Strain-Based Seismic Evaluation of Wharf Structures

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Motivation

- **California States Lands Commission (CSLC)**
  Engineering Consultants to Perform a Number of Structural Analysis Using ADINA

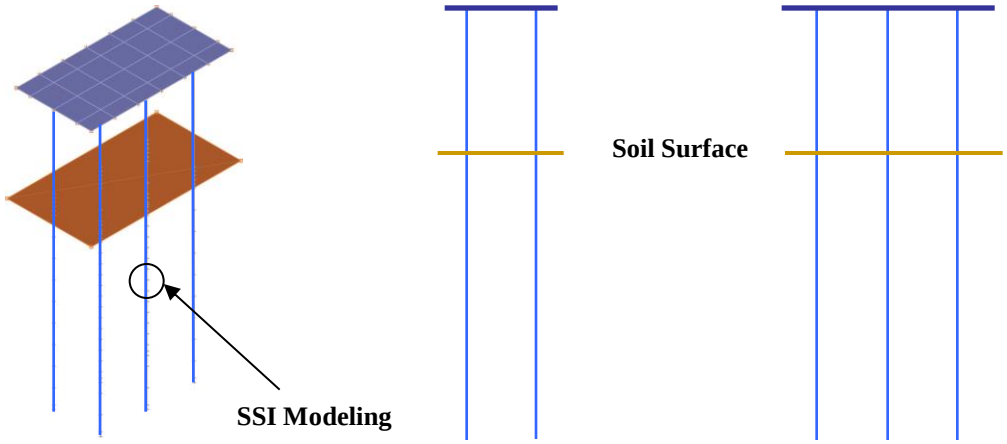
- **MOTEMS**
  Marin Oil Terminal Engineering and Maintenance Standards

- **Past Projects on Pile-Supported Wharf Structures**
  Wharf and Embankment Strengthening Program – Berth 60 to Berth 63 Port of Oakland
  Berth 22 Replacement – Port of Oakland
  Port of Long Beach Pier 3 Testing

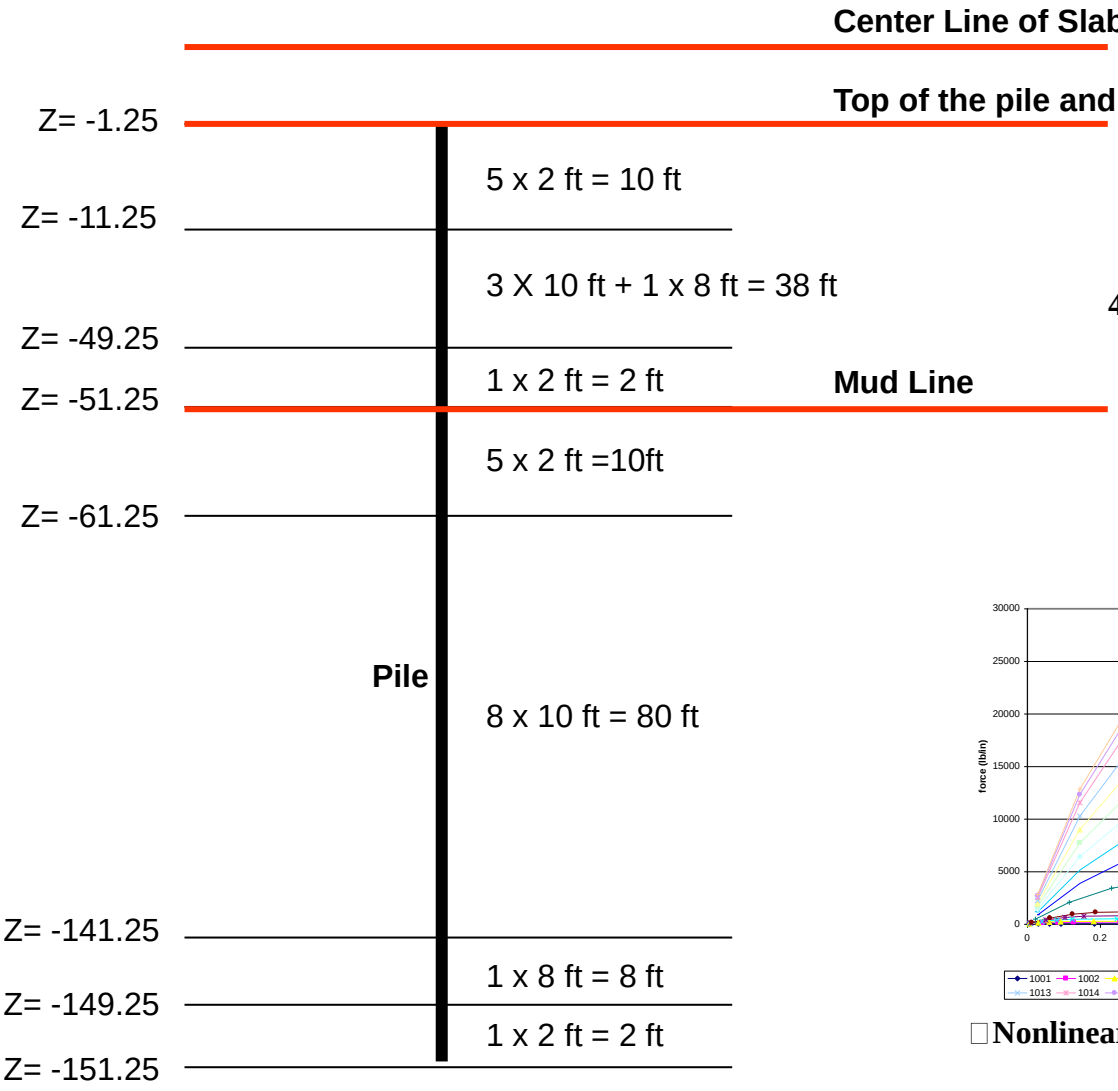
Objectives and Scope

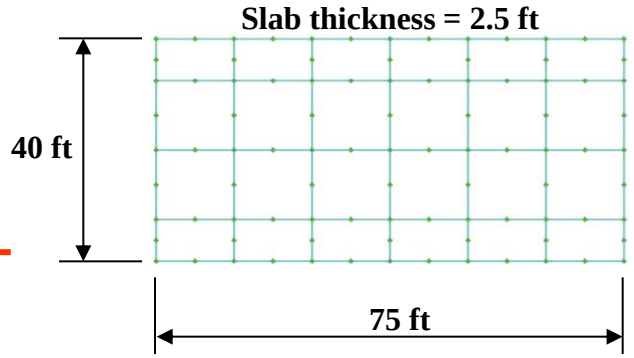
- Application of MOTEMS Requirements
- Soil-Structure Interaction in Pile-Supported Structures
- Detailed SSI Modeling vs. Simplified SSI Modeling
- Implement ADINA in a Production Environment

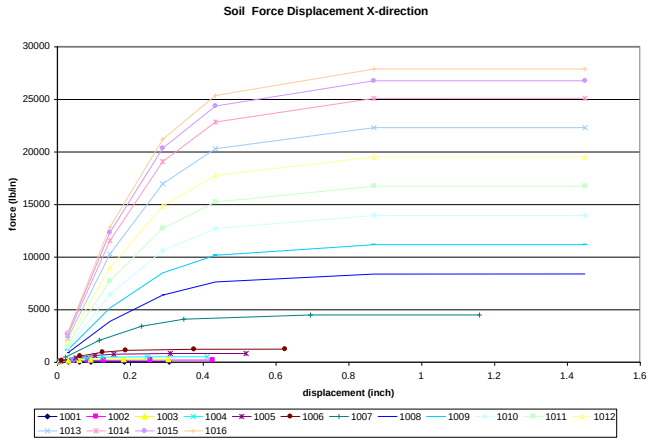
Definition of the Problem



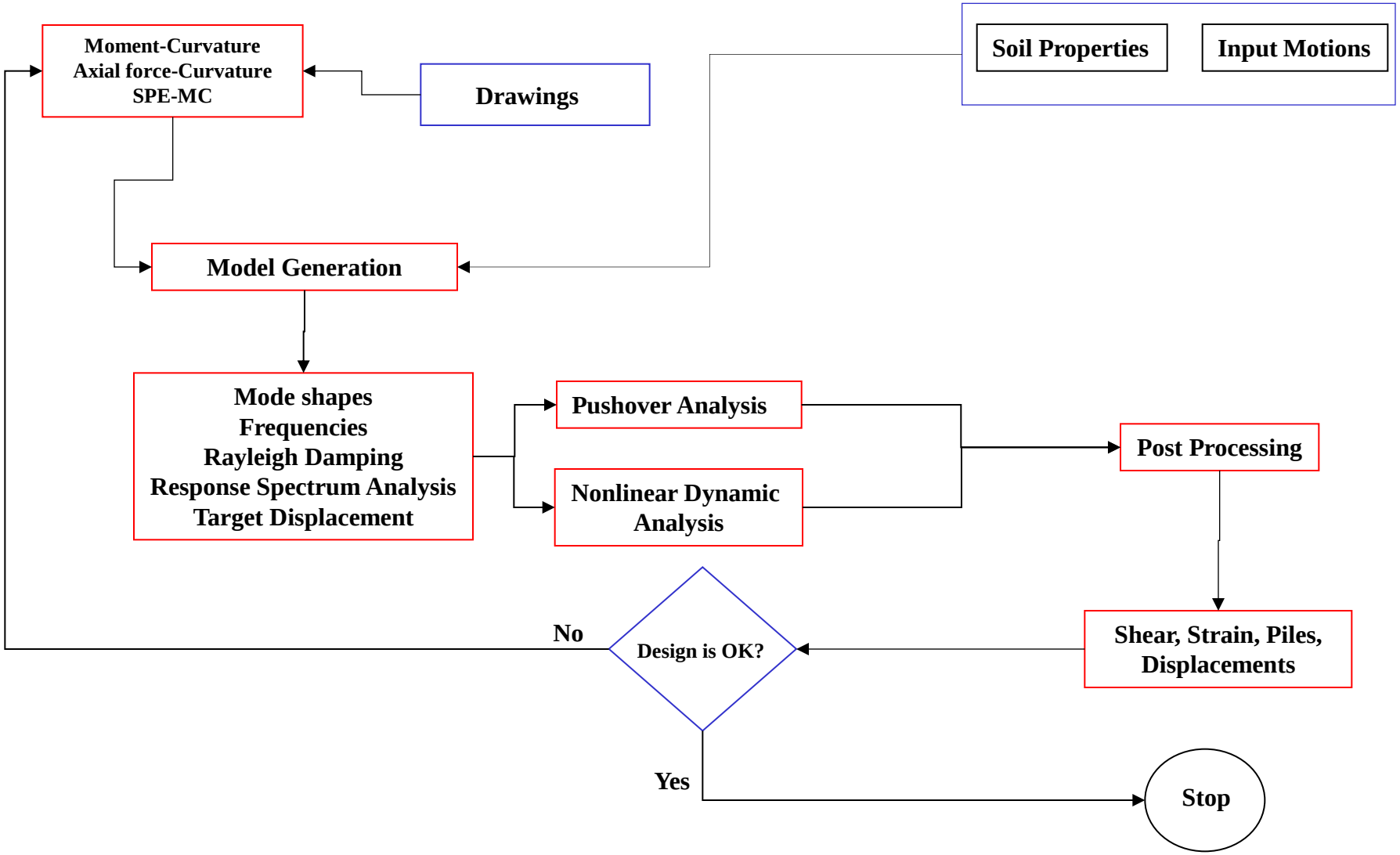
- Reinforced Concrete Piles (detailed SSI and Fixed Base Models)
- Pre-stressed Piles (detailed SSI and Fixed Base Models)
- Hollow Steel Piles (detailed SSI and Fixed Base Models)



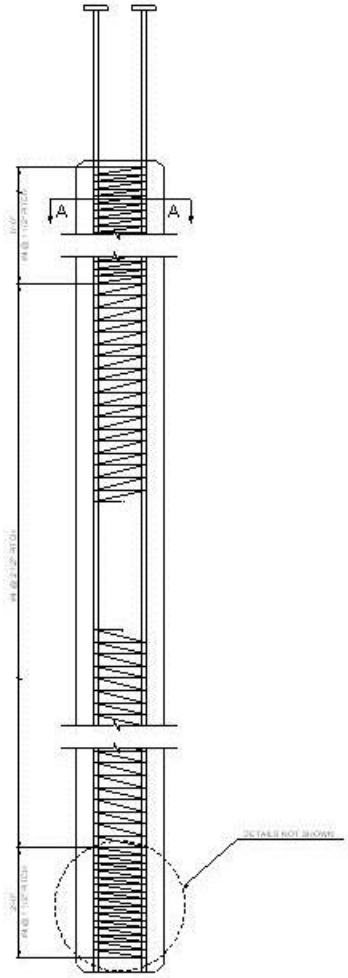


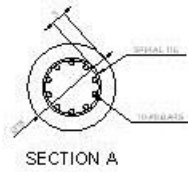


- Nonlinear Soil Properties (p-y, t-z and q-u)

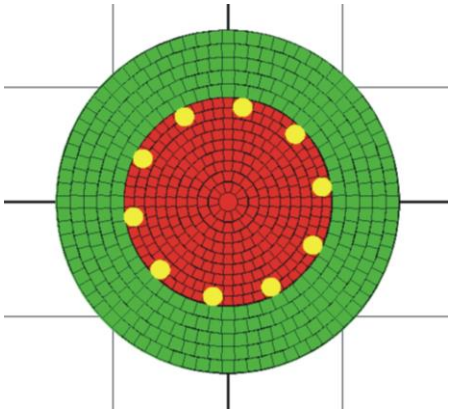


Reinforced Concrete Pile

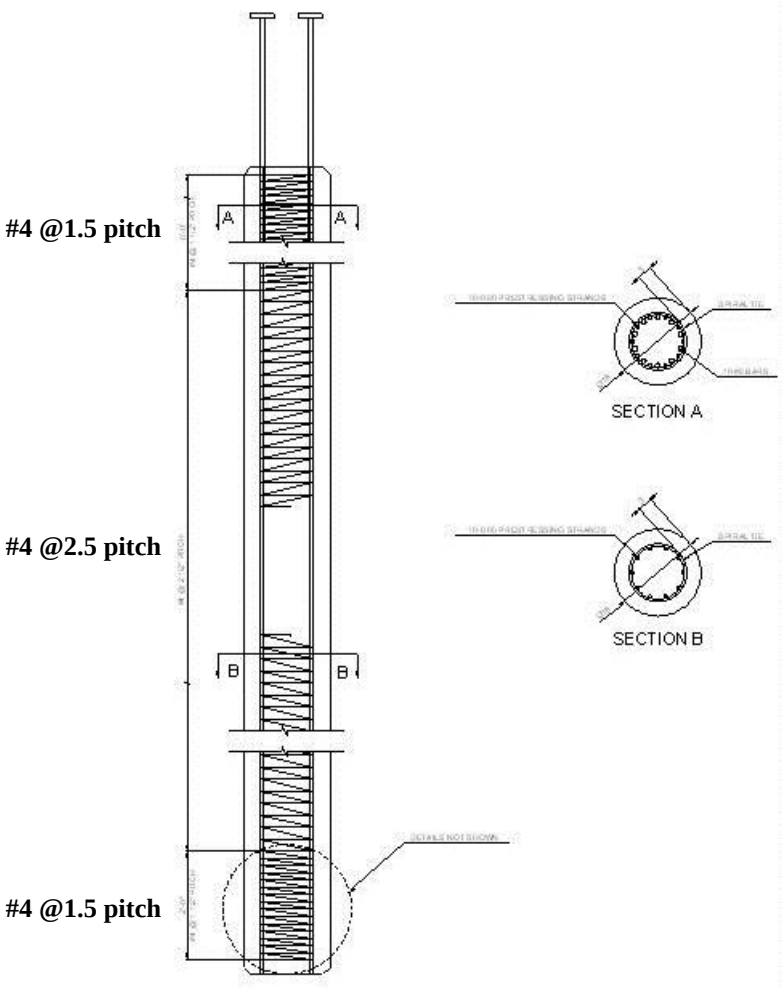




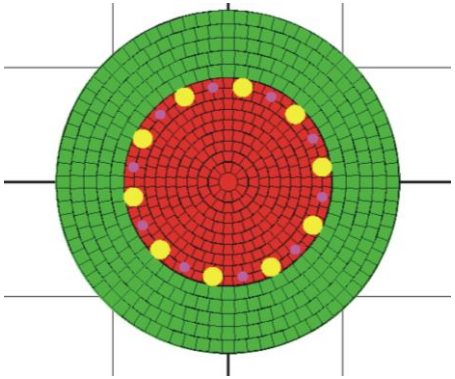
- Reinforced Concrete Piles
- 18” diameter
- Normal Weight Concrete
- f'_c = 5000 psi
- Reinforcement: ASTM A615, Fy = 40 ksi
- Cover 3”



