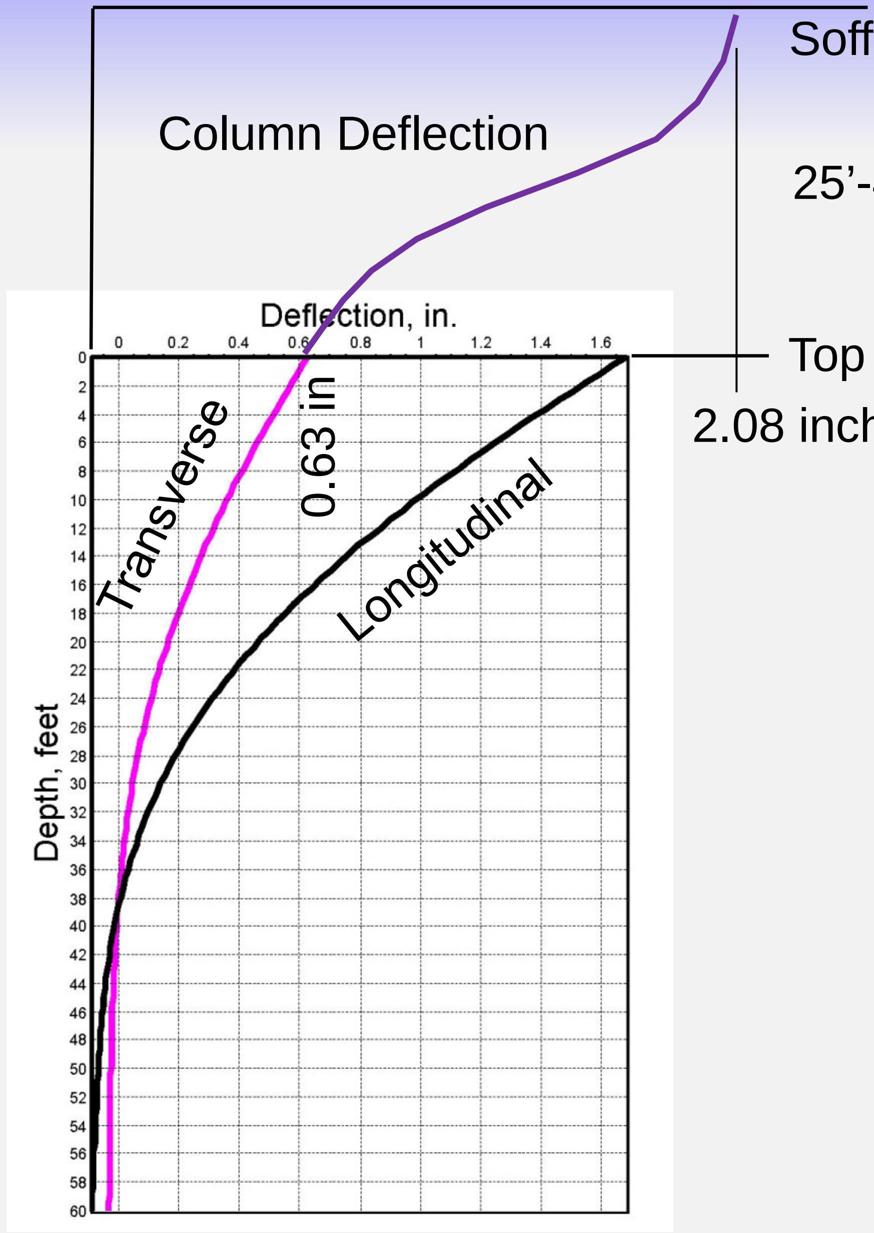
$$R_{eff} = \frac{V_{trans}}{V_{abut} + \frac{V_{pier}}{R}} = \frac{3{,}732 \cdot kips}{3{,}072 \cdot kips + \frac{660 \cdot kips}{5}} = 1.16$$

$$\left.\begin{aligned}
&R_d = \left(1 - \frac{1}{R_{eff}}\right) \cdot \frac{1.25 \cdot T_s}{T} + \frac{1}{R_{eff}} = \left(1 - \frac{1}{1.16}\right) \cdot \frac{1.06}{0.52} + \frac{1}{1.16} = 1.14 \\
&\Delta_{trans} = R_d \cdot \Delta_e = 1.14 \cdot (2.08 \cdot in.) = 2.37 \cdot in.
\end{aligned}\right\} \textbf{The structure is essentially elastic!}$$

