---The 2013 West Bridge Engineers Seminar, September 4-6, 2013, Bellevue , WA ---

Non-linear Seismic Behavior of Highly Horizontally Curved Bridge

- A case Study of Yerba Buena Island (YBI) WB On-Ramp, Bay Bridge, San Francisco, CA

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- Comparison of Results and Discussions
- Future Study
- Questions

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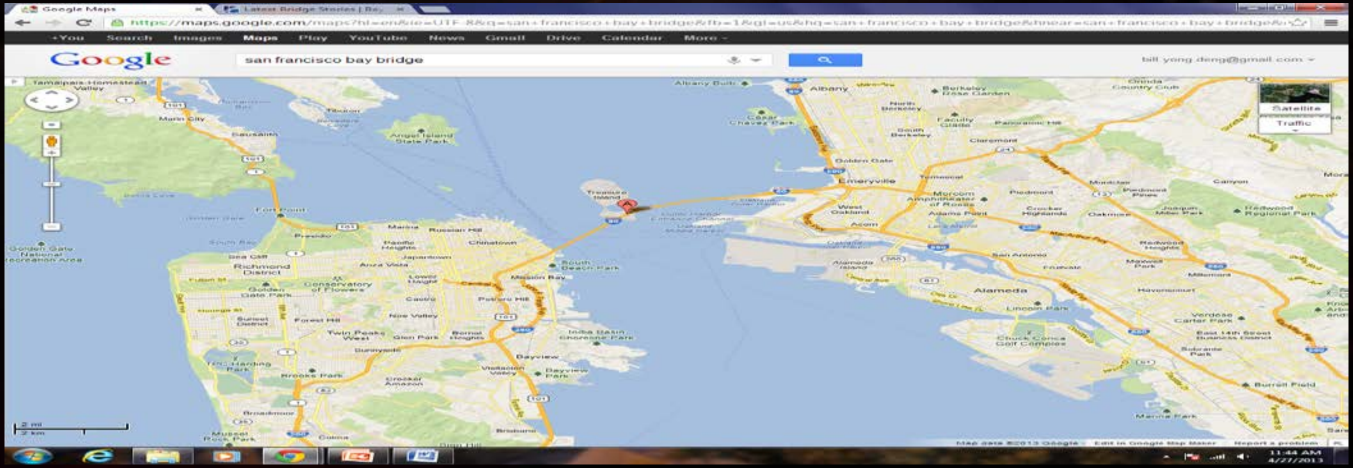
OBJECTIVES

- Discuss Non-linear behavior of highly horizontally curved bridges in High Seismic Zone

INTRODUCTION

- San Francisco Bay Bridge Project is a current world Famous Project under Construction
- Cost about $6 billion
- It connects Oakland to San Francisco



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Crews have installed the first two (of five) large moving scaffolds, known as "travelers", which will be used to maintain the new East Span. The motorized travelers are suspended from tracks beneath the bridge, providing safe access to the workers who will conduct bridge inspections, repairs and painting operations.The other three travelers are scheduled to be installed in June. The video to the left shows how the travelers were built in and transported from Southern California.

LATEST NEWS

BAY BRIDGE ROD UPDATE

For the latest on the ongoing investigation into the broken rods on the new East Span of the Bay Bridge, click here.

Self-Anchored Suspension Span Update

American Bridge/Fluor has finished painting the SAS main cable, and removed the footbridges the week of April 22.

Watch how crews painted the main cable and its 200 steel-wire suspender ropes. White was selected by architects to reflect the container cranes found at the nearby Port of Oakland.

LANE CLOSURES AND DETOURS

DAILY LANE CLOSURES AND DETOURS

Today's Bay Bridge ramp and lane closure times are APPROXIMATE. Please continue to check this site for the most up-to-date information. This page is updated daily by 4 p.m.

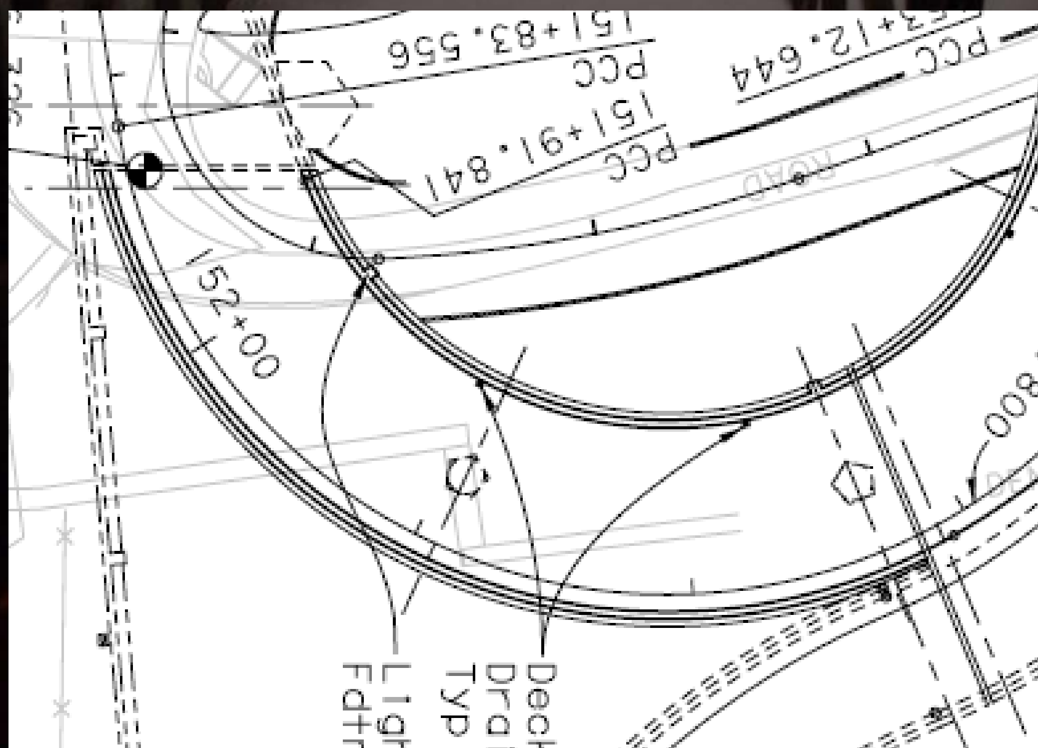
Lane and ramp closure schedule
for Friday (04/26/13) night to
Monday (04/29/13) morning:

Friday (04/26/13) night to

RELATED LINKS

GEOMETRY

- Plan View of Stand-alone WB On-Ramp
- Horizontal Curve of 127.3’ (38.8 m) Radius