Prestressed Concrete Pile

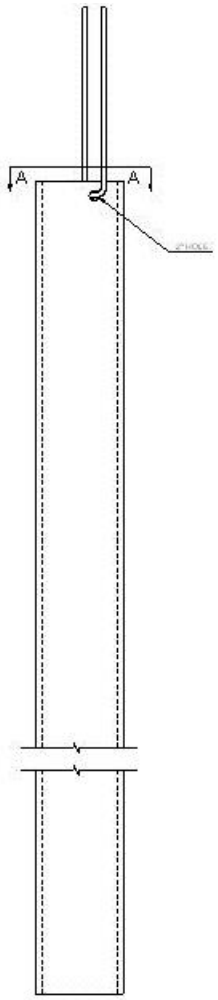


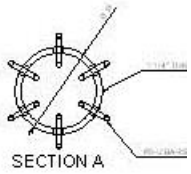
- Pre-cast Pre-stressed Concrete Piles
- 18” diameter
- Normal Weight Concrete
- f'_c = 5000 psi
- Strand ASTM A615 Grade 270
- Reinforcement: ASTM A615, Fy = 40 ksi
- Cover 3”
- Effective Pre-stress of 1000 psi

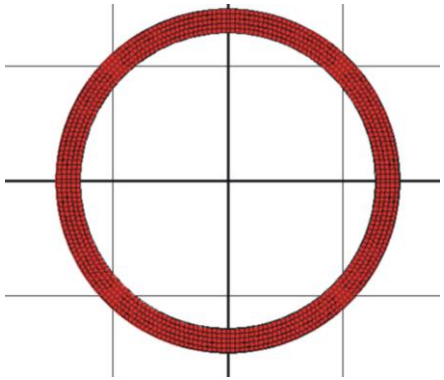


Hollow Steel Pile

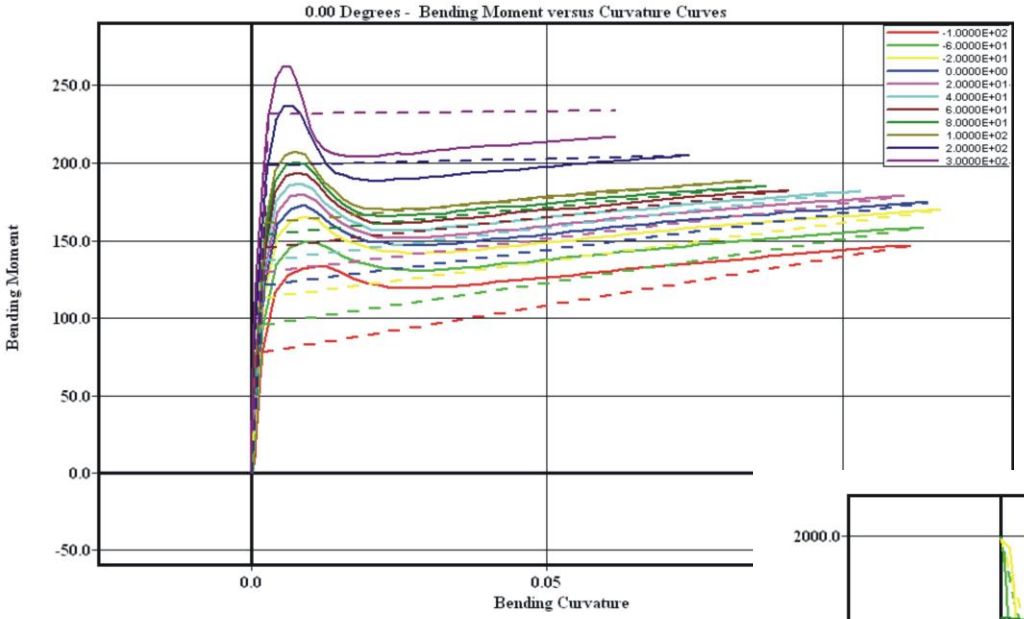
- Hollow Steel Pipe Section Piles
- Steel F_y = 60 ksi
- 18” external diameter
- 1.25” thickness

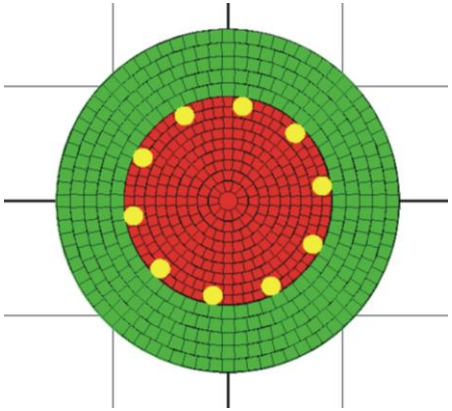


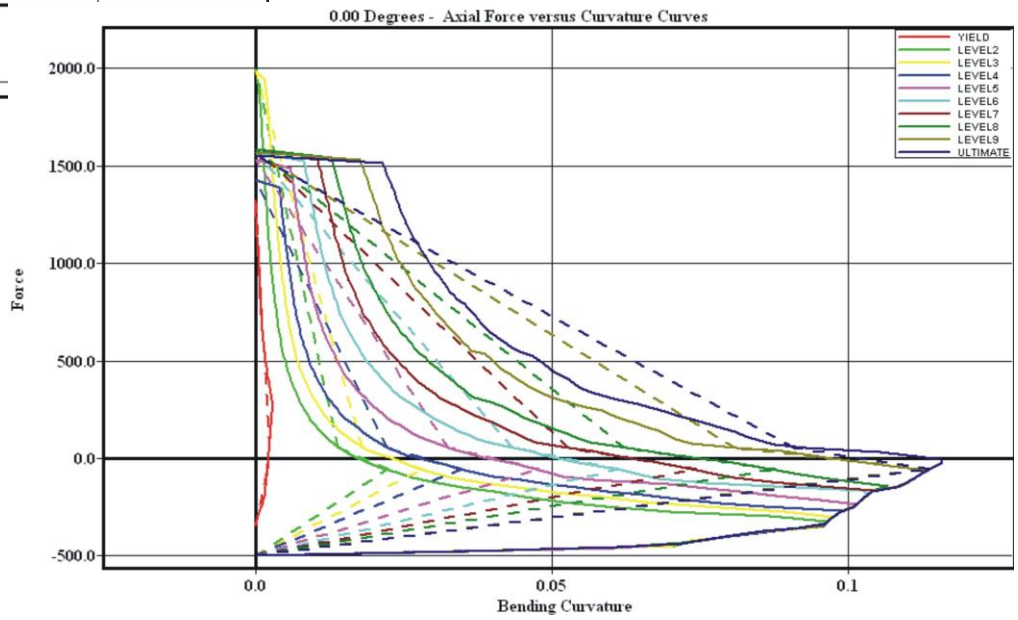




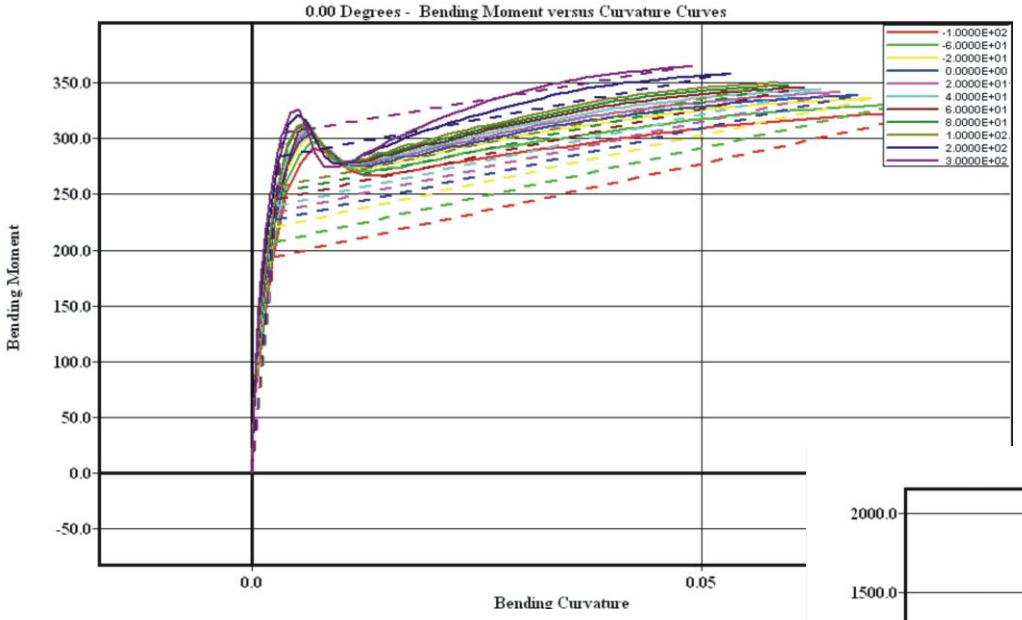
Reinforced Concrete Pile
MC and Yield Surfaces

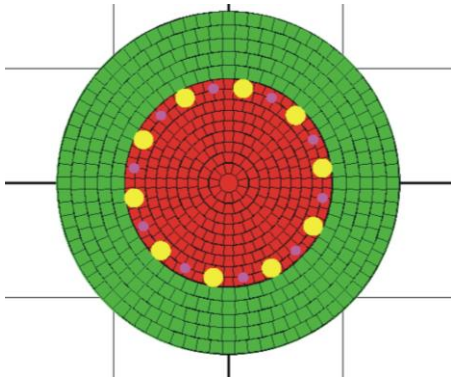


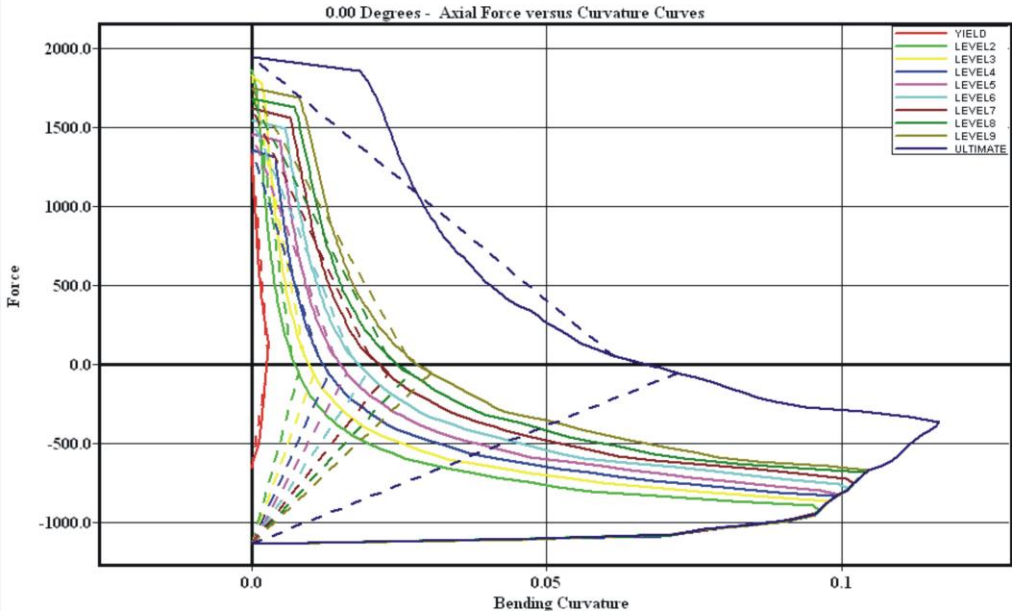




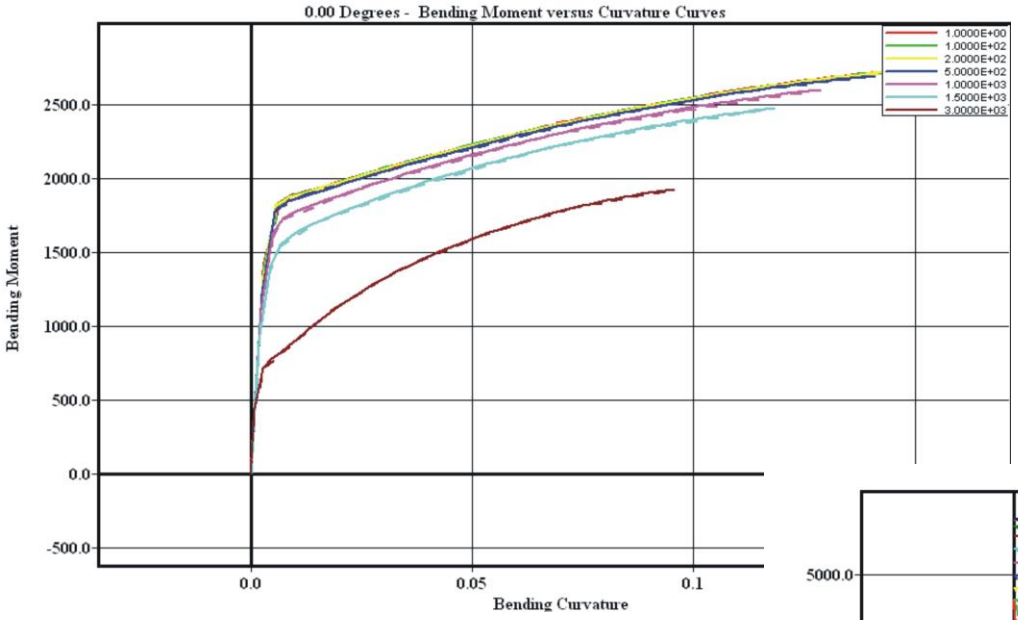
Prestressed Concrete Pile
MC and Yield Surfaces