Displacement Magnification



Lateral Deflection vs Depth for Shafts



Soffit of Box Girder

Column Deflection

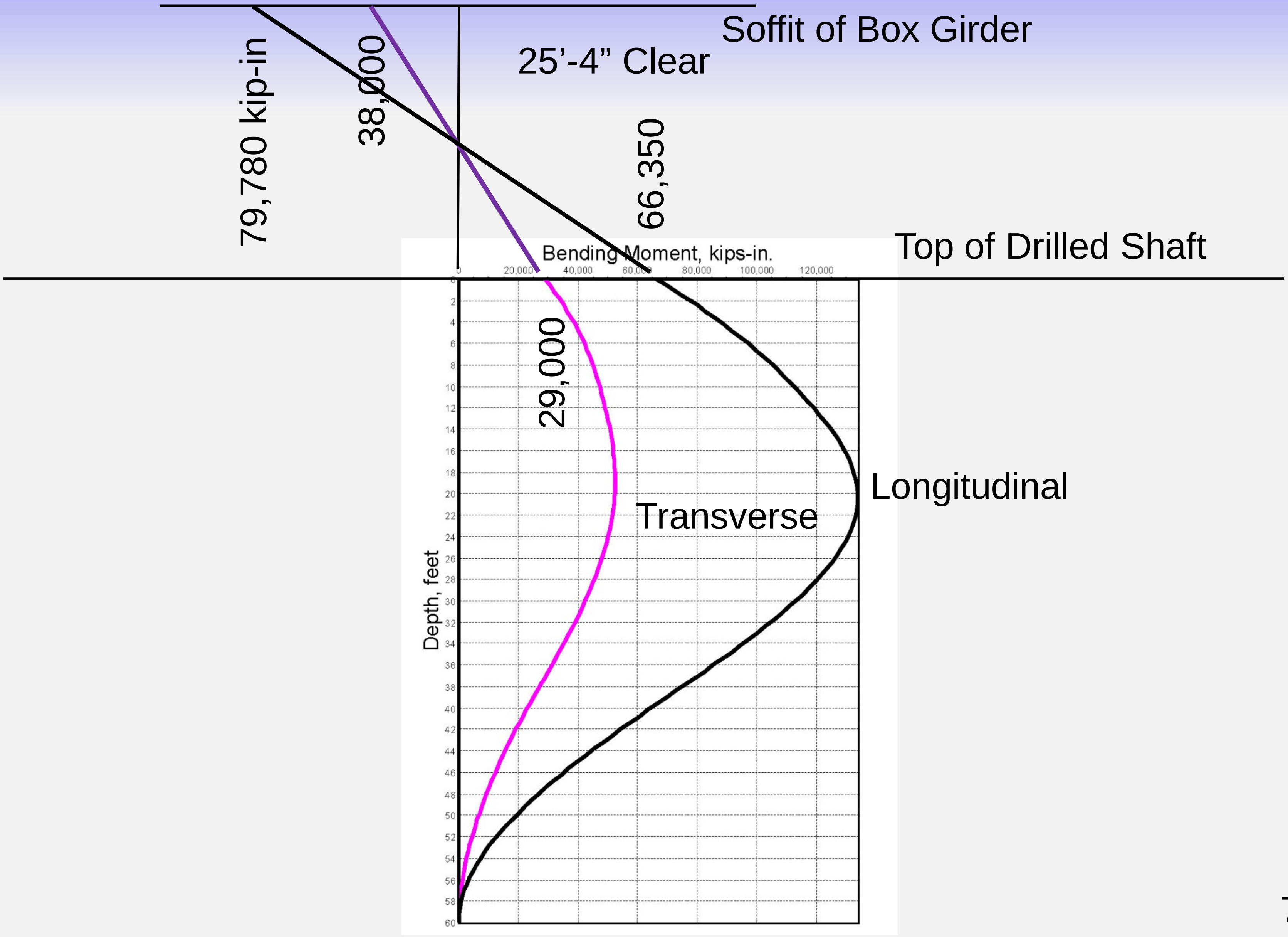
25’-4” Clear

Top of Drilled Shaft

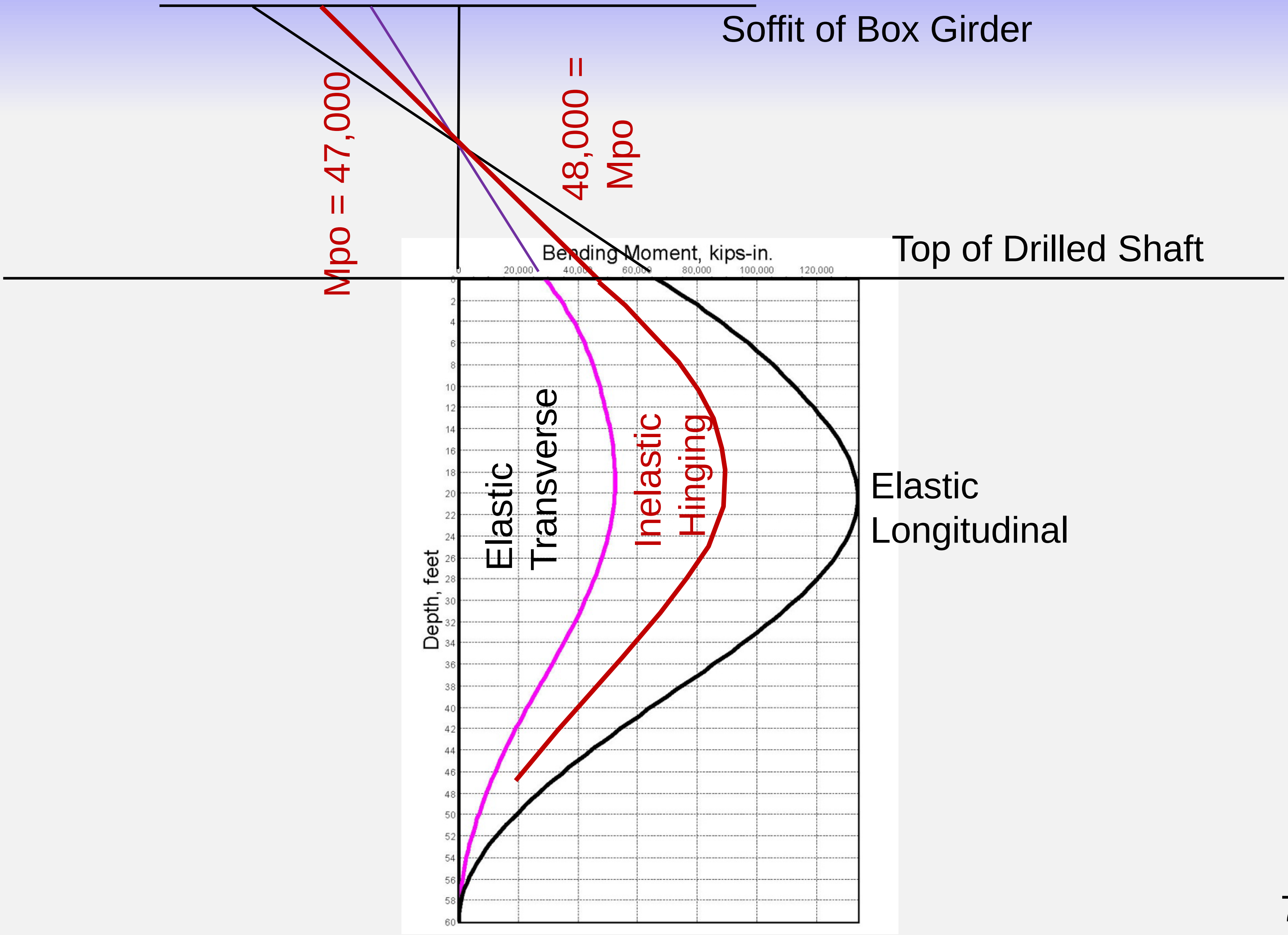
2.08 inches

Shaft Deflection

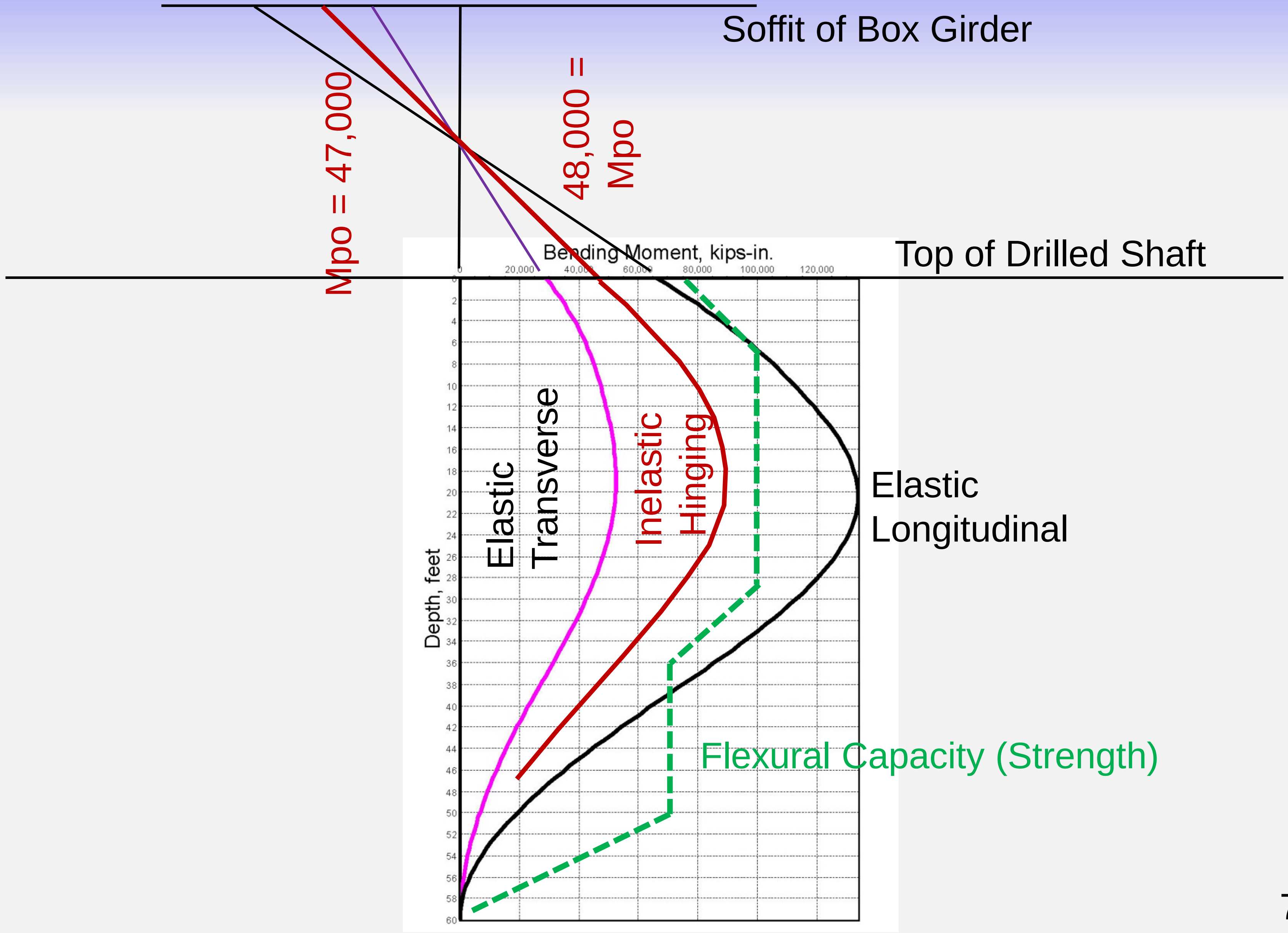
Bending Moment vs Depth/Height



Moment vs Depth at Plastic Hinging



Moment vs Depth at Plastic Hinging



Capacity Protection for this Bridge

- Column designed for overstrength shear based on plastic mechanism
- Drilled shaft designed for overstrength forces for full length (use bounding or 1.25 increase for soil variability)
- Abutments should be designed to mobilize backfill force whether or not it is counted on
- Abutment shear keys must consider post-failure response (i.e. torsion about vertical)

Webinar Summary

- Equivalent linear analysis is the workhorse of most bridge demand calculations
- Consider whether elastic or plastic overstrength conditions should be used for soil/foundation springs
- Several different foundation spring models may be used
- Assessment models should be consistent with demand models

Thank You!