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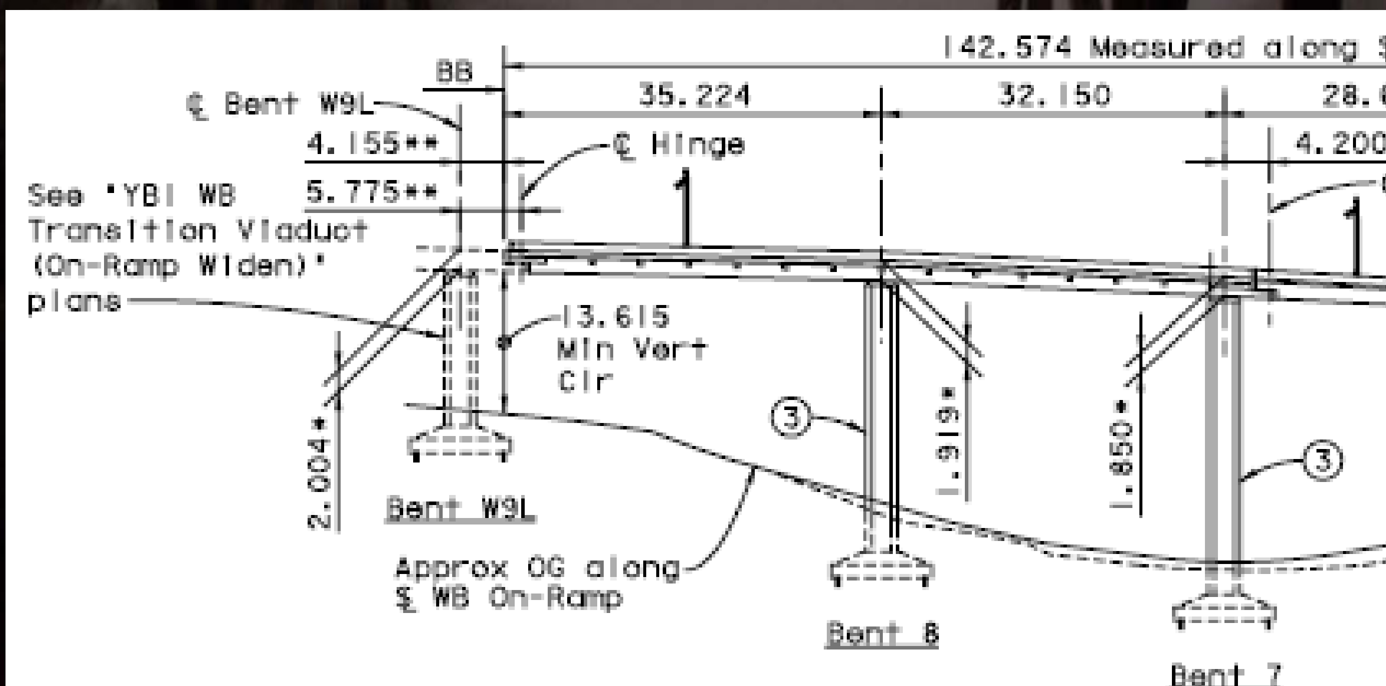
GEOMETRY

- Developed Elevation of Stand-alone WB On-Ramp
- Depth Varies With Hinges at both Ends



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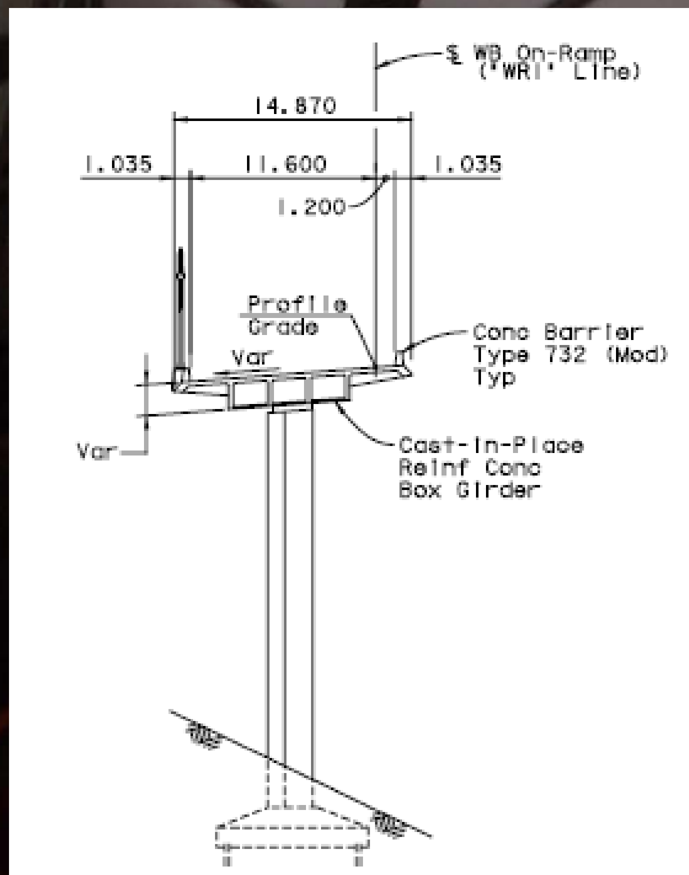
GEOMETRY

- Typical Section of Stand-alone WB On-Ramp



GEOMETRY

- Superstructure Section Properties at 10th spans

Segment	t3	t2	Area	TorsConst	I33	I22
	in	in	in^2	in^4	in^4	in^4
GD01	79	546	11,249	22,163,259	9,005,645	205,385,933
GD02	79	546	11,234	21,988,641	8,921,477	205,205,944
GD03	78	546	11,220	21,814,023	8,837,310	205,025,956
GD04	78	546	11,206	21,639,405	8,753,143	204,845,967
GD05	78	546	11,192	21,464,787	8,668,975	204,665,979
GD06	77	546	11,178	21,290,170	8,584,808	204,485,990
GD07	77	546	11,163	21,115,552	8,500,640	204,306,002
GD08	77	546	11,149	20,940,934	8,416,473	204,126,013
GD09	76	546	11,135	20,766,316	8,332,305	203,946,025
GD10	76	546	11,121	20,591,698	8,248,138	203,766,036
GD11	76	546	11,107	20,417,080	8,163,971	203,586,048
GD12	75	546	11,094	20,261,871	8,090,710	203,419,538
GD13	75	546	11,081	20,106,662	8,017,450	203,253,028
GD14	75	546	11,068	19,951,453	7,944,190	203,086,518
GD15	74	546	11,055	19,796,244	7,870,929	202,920,008
GD16	74	546	11,042	19,641,036	7,797,669	202,753,498
GD17	74	546	11,029	19,485,827	7,724,409	202,586,988
GD18	74	546	11,016	19,330,618	7,651,149	202,420,477
GD19	73	546	11,003	19,175,409	7,577,888	202,253,967
GD20	73	546	10,990	19,020,200	7,504,628	202,087,457
GD21	73	546	10,977	18,864,991	7,431,368	201,920,947
GD22	72	539	8,438	19,090,204	7,448,185	200,391,875

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SEISMIC DESIN CRITERIA

- Seismic Design Criteria for YBI was prepared by Moffatt & Nichol
- Two-level design Criteria:
  - FEE --- Functional Evaluation Earthquake: Elastical Performance Analysis
  - SEE --- Safety Evaluation Earthquake: Non-linear Analysis
- Expected Concrete Properties used for Analysis

Materials used for seismic design, (except for shear design, Bay-Bridge Design Criteria (BBDC))

Concrete:	Girder		Column			CIDH Piles				
	Mpa	ksi	Mpa	FEE(ksi)	SEE(ksi)	Mpa	FEE(ksi)	SEE(ksi)		(BBDC 7.11)
f_c' =	40	5.8	25	3.6	3.6	25	3.6	3.6	ksi	
f'_{ce}= $1.3f_c'$		7.54		4.68	4.68		5	5	ksi	(BBDC 7.9.1)
ε_{cf} =		0.004		0.004	2/3 x ε_{cu}		0.004	0.01		failure=crash
ε_{cu} =		0.01		0.005	ε_{cu}		1	1		confined
Ec =		5003		3942	3942		4074	4074	ksi	
$f'_{ce\ (KSF)}$		1085.76		673.92	673.92		720	720	ksf	
Ec (KSF)		720432		567648	567648		586656	586656	ksf	

(or use program generated data.)

SEISMIC DESIN CRITERIA

- Expected Steel Properties used for Analysis

(or use program generated data.)