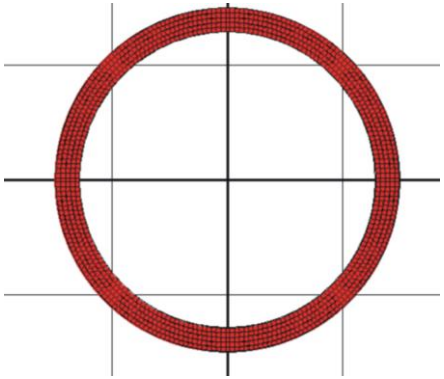


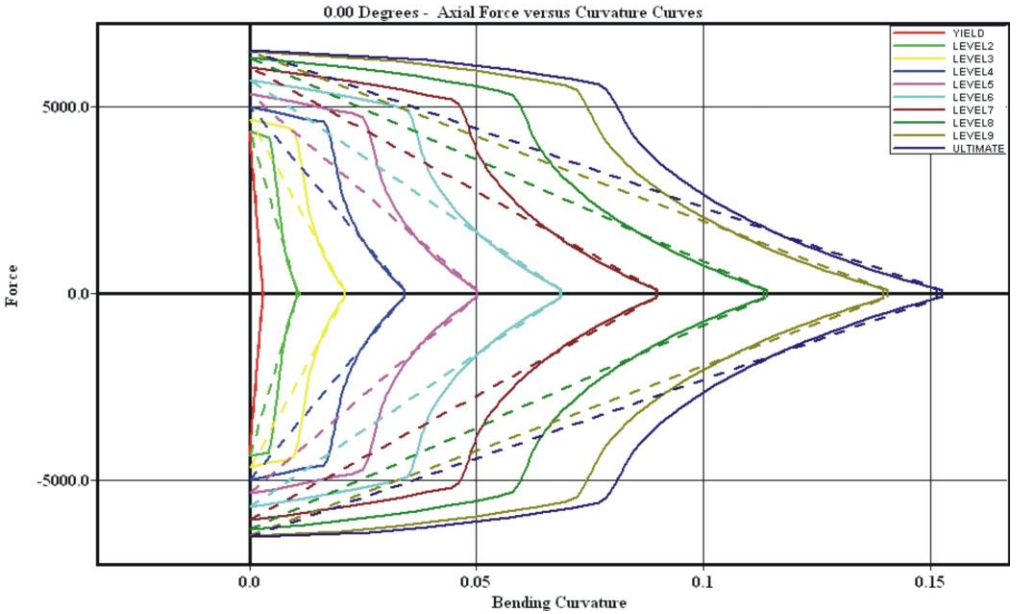


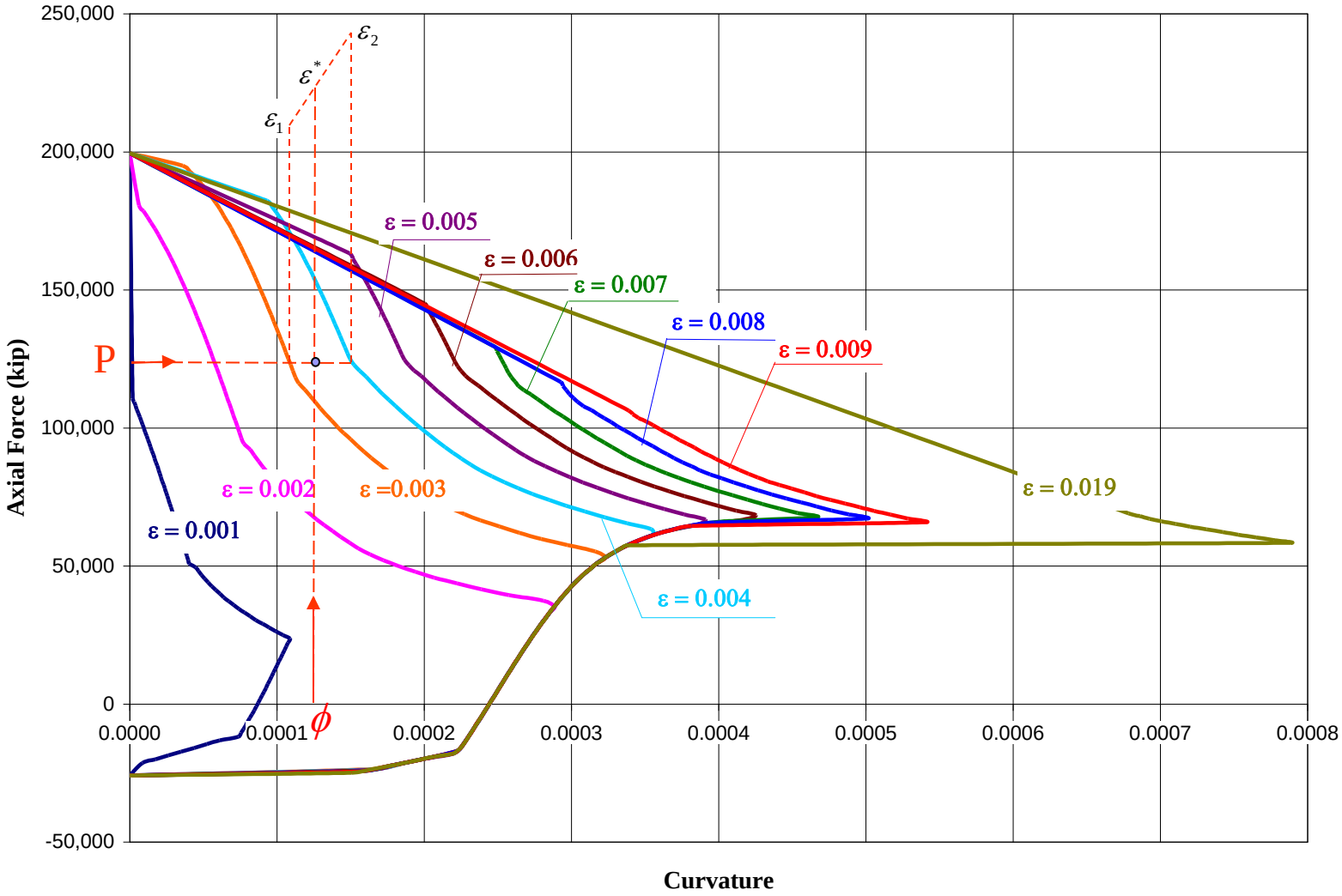


Hollow Steel Pile
MC and Yield Surfaces

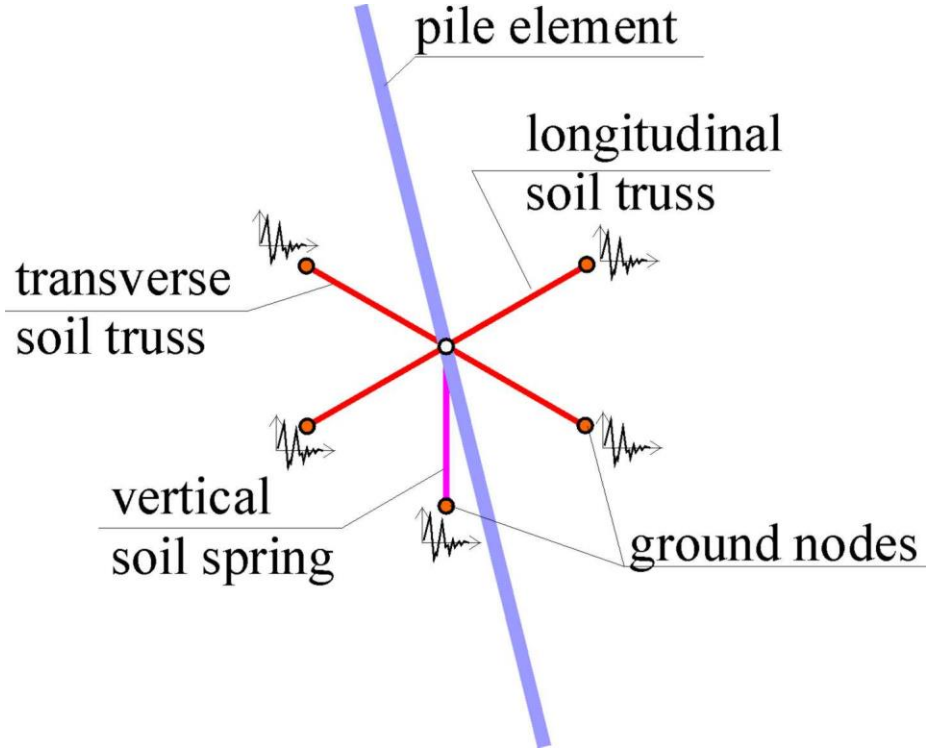


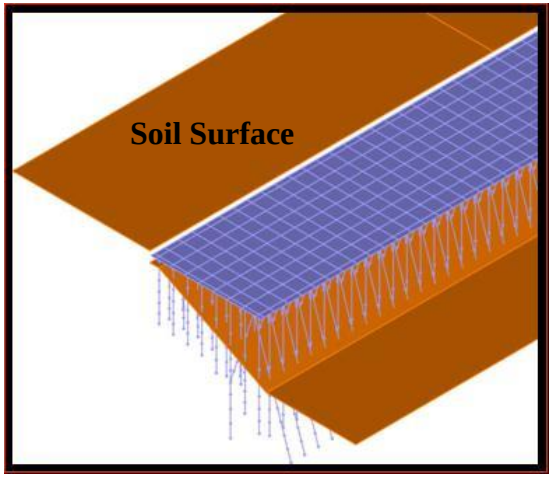


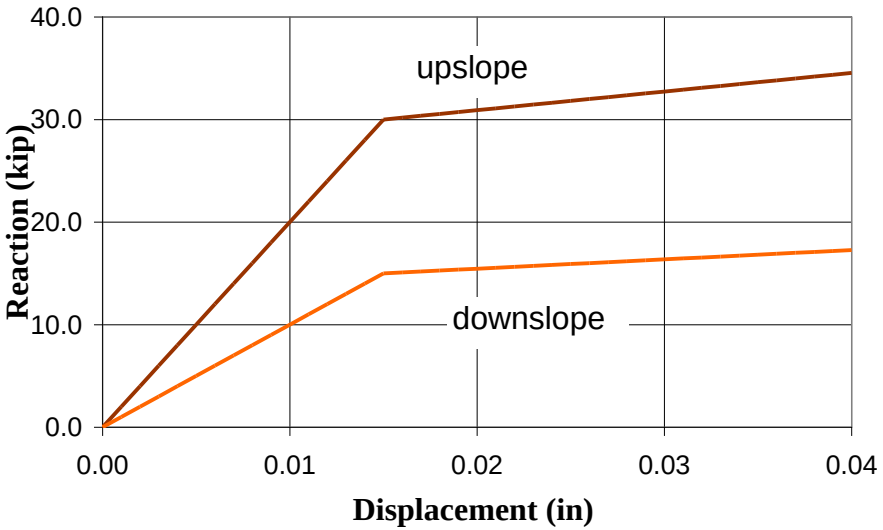


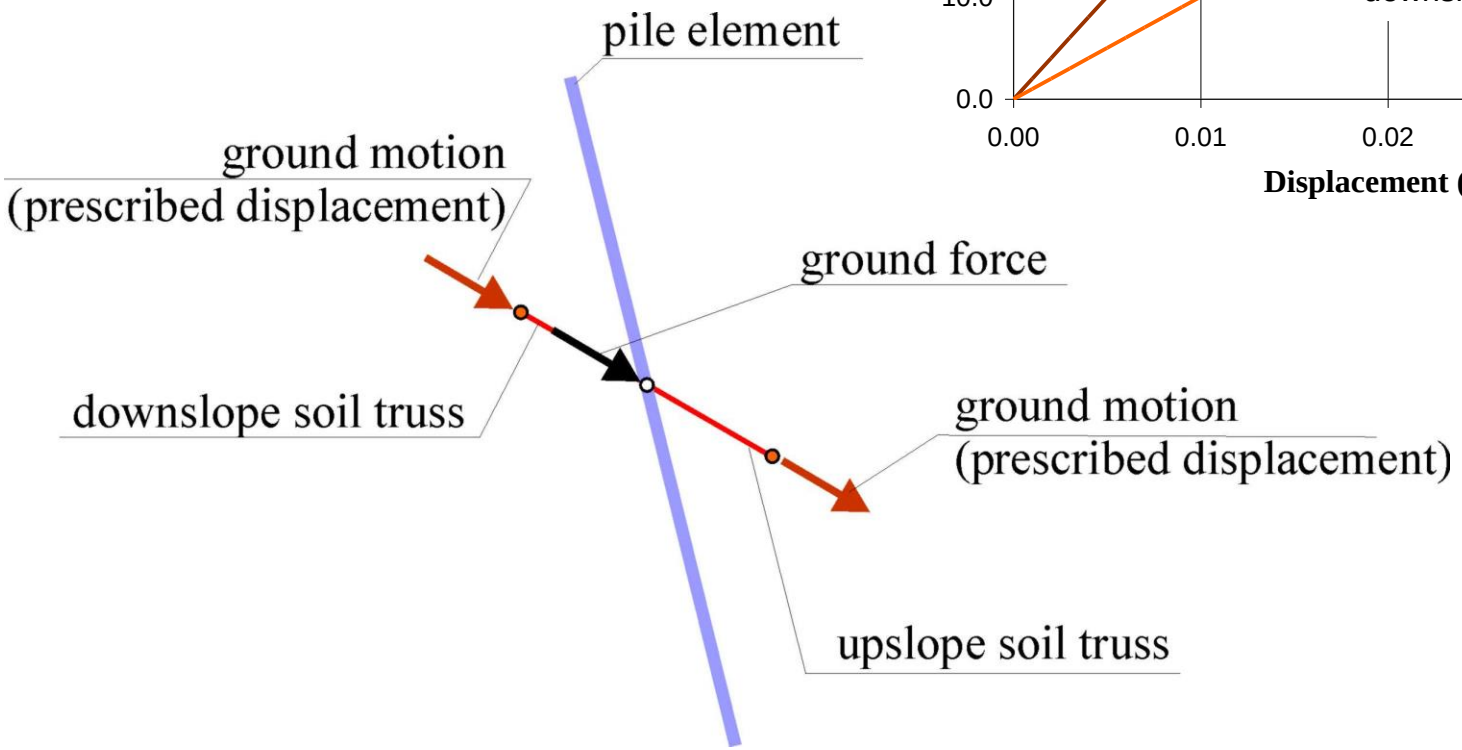


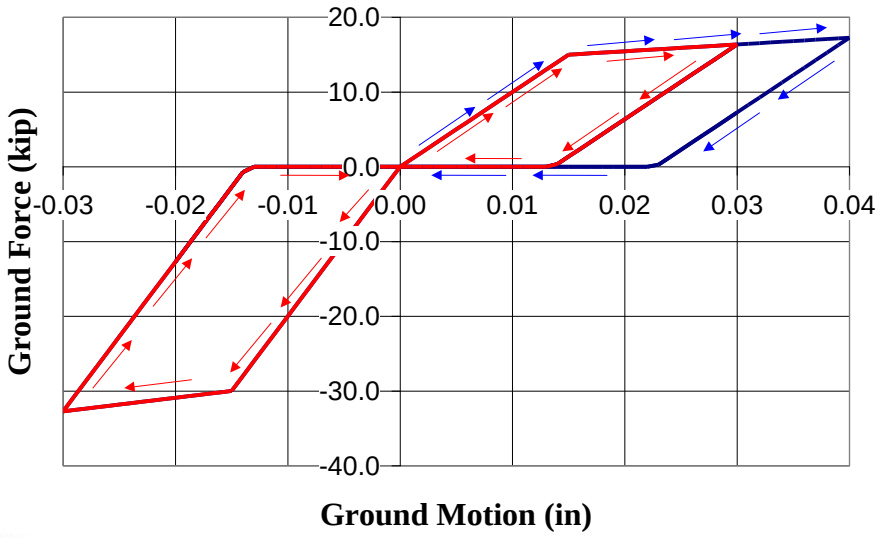
- Horizontal soil: Plasticity-based truss elements.
- Vertical soil: Nonlinear elastic springs.
- Up-slope soil resistance different from down-slope.
- Ground motions: Displacement time history at the ground nodes of soil elements.

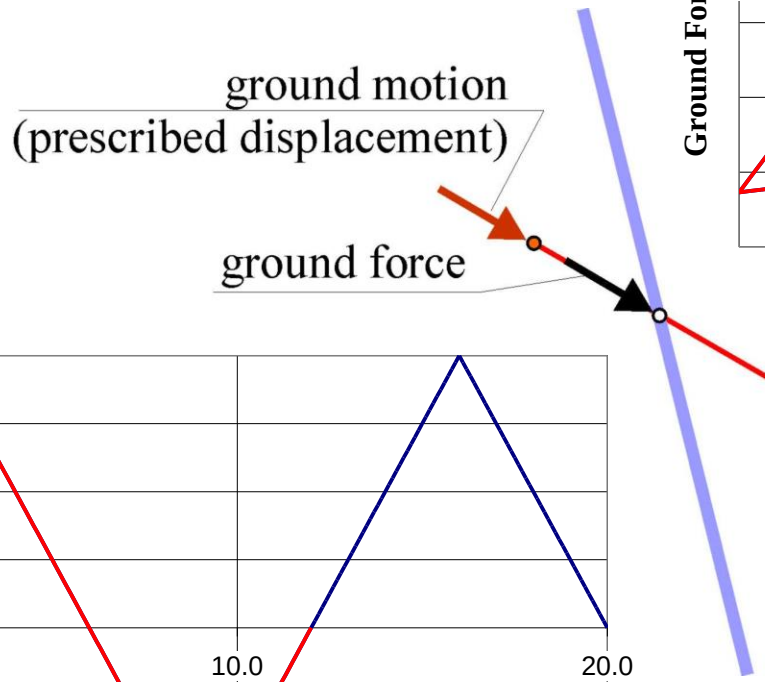


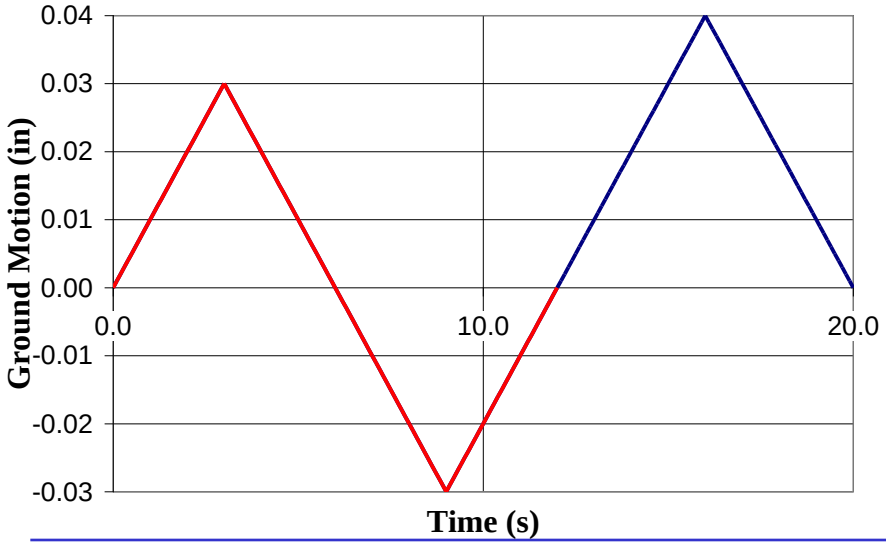








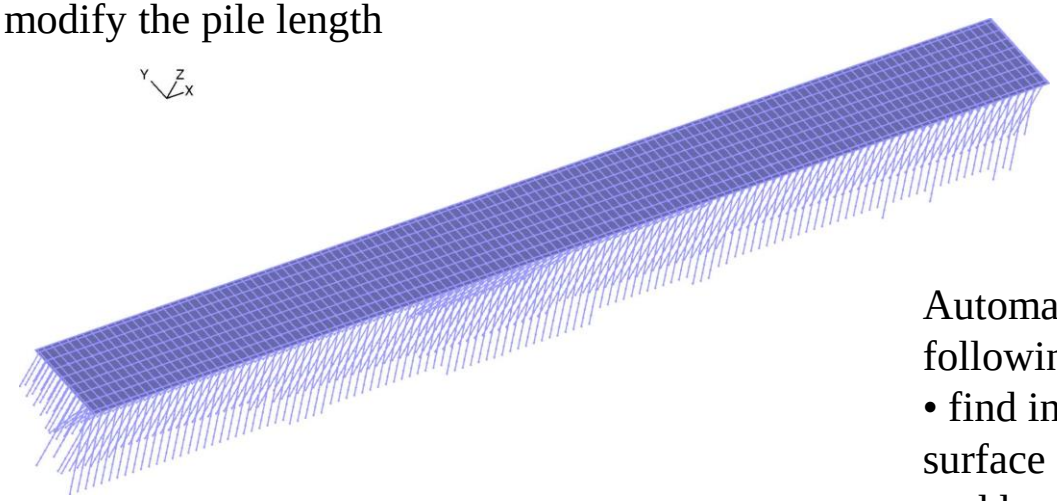


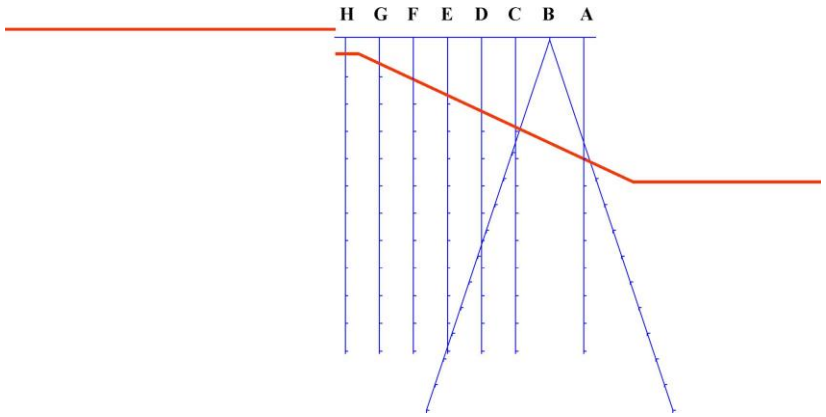


Berth 60-61 Finite Element Model

Model development steps are as follows:
- develop model with design pile length
- identify actual as built pile length
- modify the pile length

Berth 60-61: 1098 piles
18” Square

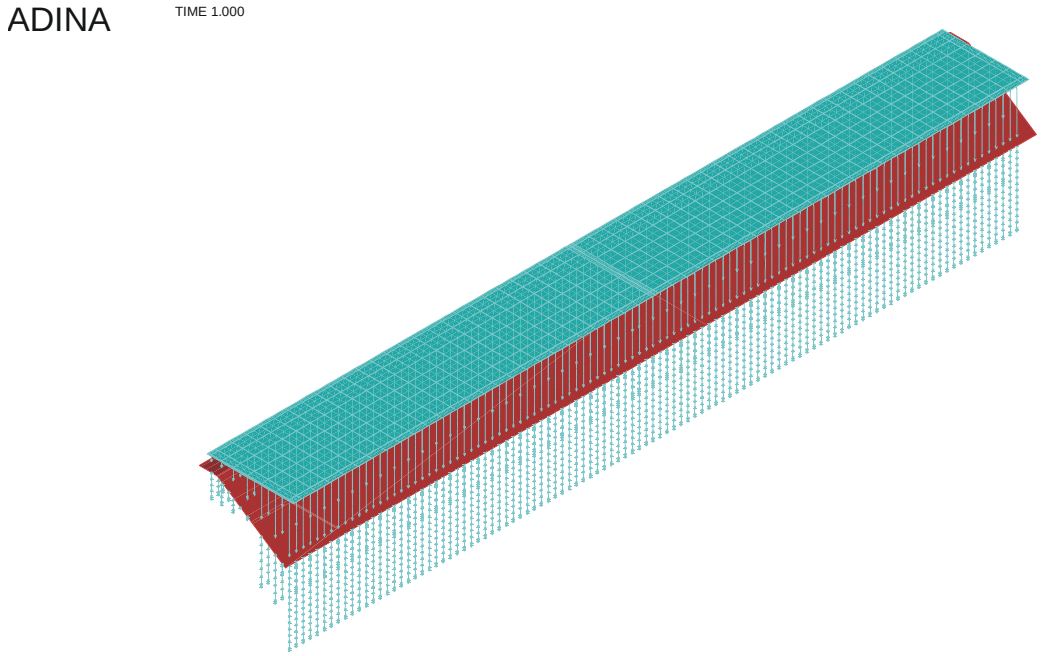


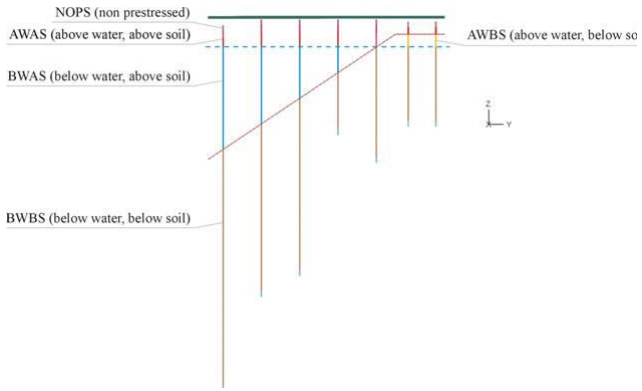


Automatic procedure includes the following steps:
- find intersections of piles with soil surface
- add soil springs below the soil surface

Total number of soil springs = 34,410

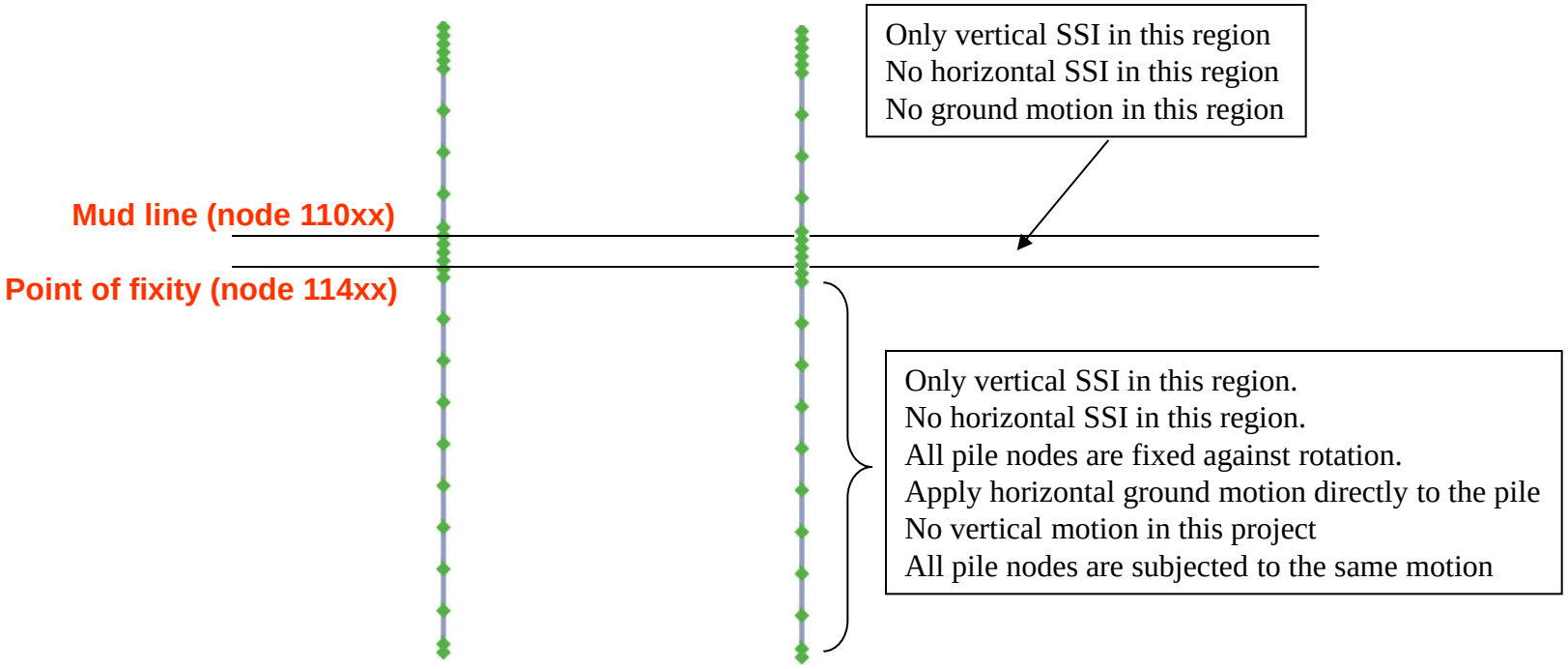
Berth 22 Finite Element Model





Berth 22: 592 Piles

24” Octagonal
Carbon Wrap at the Pile Head



1. **Axial stiffness of the pile will be included.**
2. **Skin friction will be included.**

Pile Type	Point of Fixity for Pile distance beneath the mudline (ft)
Reinforced Concrete Pile	8
Prestressed Concrete	9
Hollow Steel Pipe	13

Mode Shapes/Response Spectrum Analysis/Target Displacement

Mode	Frequency (Hz)	Period (sec)	Mass(X) (%)	Mass(Y) (%)	Mass(Z) (%)	Description
1	0.1332	7.5063	0.00	0.00	0.00	Torsional
2	0.1391	7.1900	0.00	87.19	0.00	Transverse translation
3	0.1392	7.1829	87.20	0.00	0.00	Longitudinal translation
4	3.3138	0.3018	0.00	0.00	0.00	
5	3.3152	0.3016	0.00	0.00	0.00	
6	3.3164	0.3015	0.00	0.25	0.00	
7	3.3177	0.3014	0.14	0.00	0.00	
8	3.3321	0.3001	0.00	0.00	0.01	
9	3.3406	0.2993	0.00	0.00	0.00	
10	3.3423	0.2992	0.01	0.00	0.00	
11	3.3421	0.2992	0.00	0.00	0.00	
12	3.3432	0.2991	0.00	0.02	0.00	
13	3.3488	0.2986	0.00	0.81	0.00	
14	3.3516	0.2984	0.93	0.00	0.00	
15	3.3600	0.2976	0.00	0.00	0.00	
16	4.8554	0.2060	0.01	0.00	0.00	
17	5.2174	0.1917	0.00	0.00	83.73	Vertical translation
18	5.5547	0.1800	0.00	0.01	0.00	
19	6.2782	0.1593	0.00	0.00	11.28	
20	7.5033	0.1333	0.00	0.00	0.00	
99	61.5527	0.0162	0.00	0.00	0.00	
100	61.5570	0.0162	0.00	0.53	0.00	
		Total	88.28	88.81	95.03	

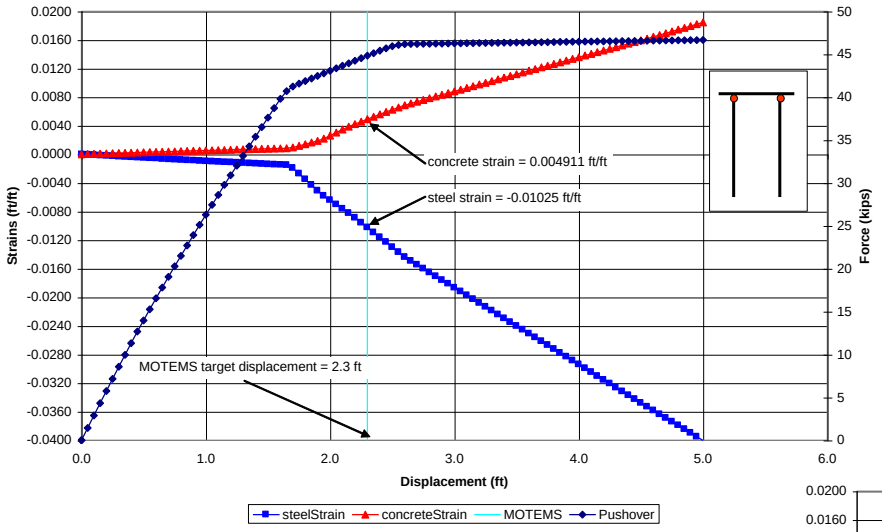
Comparison of Frequencies

	Reinforced Concrete Pile		Pre-stressed Pile		Hollow Steel Pile	
	Detailed SSI	fixed- base	Detailed SSI	fixed- base	Detailed SSI	fixed- base
Mode	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)
1	7.5063	7.8170	6.8850	7.3020	3.2160	3.5140
2	7.1900	7.4890	6.5840	6.9810	3.0890	3.3730
3	7.1829	7.4810	6.5760	6.9740	3.0770	3.3610
4	0.3018	0.3165	0.2771	0.2972	0.1794	0.1794
5	0.3016	0.3163	0.2765	0.2966	0.1692	0.1696
6	0.3015	0.3162	0.2763	0.2964	0.1538	0.1557
7	0.3014	0.3161	0.2763	0.2965	0.1423	0.1454
8	0.3001	0.3144	0.2762	0.2963	0.1300	0.1398
9	0.2993	0.3137	0.2760	0.2962	0.1228	0.1364
10	0.2992	0.3135	0.2760	0.2961	0.1227	0.1364
11	0.2992	0.3135	0.2760	0.2961	0.1225	0.1362
12	0.2991	0.3134	0.2759	0.2960	0.1222	0.1359
13	0.2986	0.3128	0.2757	0.2955	0.1219	0.1356
14	0.2984	0.3125	0.2751	0.2949	0.1217	0.1354
15	0.2976	0.3118	0.2744	0.2944	0.1217	0.1354
16	0.2060	0.2060	0.2057	0.2051	0.1212	0.1348
17	0.1917	0.1917	0.1916	0.1910	0.1204	0.1337
18	0.1800	0.1801	0.1797	0.1792	0.1188	0.1303
19	0.1593	0.1594	0.1590	0.1589	0.1181	0.1280
20	0.1333	0.1334	0.1330	0.1329	0.1141	0.1180
99	0.0162	0.0142	0.0141	0.0142	0.0129	0.0123
100	0.0162	0.0141	0.0135	0.0141	0.0129	0.0123

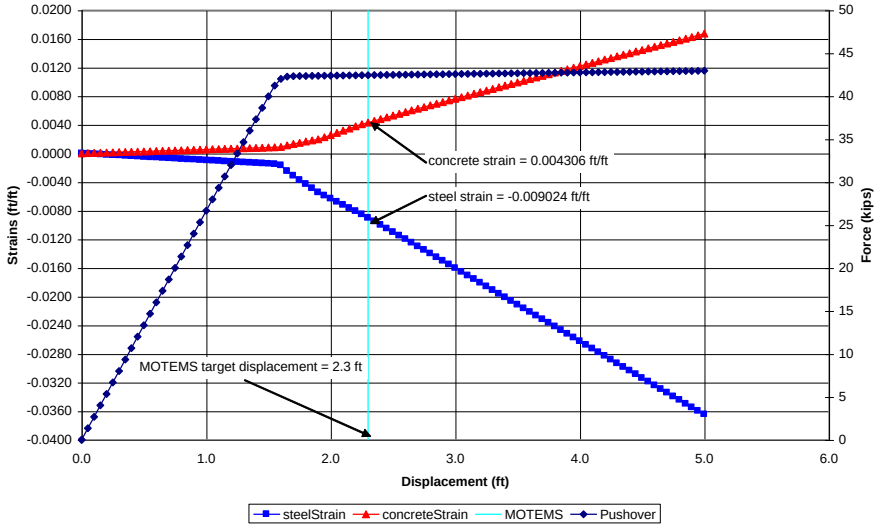
Linearized soil properties were used for the response spectrum analysis
CLE: Target displacement from RSA = 2.2 ft to 2.3 ft
MCE: Target displacement from RSA = 2.97 ft to 3.09 ft