Steel: A706	Piers		Piles				
	FEE	SEE	FEE	SEE			
f_{ye} =1.1f_y =	66	66	66	66	ksi	(Plastic Hinge)	(BBDC 7.9.1)
f_{oe} =1.25f_y =	75	75	75	75	ksi	(overstrength)	
f_{ue} =	95	95	95	95	ksi		(SDC 3.2.3)
ε_{ye} =	0.015	2/3 x ε_{su}	0.0023	0.0023			
ε_{su} =	0.12	0.12	0.12	0.12		(# 10 and smaller for confinement bars)	
	0.09	0.09	0.09	0.09		(#9 and larger for main bars)	
ε_{sh} =	0.015	0.015	0.015	0.015		(#8 and smaller)	
	0.01	0.01	0.01	0.01		(#9)	
	0.01	0.01	0.01	0.01		(#10 & #11)	
	0.0075	0.0075	0.0075	0.0075		(#14)	
	0.005	0.005	0.005	0.005		(#18)	
Es =	2900	ksi =	417600	ksf			

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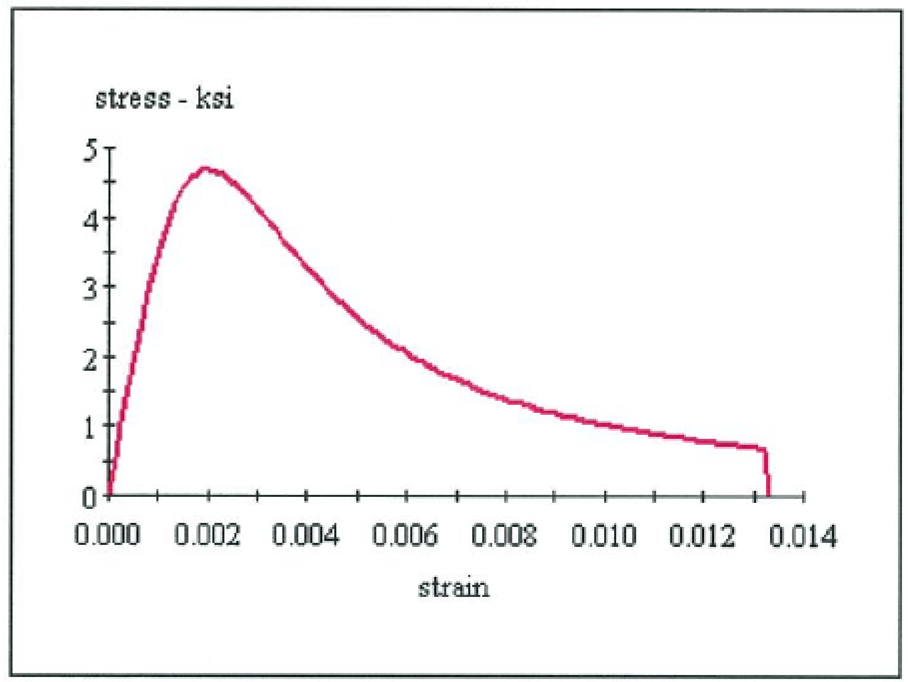
SEISMIC DESIN CRITERIA

- Unconfined Concrete Property

Input Parameters:

Tension Strength:	0 ksi
28 Day Strength:	4.680 ksi
Post Crushing Strength:	0 ksi
Tension Strain Capacity:	0 Ten
Spalling Strain:	5.000E-3 Comp
Failure Strain:	13.33E-3 Comp
Elastic Modulus:	3899 ksi
Secant Modulus:	2340 ksi

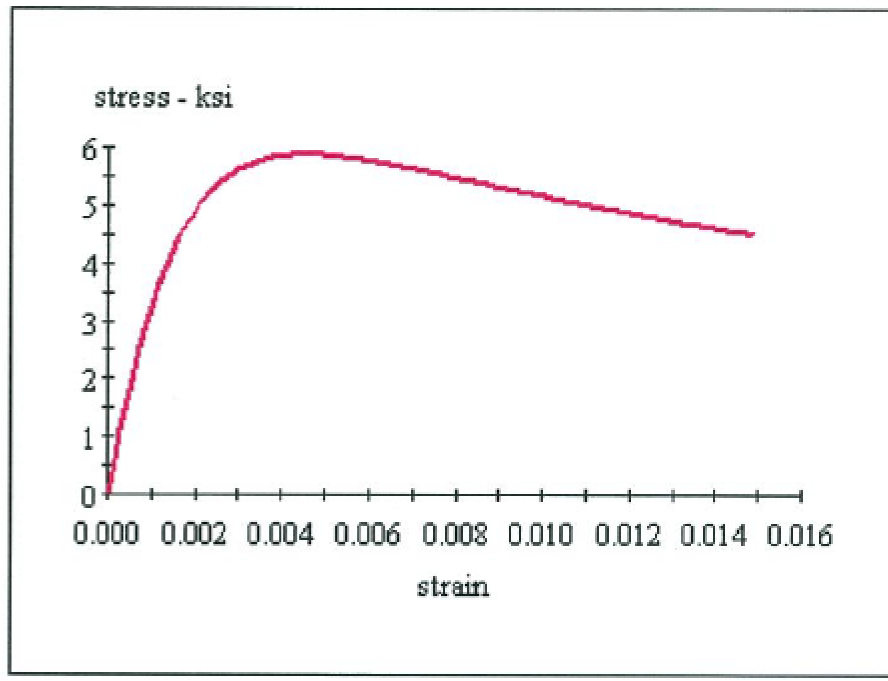


SEISMIC DESIN CRITERIA

- Confined Concrete Property

Input Parameters:

Tension Strength:	0 ksi
28 Day Strength:	4.680 ksi
Confined Concrete Strength:	5.868 ksi
Tension Strain Capacity:	0 Ten
Strain at Peak Stress:	4.538E-3
Crushing Strain:	14.86E-3 Comp
Elastic Modulus:	3899 ksi
Secant Modulus:	1293 ksi



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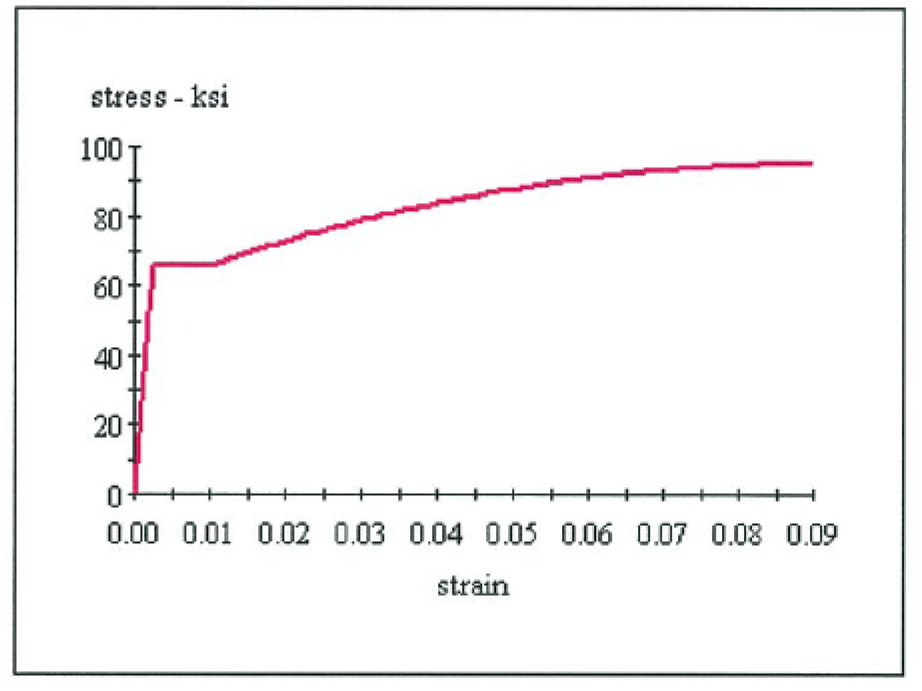
SEISMIC DESIN CRITERIA