Reinforced Concrete Pile Transverse CLE Pushover

Concrete Pile Detailed SSI



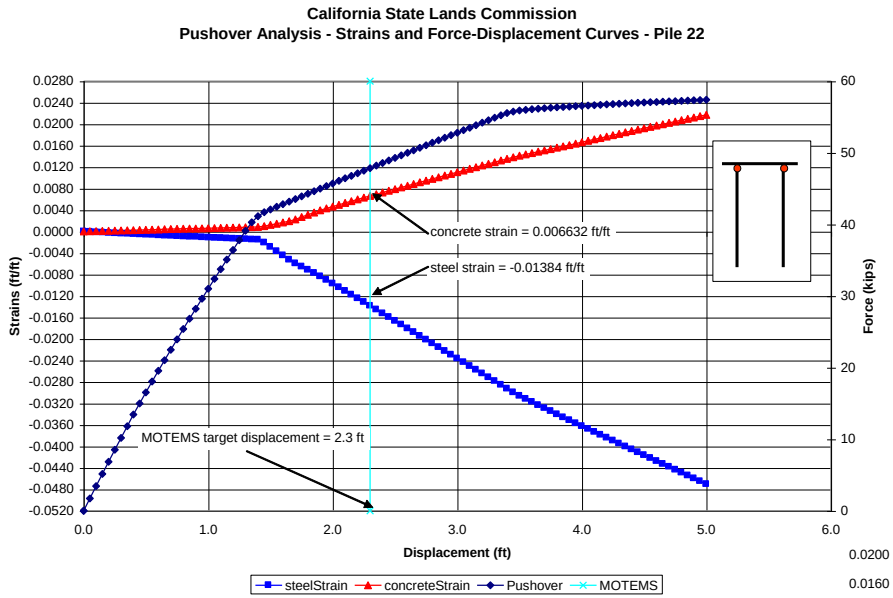
Concrete Pile Fixed Base



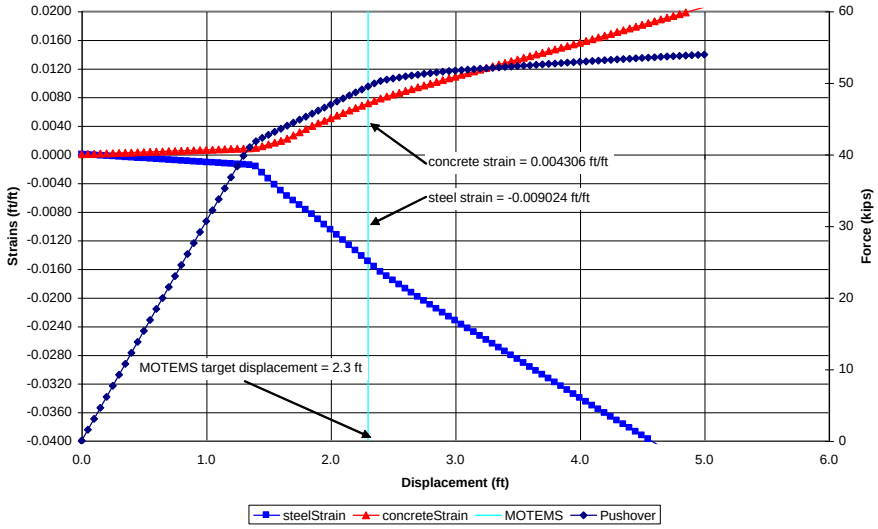
CLE

SC SOLUTIONS

Prestresssed Concrete Pile Detailed SSI



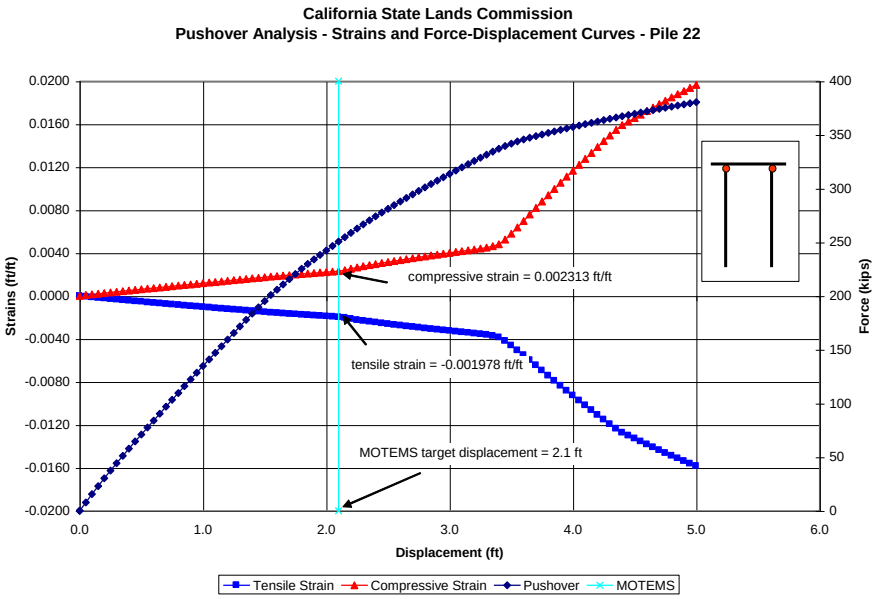
Prestressed Concrete Pile Fixed Base



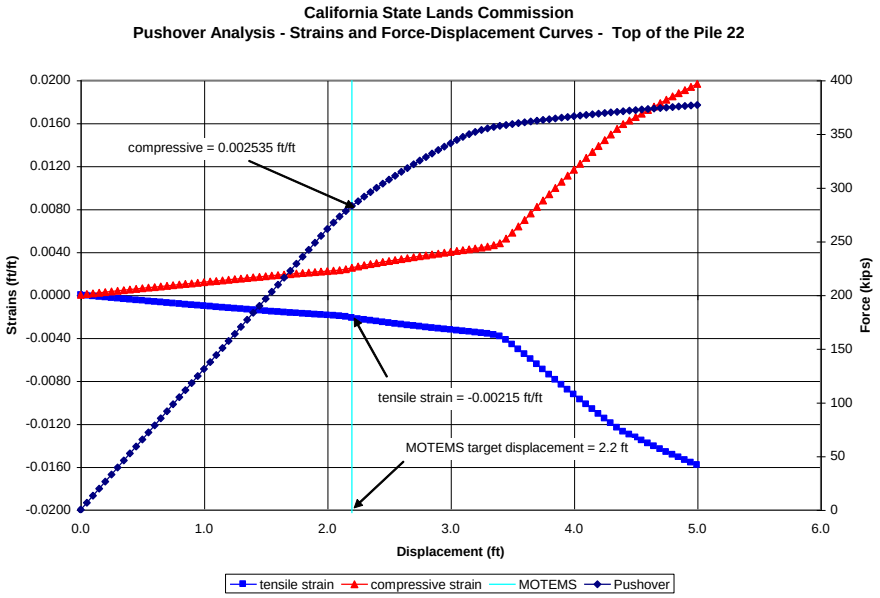
CLE

Hollow Steel Pile Transverse CLE Pushover

Hollow Steel Pile Detailed SSI

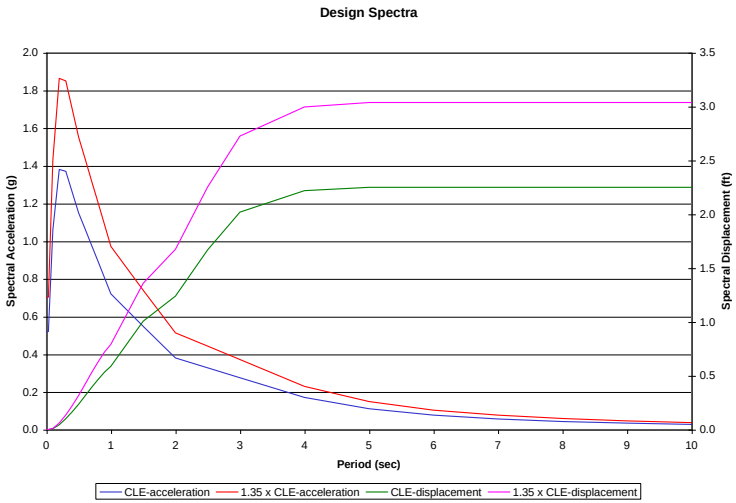


Hollow Steel Pile Fixed Base

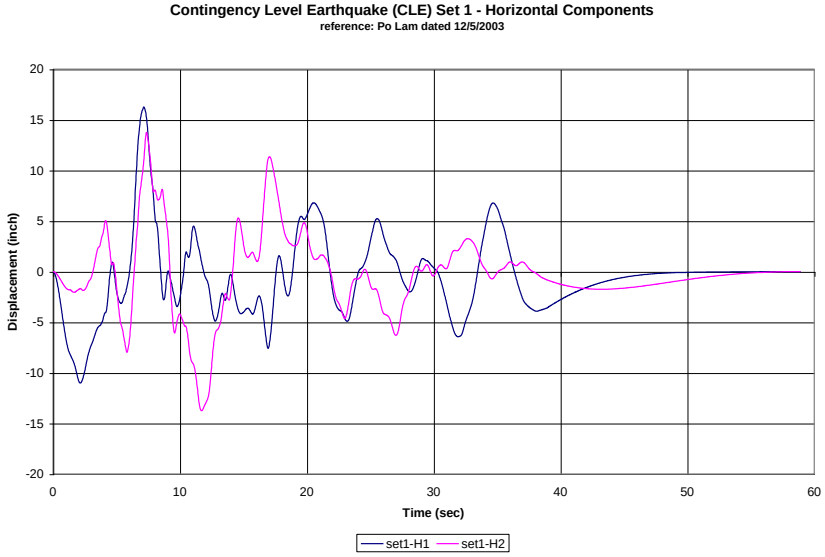


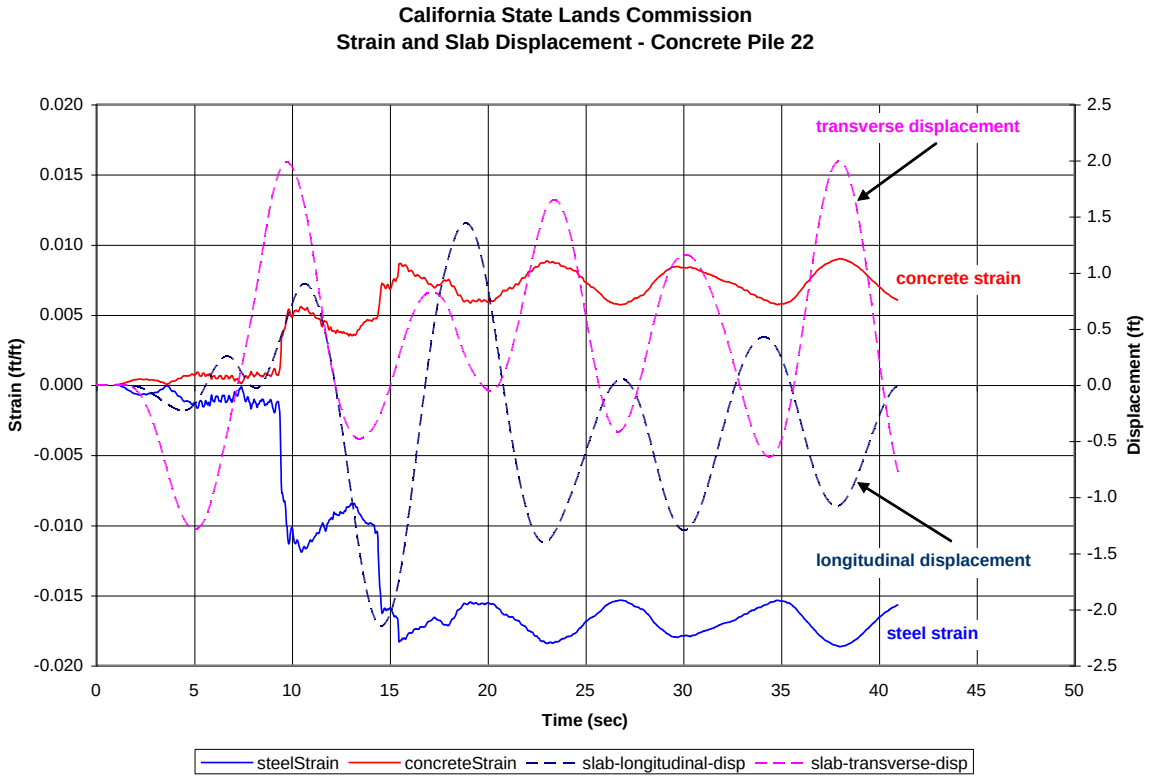
CLE

SC SOLUTIONS

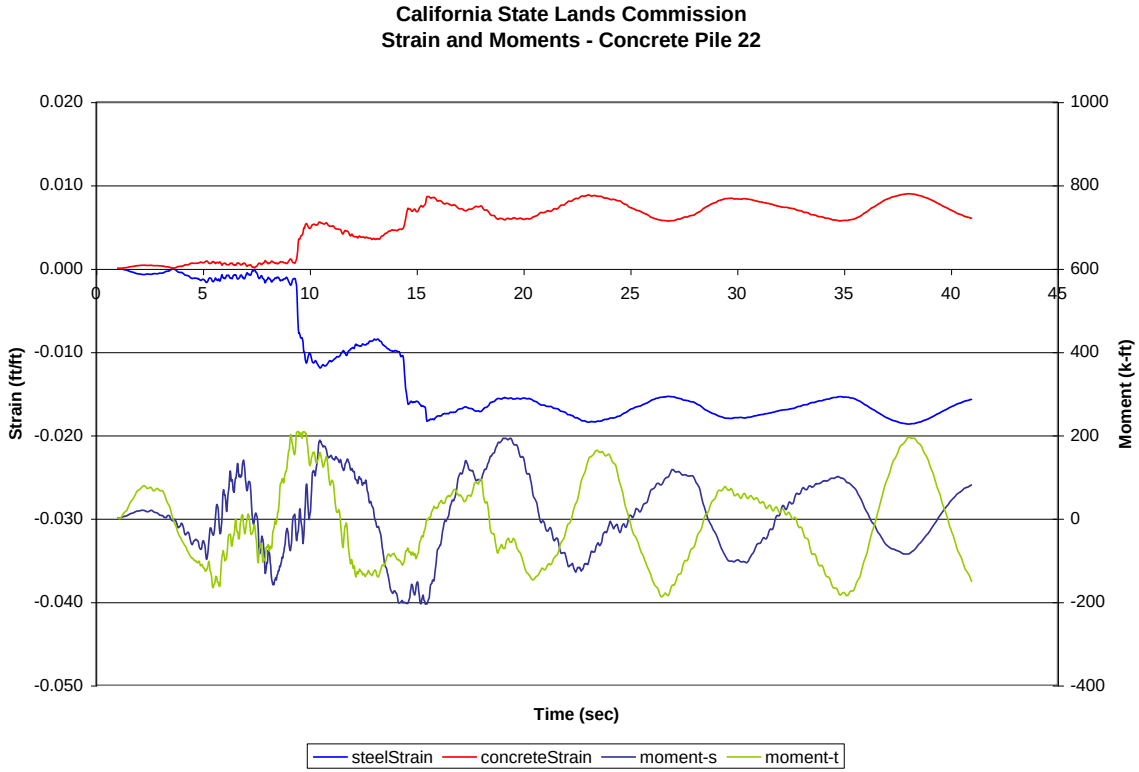


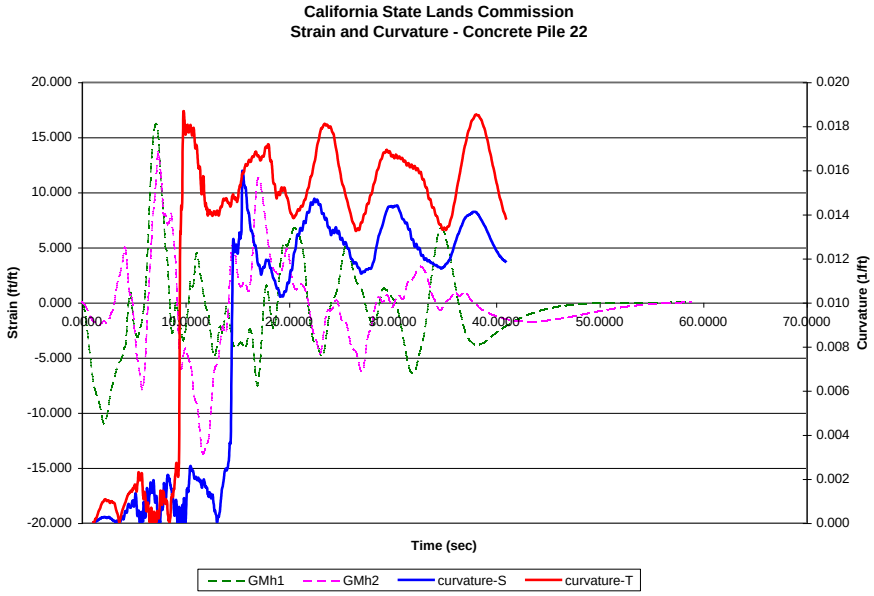
- **Contingency Level Earthquake (CLE)**
- **NEHRP upper bound limit on the shaking level: Maximum Considered Earthquake (MCE)**

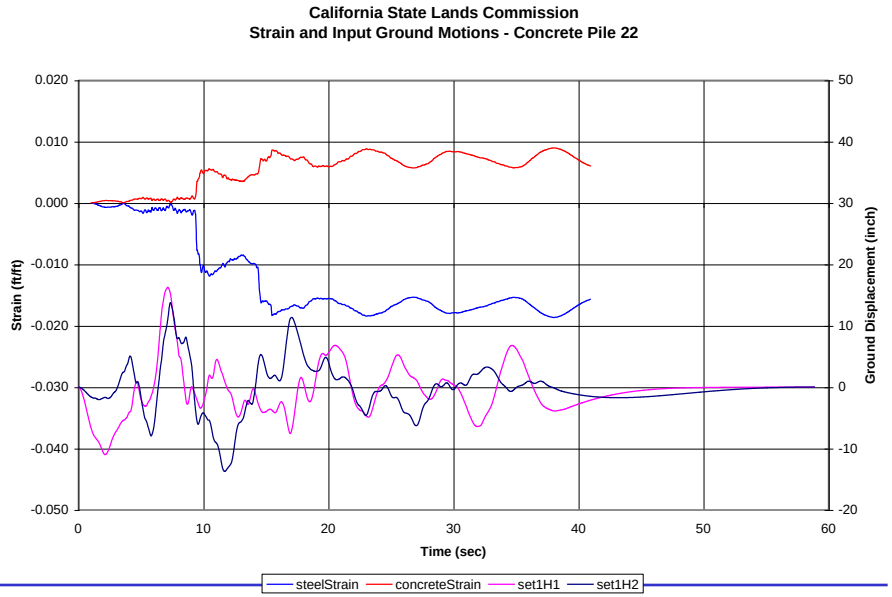




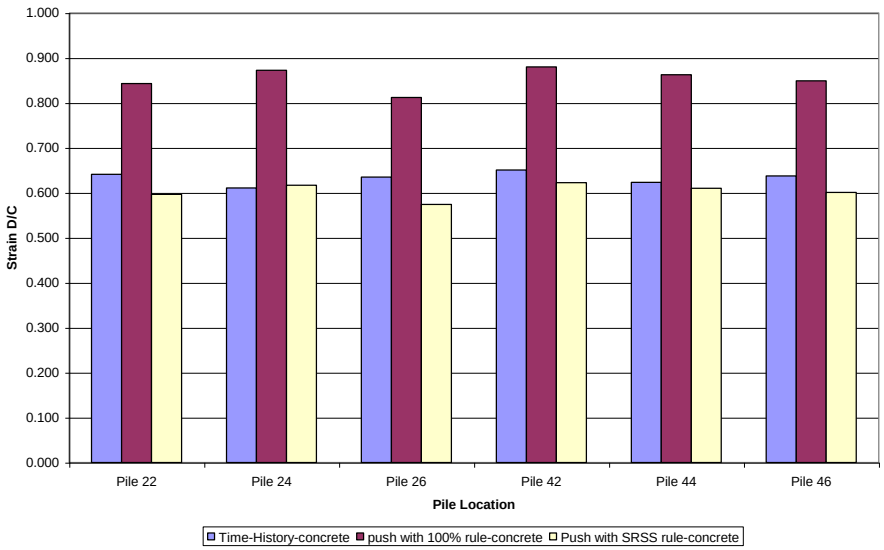
Unlike Forces and Moments
Deformations Increase After Yielding







Maximum Strain D/C in Concrete



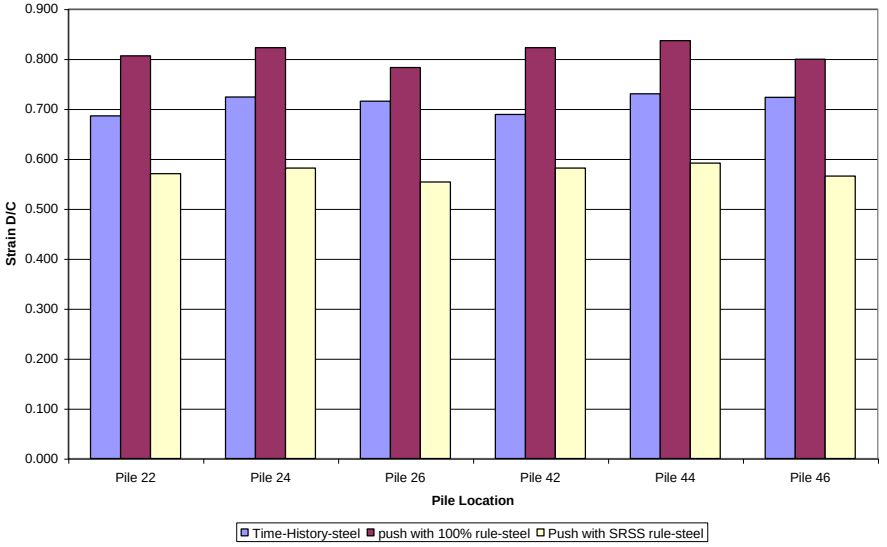
TH smaller than pushover with 100% rule
TH larger than pushover with SRSS rule

Time-History Analysis

Pushover with 100% rule

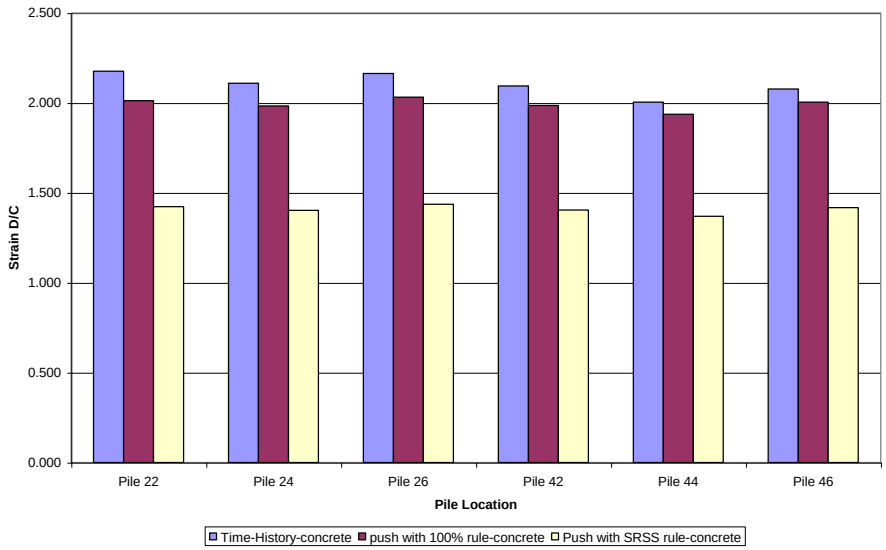
Pushover with SRSS rule

Maximum Strain D/C in Steel



SC SOLUTIONS

Maximum Strain D/C in Concrete



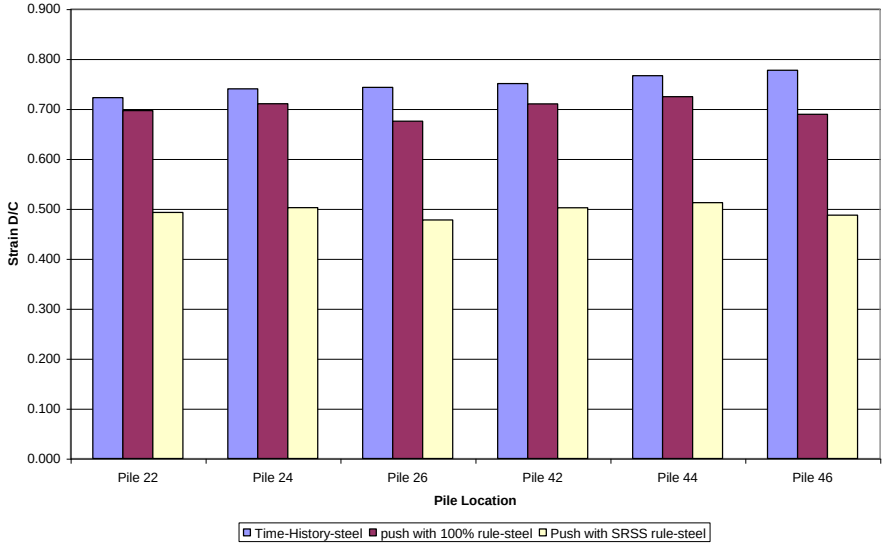
TH larger than pushover with 100% rule
TH larger than pushover with SRSS rule

Time-History Analysis

Pushover with 100% rule

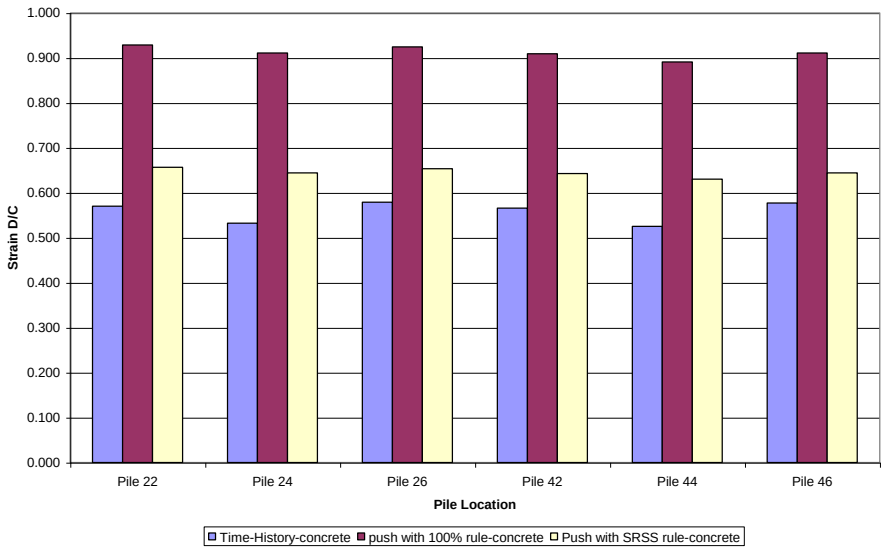
Pushover with SRSS rule

Maximum Strain D/C in Steel



SC SOLUTIONS

Maximum Strain D/C in Concrete



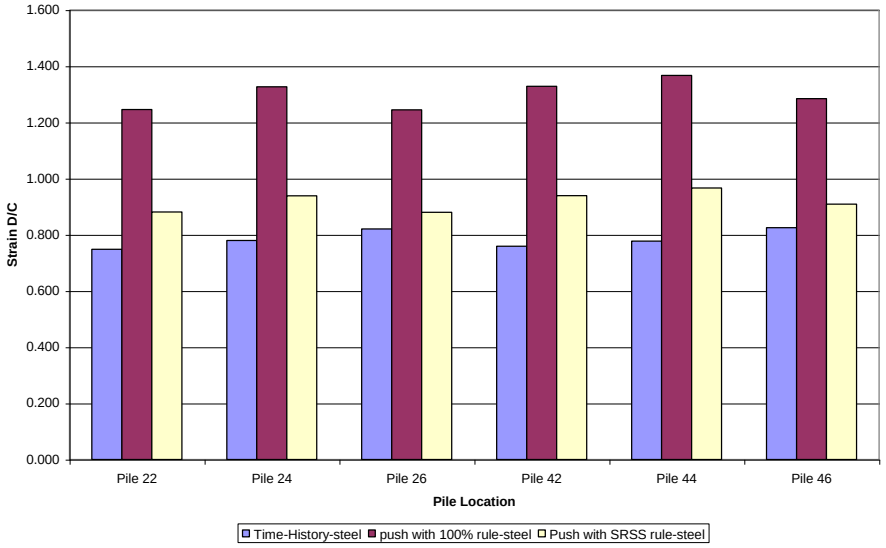
TH smaller than pushover with 100% rule
TH smaller than pushover with SRSS rule

Time-History Analysis

Pushover with 100% rule

Pushover with SRSS rule

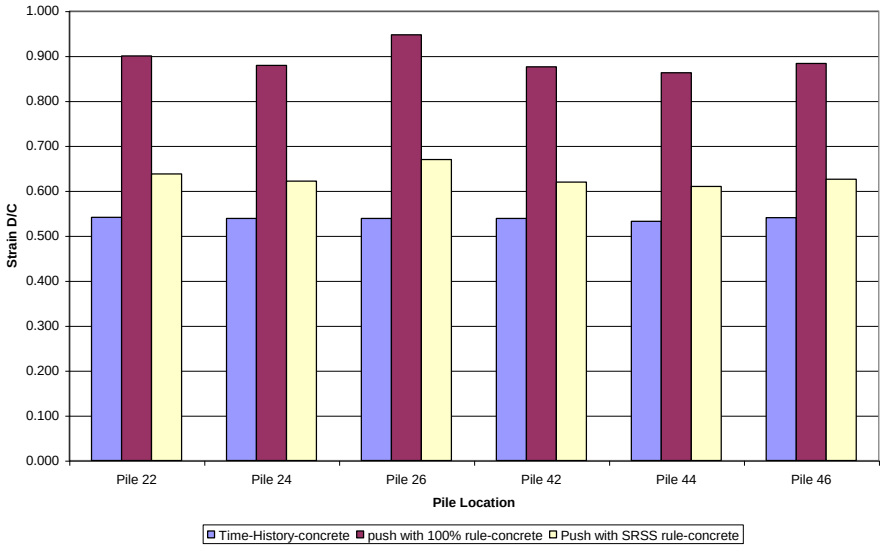
Maximum Strain D/C in Steel



SC SOLUTIONS

MCE – Prestressed Concrete – Fixed Base

Maximum Strain D/C in Concrete



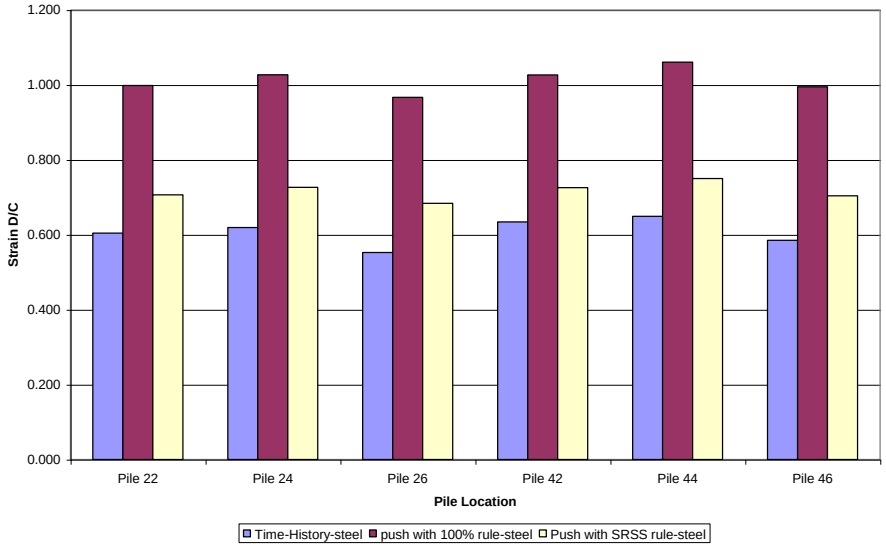
TH smaller than pushover with 100% rule
TH smaller than pushover with SRSS rule