- Reinforcement Property



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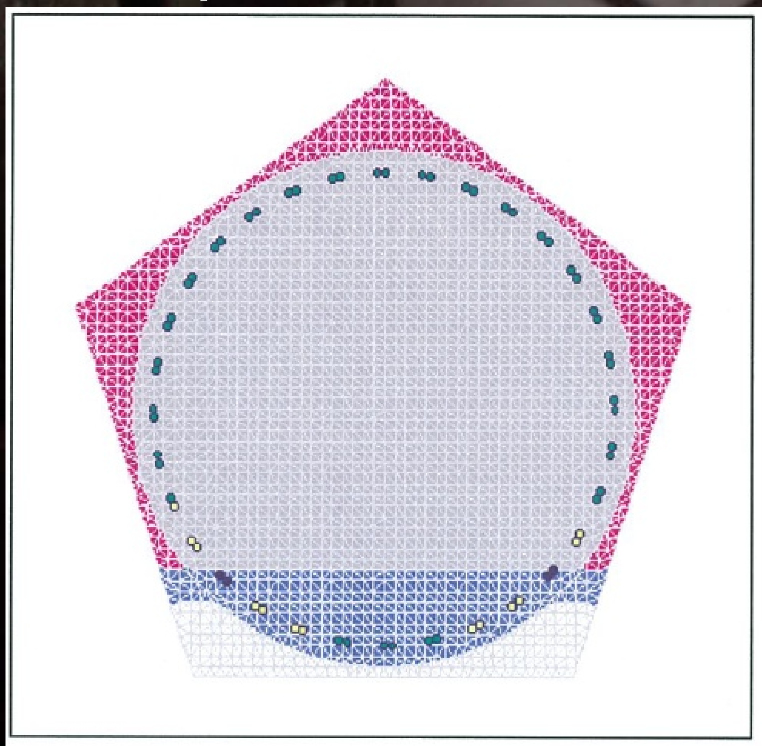
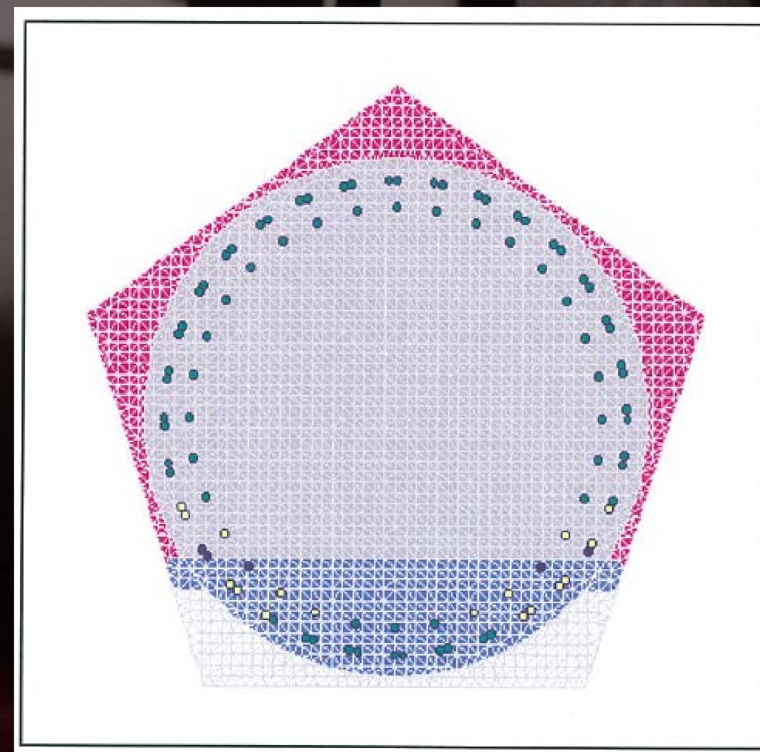
GEOMETRY

- Column Section and Properties at SEE
  - Top of Column Bottom of Column





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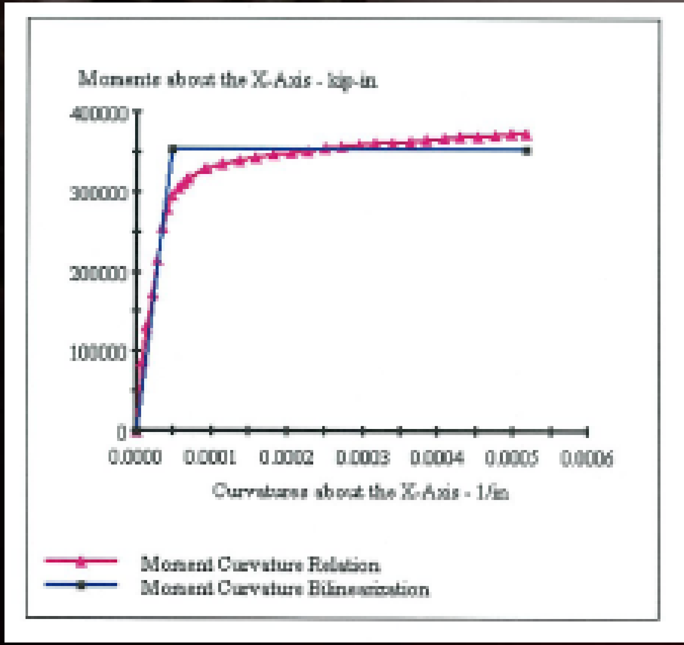
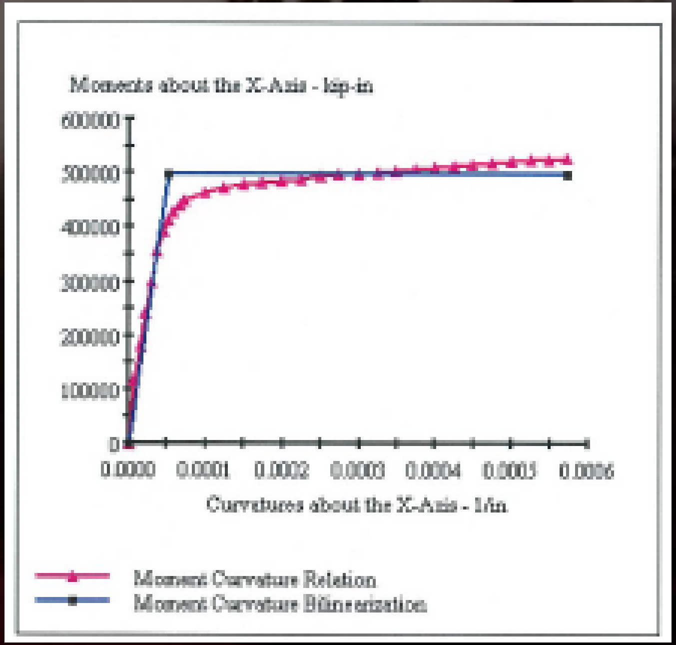
GEOMETRY

- Column Section Properties
  - XTRACT Output
    - ✓Top Bottom





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GEOMETRY

- Transverse Hinge Summary

XTRACT Hinges-Transverse-Strong Axis

			Pc (kips)	(SF*) θ_y(rad)	θ_u(rad)	θ_y/SF	M^*_y(k-in)	M^*_u(k-in)	M/My	θ_p(rad)	I_e(ft^4)	I_g(ft^4)	I_e/I_g factor	Ave. Ie
Bent 7	FEE	Top	-1711	0.004688	0.023291	4.97	337700	352300	1.043	0.22322888	92.27	207.85	0.444	0.51
Bent 8	FEE	Top	-1856	0.004399	0.021444	4.87	342600	356600	1.041	0.20454648	93.51	207.85	0.45	0.514
--														
Bent 7	FEE	Bot.	-2574	0.005013	0.018090	3.61	468200	482800	1.031	0.15691294	119.73	207.85	0.576	
Bent 8	FEE	Bot.	-2652	0.004703	0.016852	3.58	470700	484900	1.030	0.14578844	120.10	207.85	0.578	
--														
Bent 7	SEE	Top	-1711	0.004919	0.053595	10.9	354300	373200	1.053	0.58411247	80.68	207.85	0.388	0.4455
Bent 8	SEE	Top	-1856	0.004605	0.049557	10.76	358700	376800	1.05	0.53942304	81.76	207.85	0.393	0.449
--														
Bent 7	SEE	Bot.	-2574	0.005329	0.059387	11.14	497700	526900	1.059	0.64868785	104.58	207.85	0.503	
Bent 8	SEE	Bot.	-2652	0.004994	0.055401	11.09	499700	528600	1.058	0.60489096	105.02	207.85	0.505	
--														