Time-History Analysis

Pushover with 100% rule

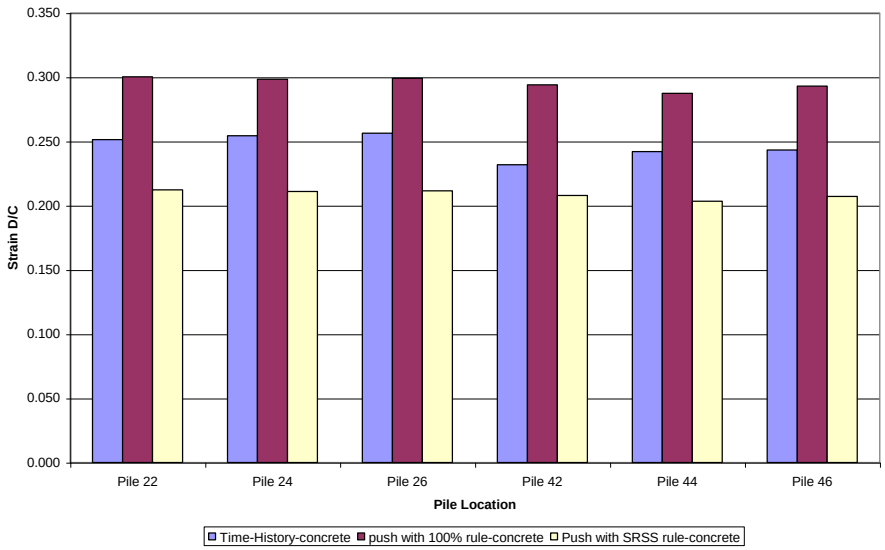
Pushover with SRSS rule

Maximum Strain D/C in Steel



SC SOLUTIONS

Maximum Strain D/C in Concrete



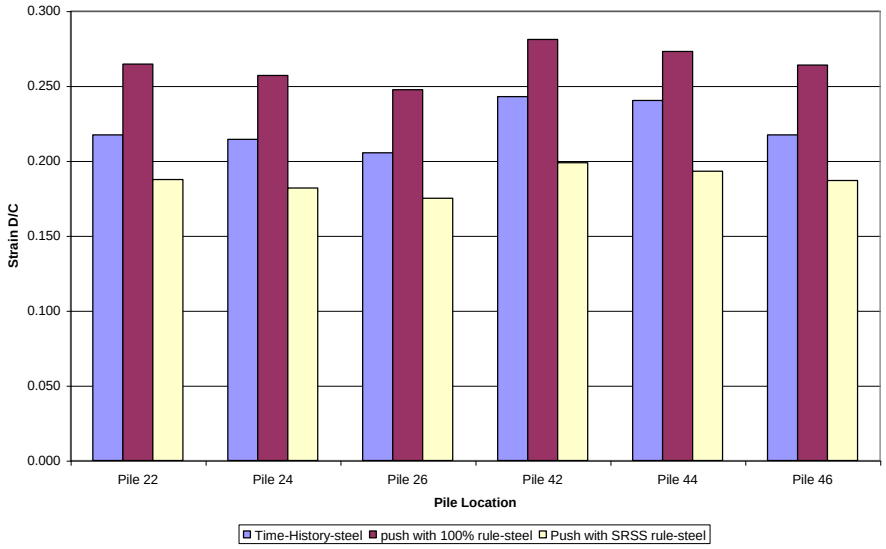
TH smaller than pushover with 100% rule
TH larger than pushover with SRSS rule

Time-History Analysis

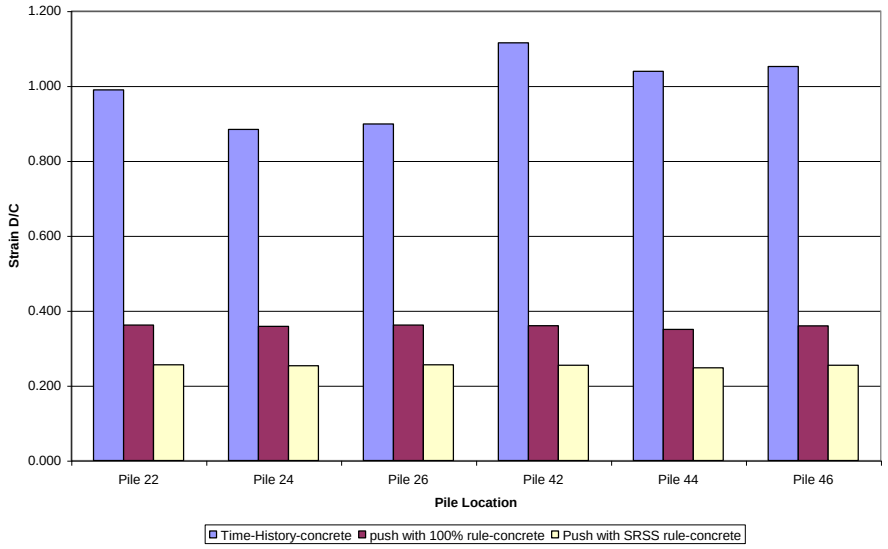
Pushover with 100% rule

Pushover with SRSS rule

Maximum Strain D/C in Steel



Maximum Strain D/C in Concrete



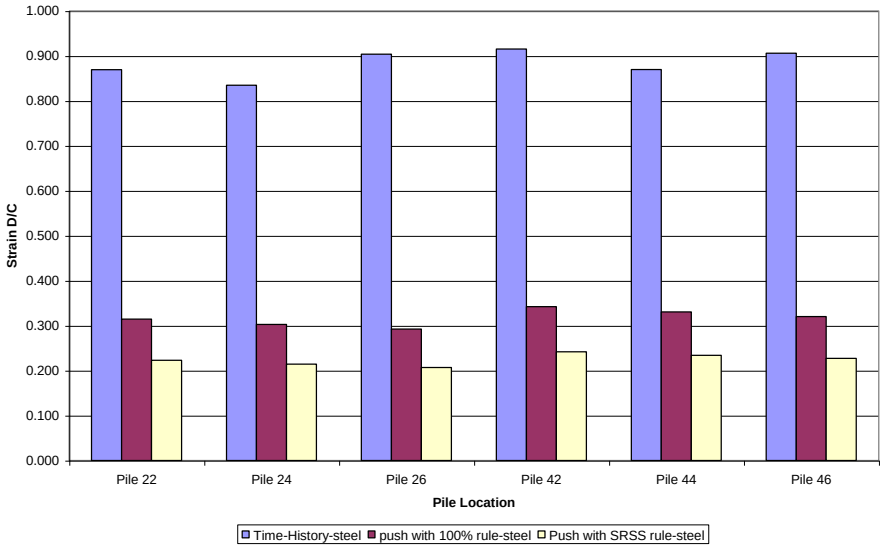
TH larger than pushover with 100% rule
TH larger than pushover with SRSS rule

Time-History Analysis

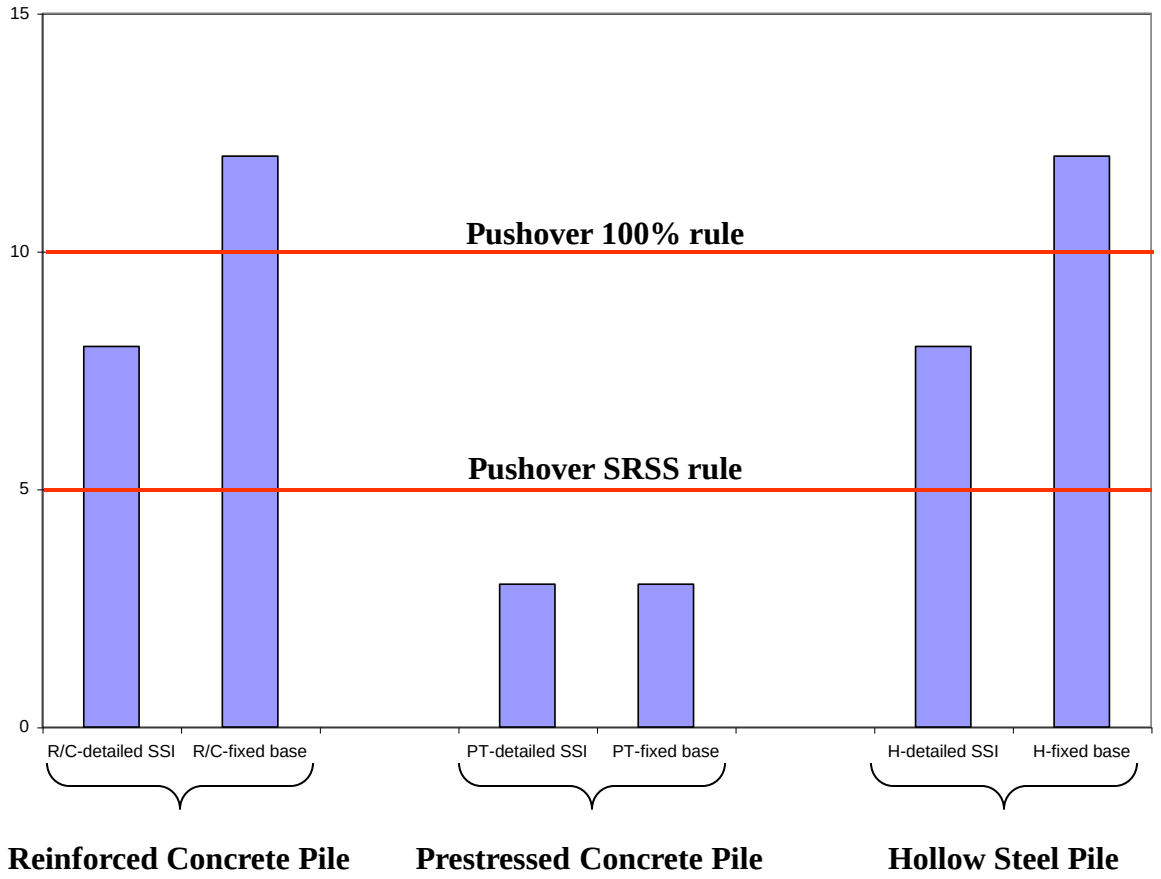
Pushover with 100% rule

Pushover with SRSS rule

Maximum Strain D/C in Steel

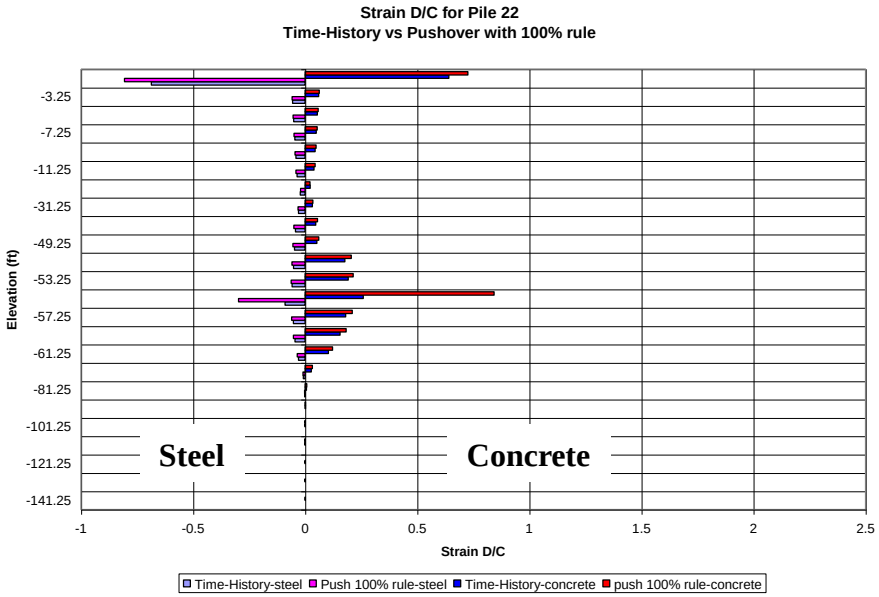


Schematic Distribution of Maximum Strain Due to TH Analysis vs. the Pushover Analysis Rule

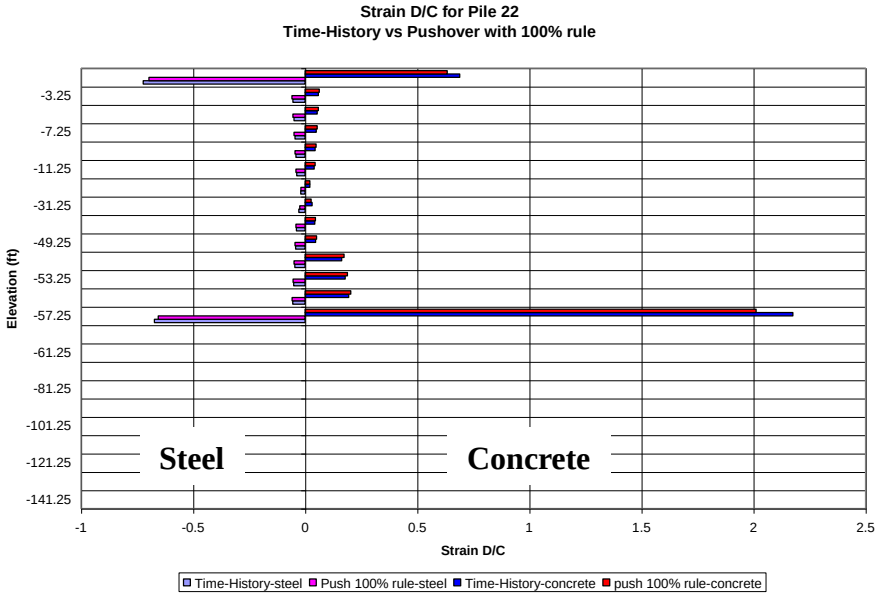


MCE Reinforced Concrete Pile

Detailed SSI



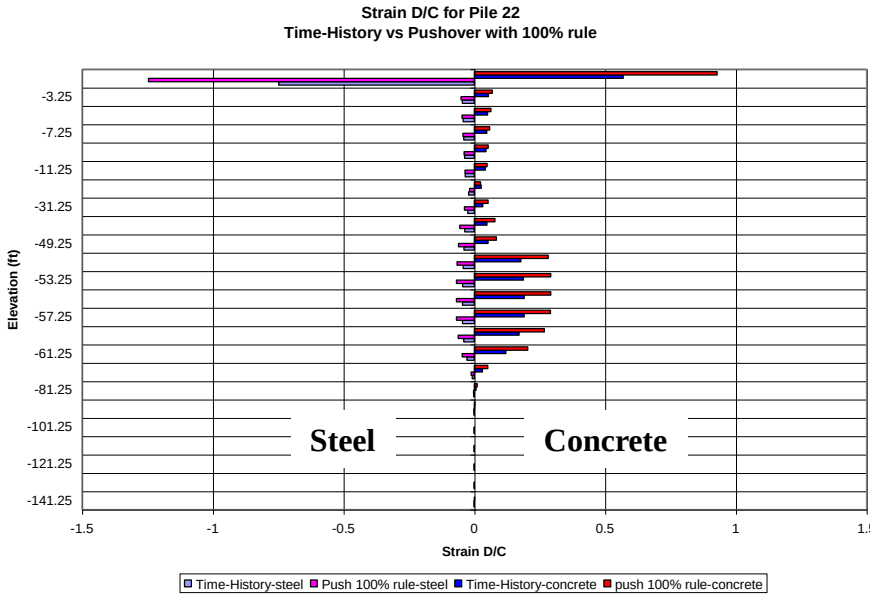
Fixed Base



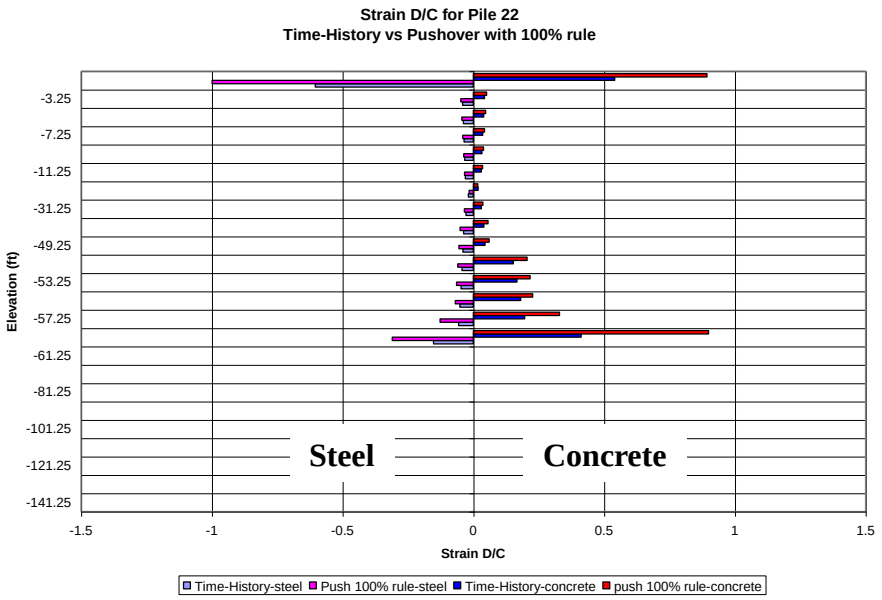
SC SOLUTIONS

MCE Prestressed Concrete Pile

Detailed SSI



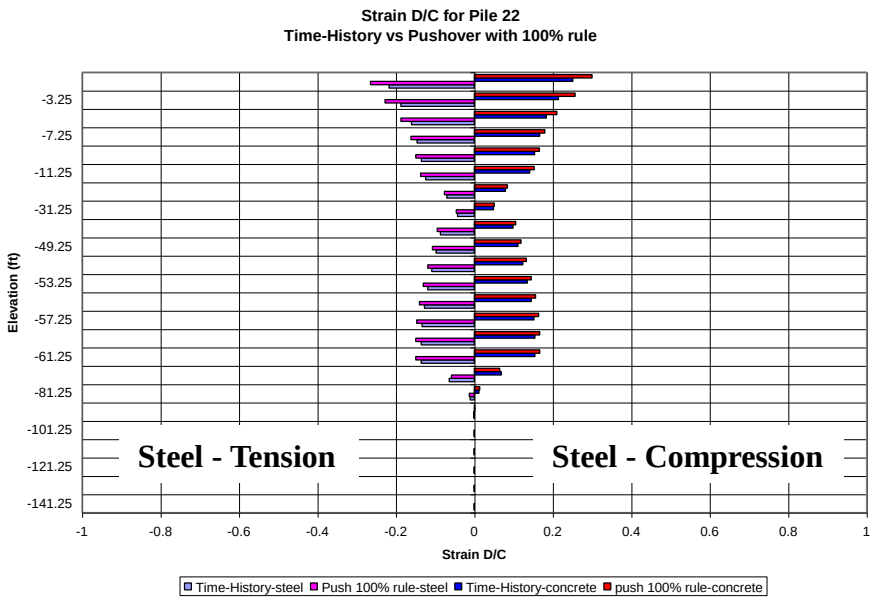
Fixed Base



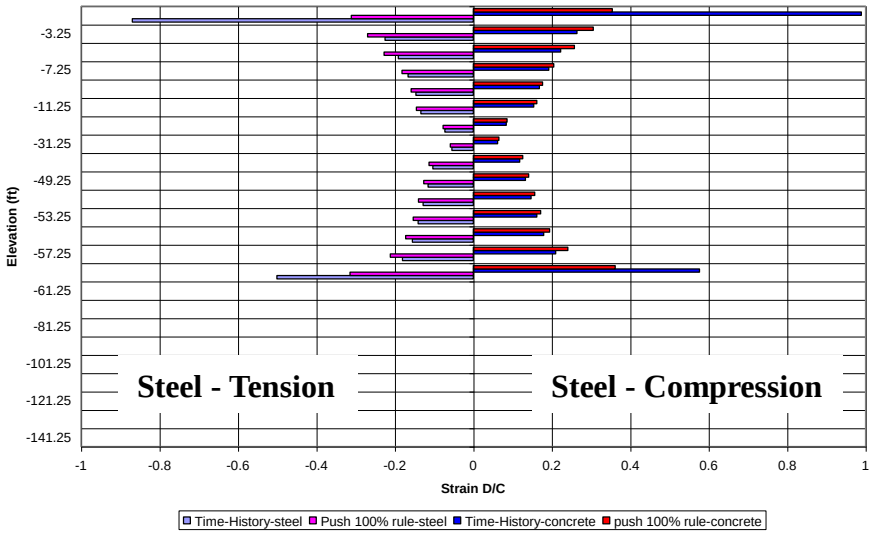
SC SOLUTIONS

MCE Hollow Steel Pile

Detailed SSI



Fixed Base



SC SOLUTIONS

Conclusions:

- MOTEMS Specifies Strain Limits for Various Performance Levels

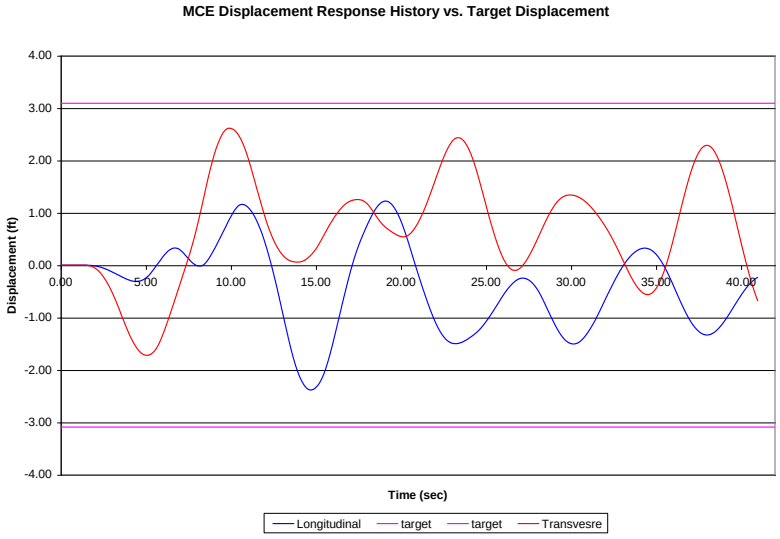
- The Concept of Pushover Analysis is Based on a Single-Degree-of-Freedom System
  Wharf Structures are in General:
    Unsymmetrical in Geometry
    Unsymmetrical in Material (upslope vs. downslope soil properties)

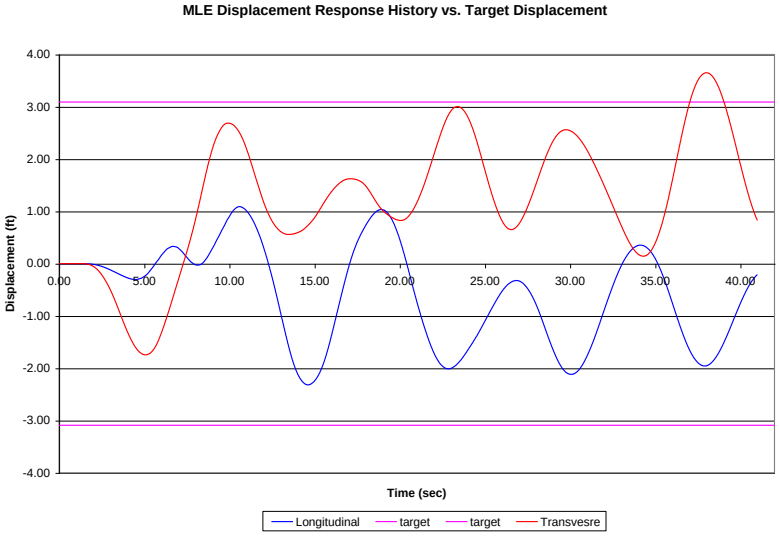
- In a Pushover Analysis
  Direction of Push,
  Method of Push, and
  Combination Rule
  Need to be Considered Properly

- Fixed-Base Analysis Based on the Point of Fixity May Not Always Provide The Same Damage Prediction as in the Detailed SSI Modeling

Thank You

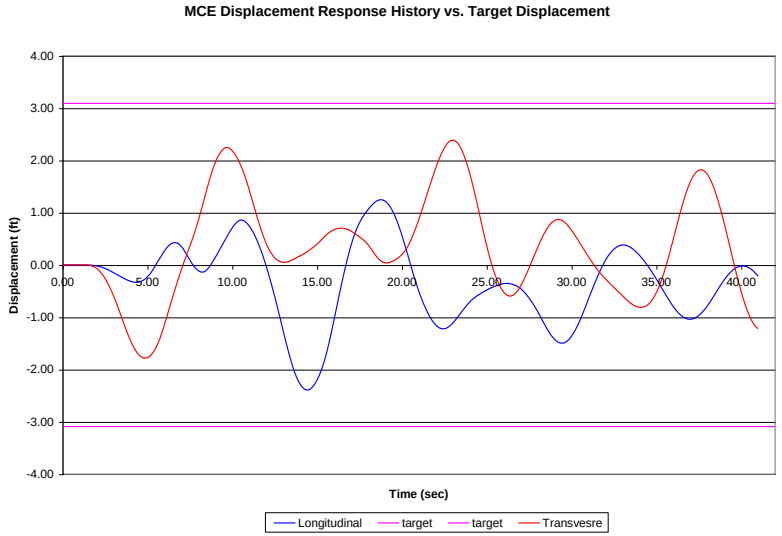
Strain-Based Evaluations of Wharf Structures

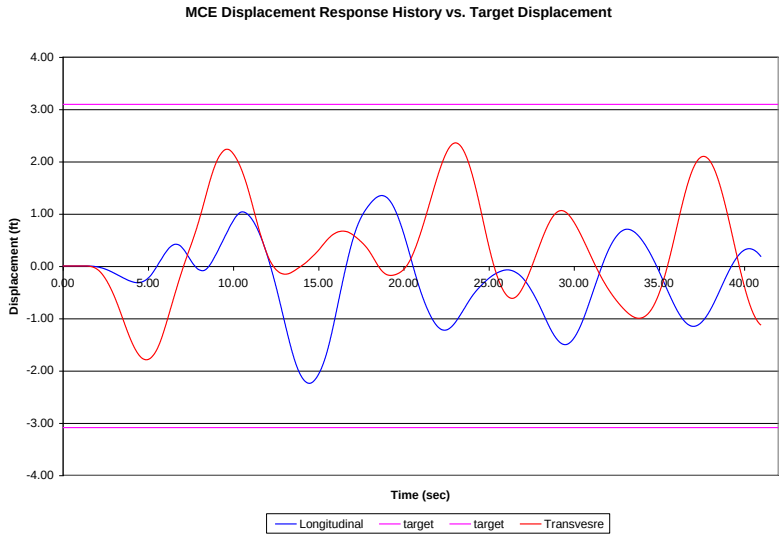




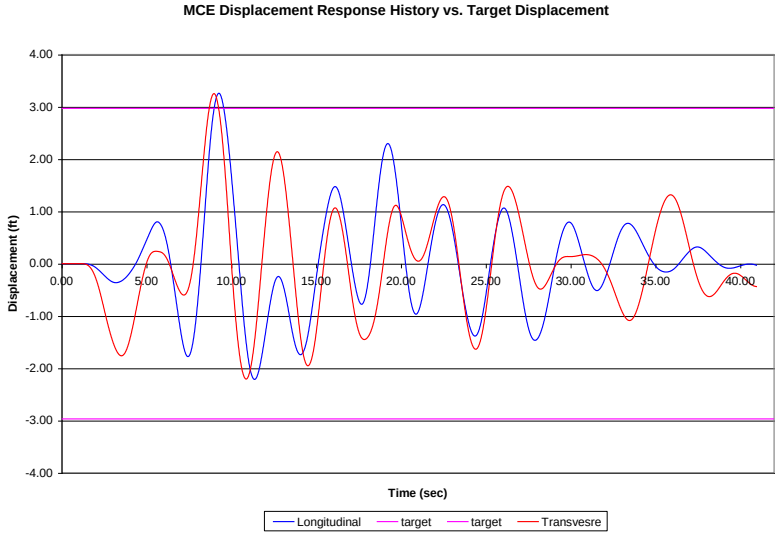
SC SOLUTIONS

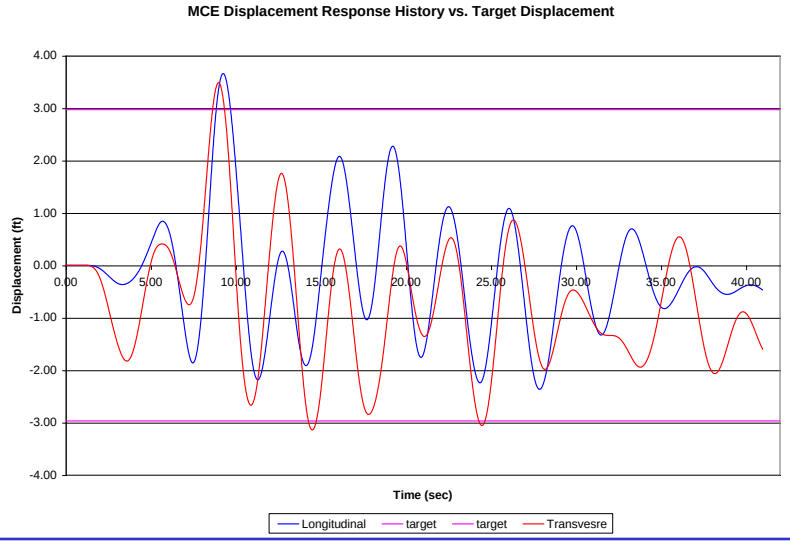
MCE Prestressed Concrete Pile

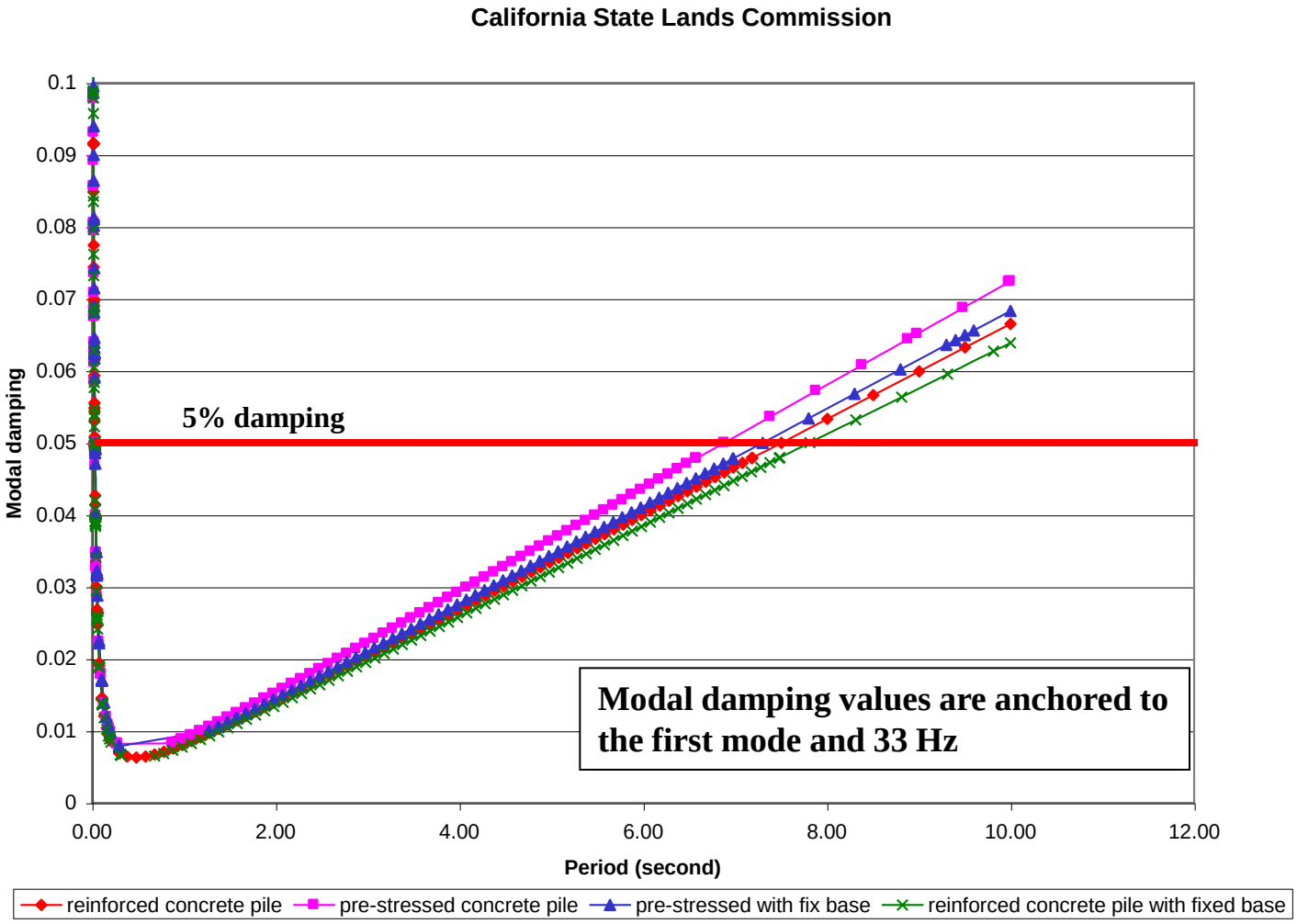




MCE Hollow Steel Pile







Strain-Based Evaluations of Wharf Structures

CLE Event

	time-history		push with 100% rule		push with SRSS rule	
	steel	conc.	steel	conc.	steel	conc.
Reinforced Concrete Detailed SSI	0.43	0.37	0.47	0.39	0.33	0.28
Reinforced Concrete Fixed-Base	0.53	1.46	0.40	1.03	0.29	0.73
Pre-Stress Detailed SSI	0.54	0.38	0.80	0.53	0.56	0.38
Pre-Stress Fixed-Base	0.61	0.39	0.85	0.57	0.60	0.40
Hollow Steel Detailed SSI	0.16	0.17	0.17	0.18	0.12	0.13
Hollow Steel Fixed-Base	0.20	0.23	0.21	0.24	0.15	0.17

MCE Event

	time-history		push with 100% rule		push with SRSS rule	
	steel	conc.	steel	conc.	steel	conc.
Reinforced Concrete Detailed SSI	0.73	0.65	0.84	0.88	0.59	0.62
Reinforced Concrete Fixed-Base	0.78	2.18	0.72	2.03	0.51	1.44
Pre-Stress Detailed SSI	0.83	0.58	1.37	0.93	0.97	0.66
Pre-Stress Fixed-Base	0.65	0.54	1.06	0.95	0.75	0.67
Hollow Steel Detailed SSI	0.24	0.26	0.28	0.30	0.20	0.21
Hollow Steel Fixed-Base	0.92	1.11	0.34	0.36	0.24	0.26