Note*: SF=Scale Scale factor

- Longitudinal Hinge Summary

XTRACT Hinges-Longitudinal-Weak Axis

			Pc (kips)	Φ_y(rad/in)	Φ_u(rad/in)	θ_y/SF	M_p(k-in)	M^*_u(k-in)	M/SF	Φ_p(rad/in)	I_e(ft^4)	I_g(ft^4)	I_e/I_g factor	Ave. Ie
Bent 7	FEE	Top	-1711	0.0000038	0.00001873	4.97	337700	352300	1.043	0.06896228	92.27	207.85	0.444	0.51
Bent 8	FEE	Top	-1856	0.0000038	0.00001841	4.88	342600	356600	1.041	0.06469031	93.51	207.85	0.45	0.514
--														
Bent 7	FEE	Bot.	-2574	0.0000484	0.00017460	3.61	468200	482800	1.031	0.09694957	119.73	207.85	0.576	
Bent 8	FEE	Bot.	-2652	0.0000485	0.00017360	3.58	470700	484900	1.030	0.09005123	120.10	207.85	0.578	
--														
Bent 7	SEE	Top	-1711	0.0000475	0.00051730	10.9	354300	373200	1.053	0.17969262	80.68	207.85	0.388	0.4455
Bent 8	SEE	Top	-1856	0.0000474	0.00051050	10.76	358700	376800	1.05	0.16985226	81.76	207.85	0.393	0.449
--														
Bent 7	SEE	Bot.	-2574	0.0000514	0.00057320	11.14	497700	526900	1.059	0.40247857	104.58	207.85	0.503	
Bent 8	SEE	Bot.	-2652	0.0000514	0.00057070	11.09	499700	528600	1.058	0.37530659	105.02	207.85	0.505	
--														

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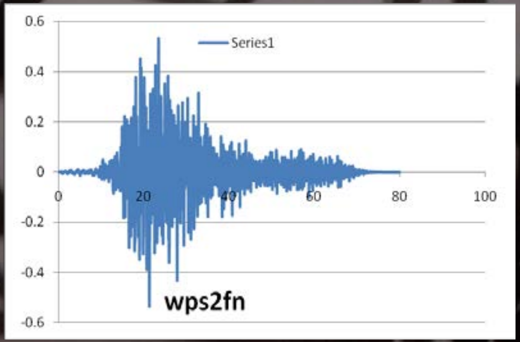
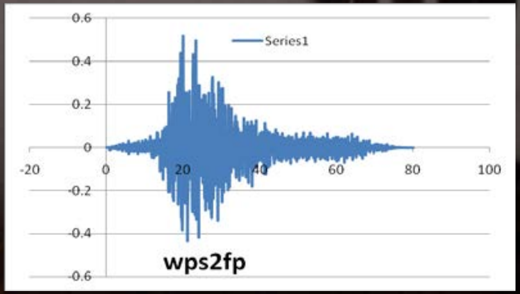
GROUND MOTION HISTORY

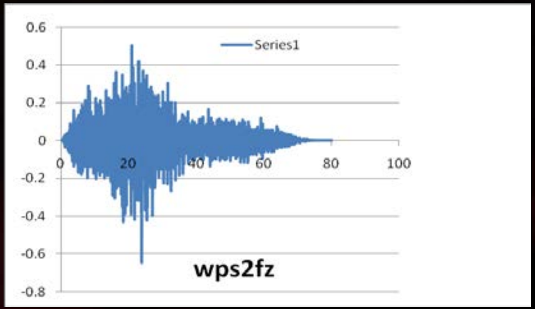
- Normal to Fault



- Parallel to Fault



- Vertical



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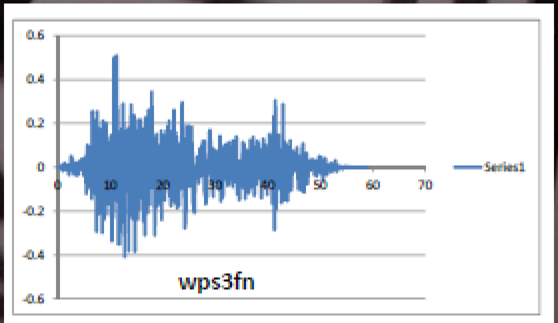
GROUND MOTION HISTORY

- Normal to Fault



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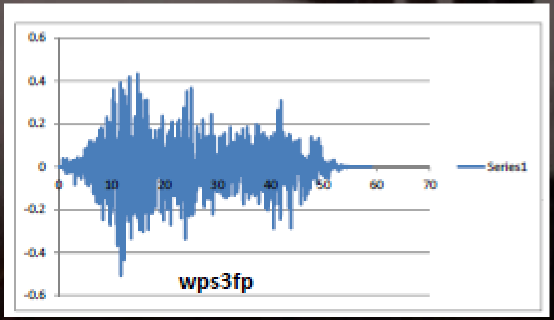
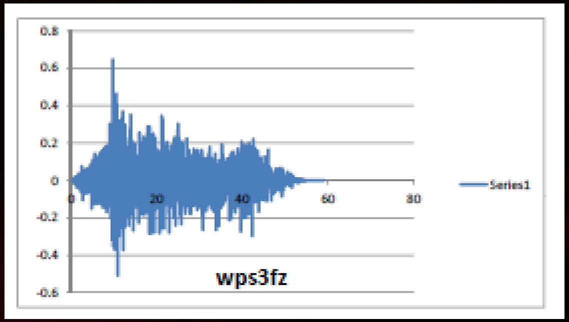


- Vertical



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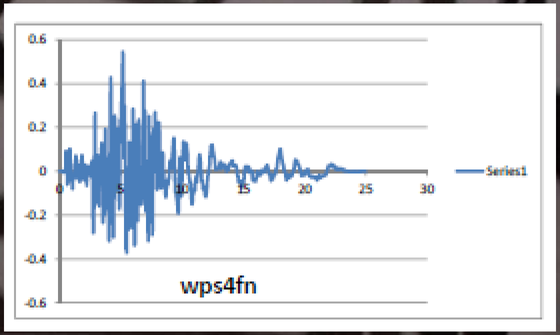
GROUND MOTION HISTORY

- Normal to Fault



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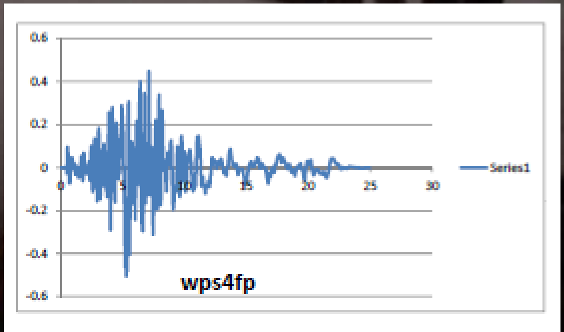

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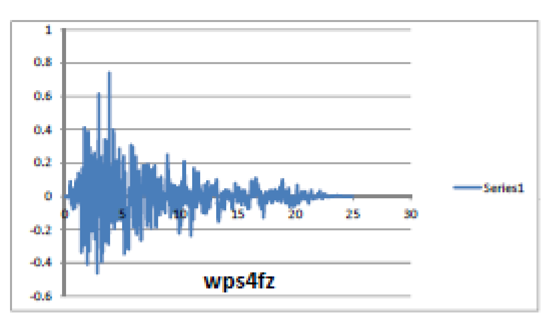

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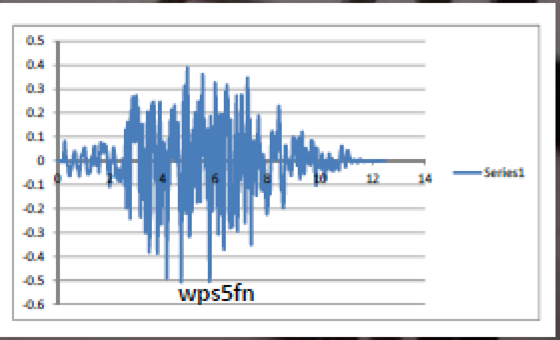
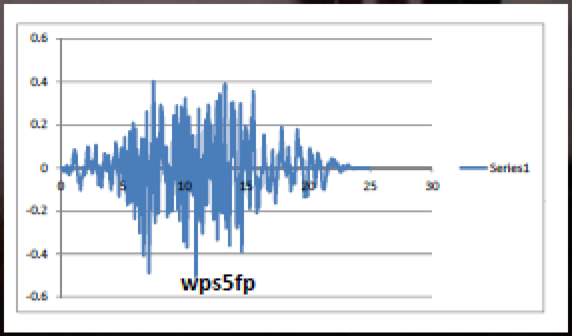
GROUND MOTION HISTORY

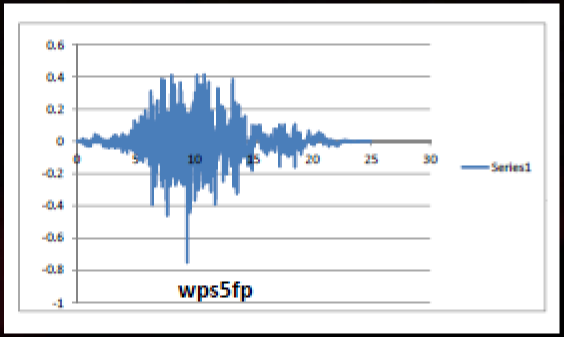
- Normal to Fault



- Parallel to Fault

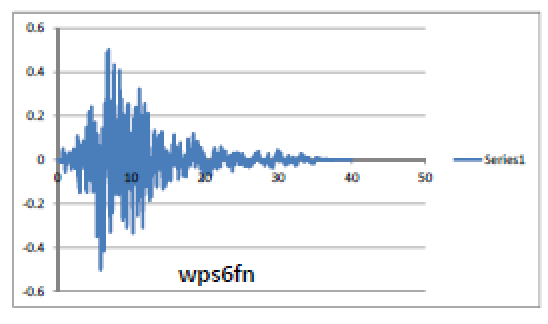


- Vertical

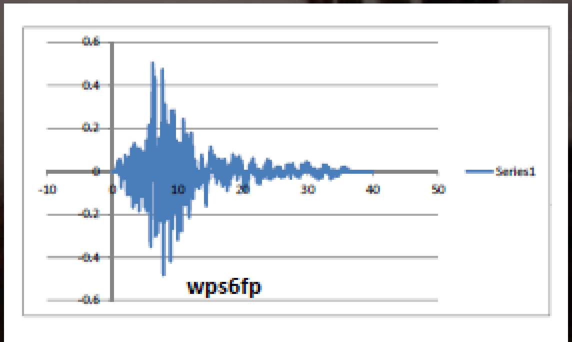


GROUND MOTION HISTORY

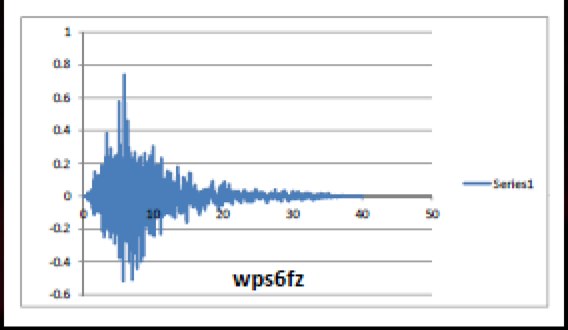
- Normal to Fault



- Parallel to Fault



- Vertical



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Non-Linear Time History Analysis by SAP 2000

- Standalone Structure (Hinge-to-hinge)
- Five groups of time history
- Time Histories are scaled so as similar to SEE ARS response
- Direct Hiber-Hughes-Talor Nonlinear Time History Analysis (HHT-NLTHA)

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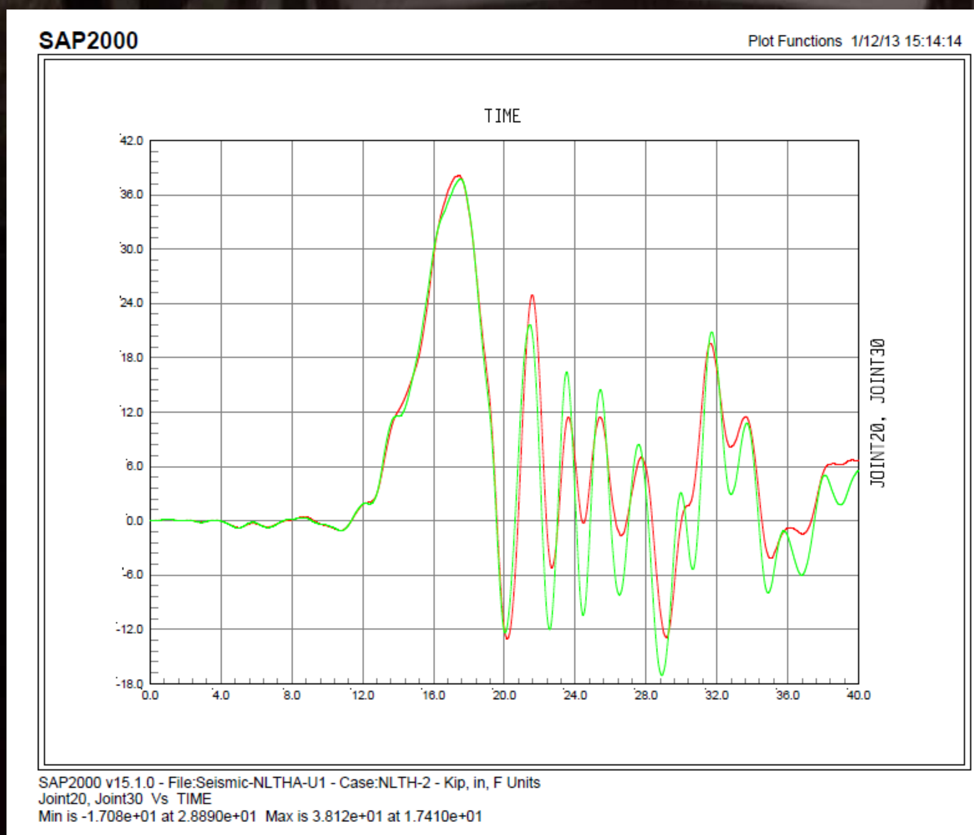
Non-Linear Time History Analysis by SAP 2000

- (continue.)
- NLTHA is performed after non-linear dead load analysis
- Longitudinal Combination:
  100% Long.+30% Tran.+30% Vert.
- Transverse Combination:
  100% trans.+30% Long.+30% Vert.

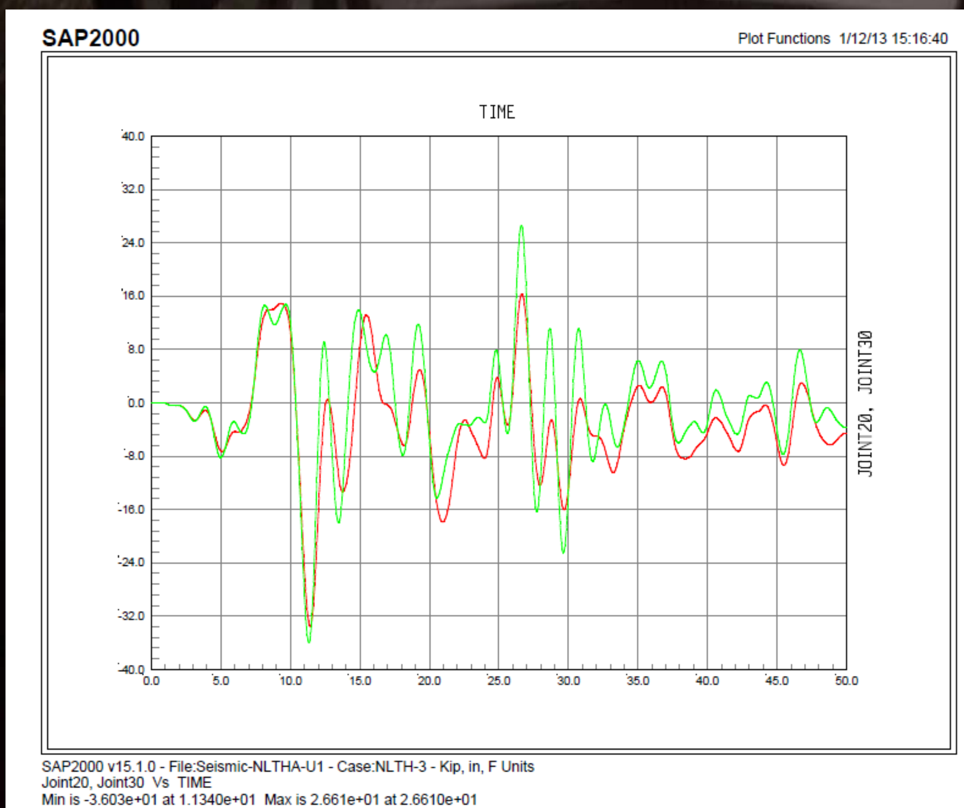
Non-Linear Time History Analysis by SAP 2000

- Group 2-Longitudinal Displacement vs. Time at Top of Bent 7 & Bent 8-U1 Direction



Non-Linear Time History Analysis by SAP 2000

- Group 3-Longitudinal Displacement vs. Time at Top of Bent 7 & Bent 8-U1 Direction



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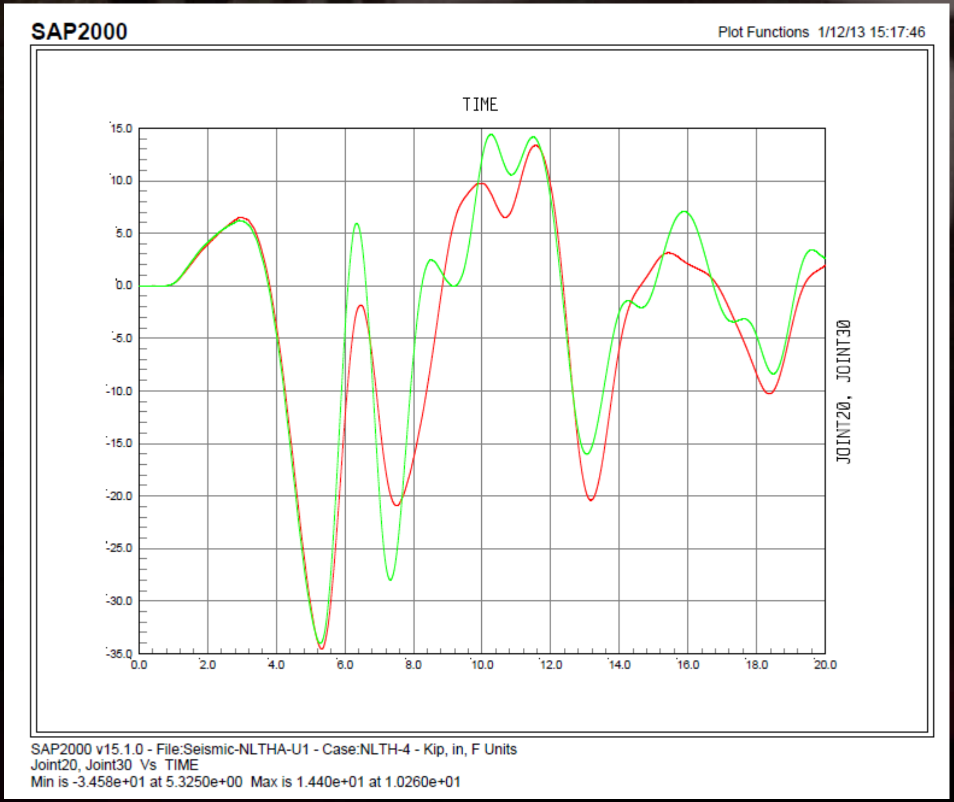
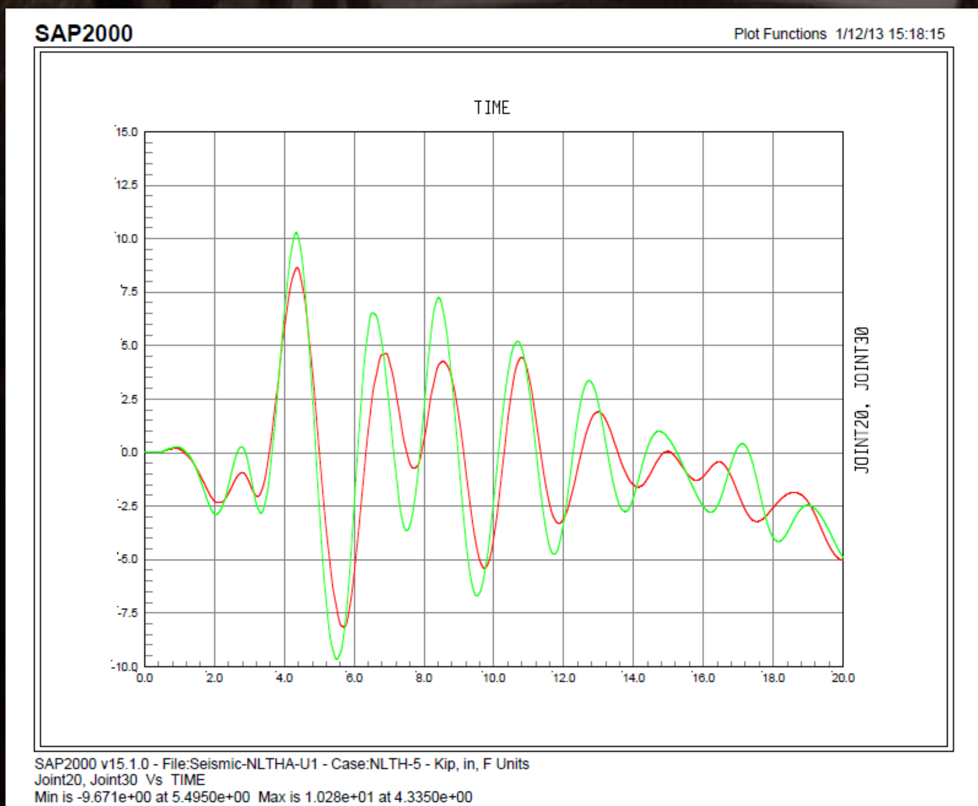
Non-Linear Time History Analysis by SAP 2000

- Group 4 - Longitudinal Displacement vs. Time at Top of Bent 7 & Bent 8-U1 Direction



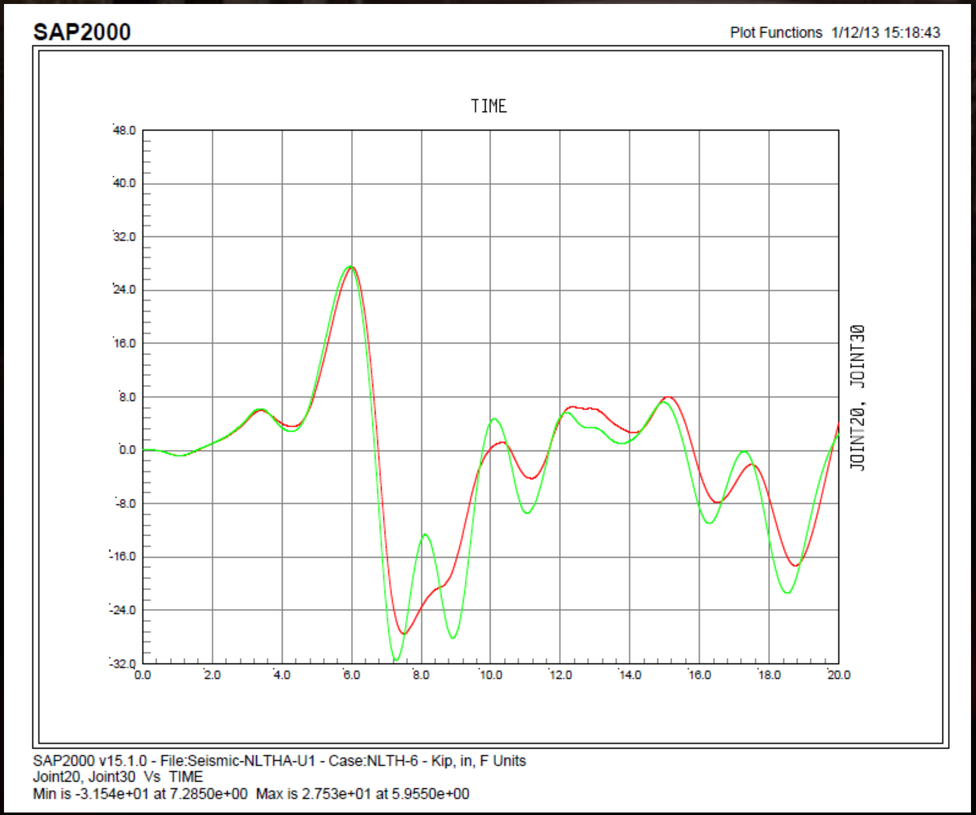
Non-Linear Time History Analysis by SAP 2000

- Group 5 - Longitudinal Displacement vs. Time at Top of Bent 7 & Bent 8-U1 Direction



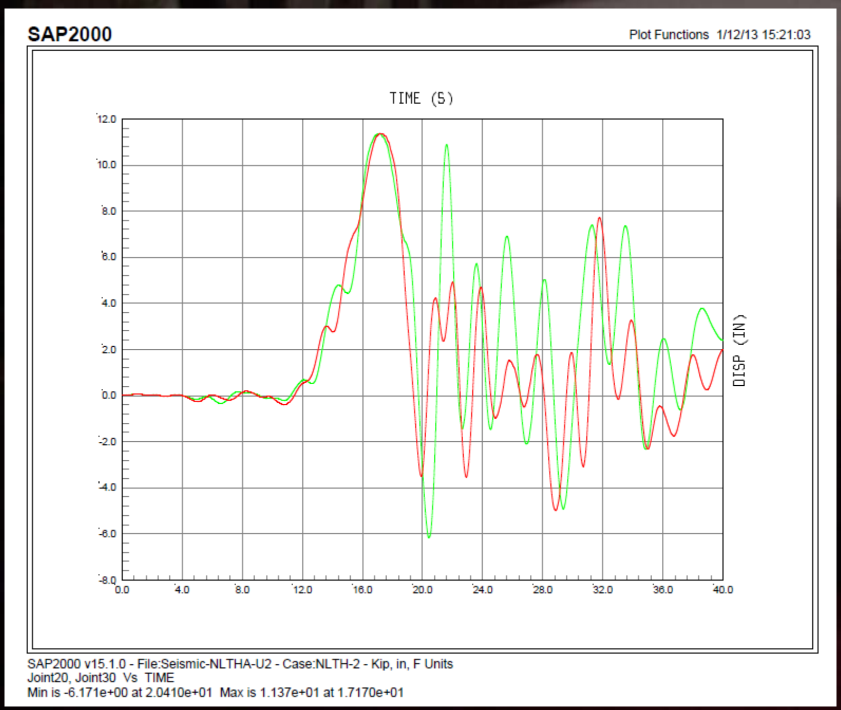
Non-Linear Time History Analysis by SAP 2000

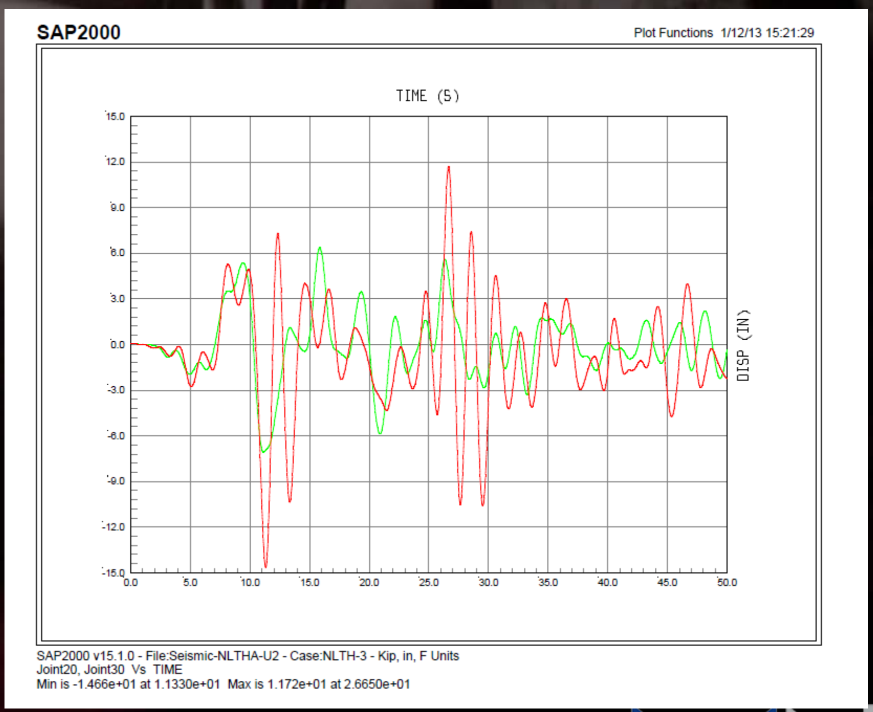
- Group 6 - Longitudinal Displacement vs. Time at Top of Bent 7 & Bent 8-U1 Direction



Non-Linear Time History Analysis by SAP 2000

- Groups 2 & 3 - Transverse Displacement vs. Time at Top of Bents 7 & 8-U2 Direction





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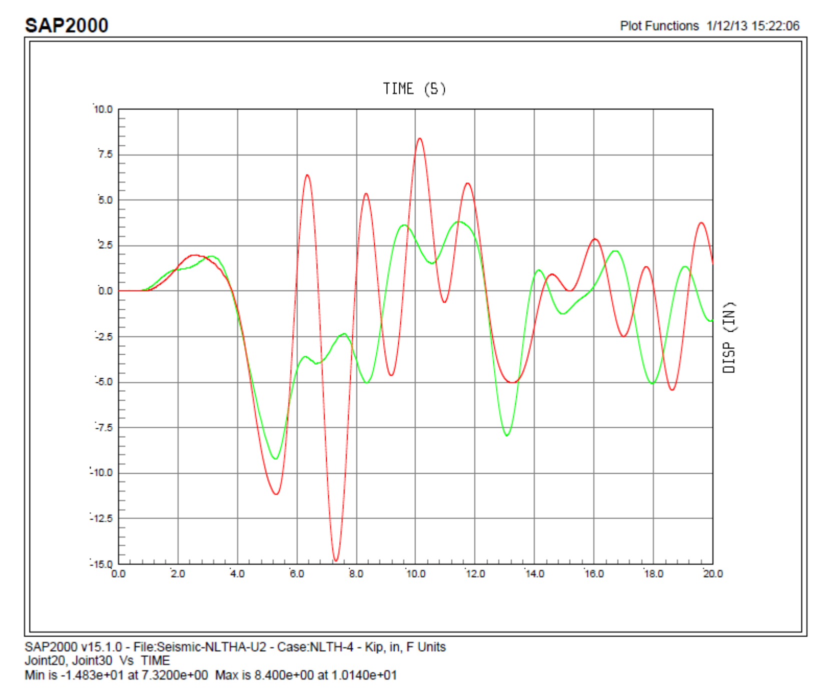
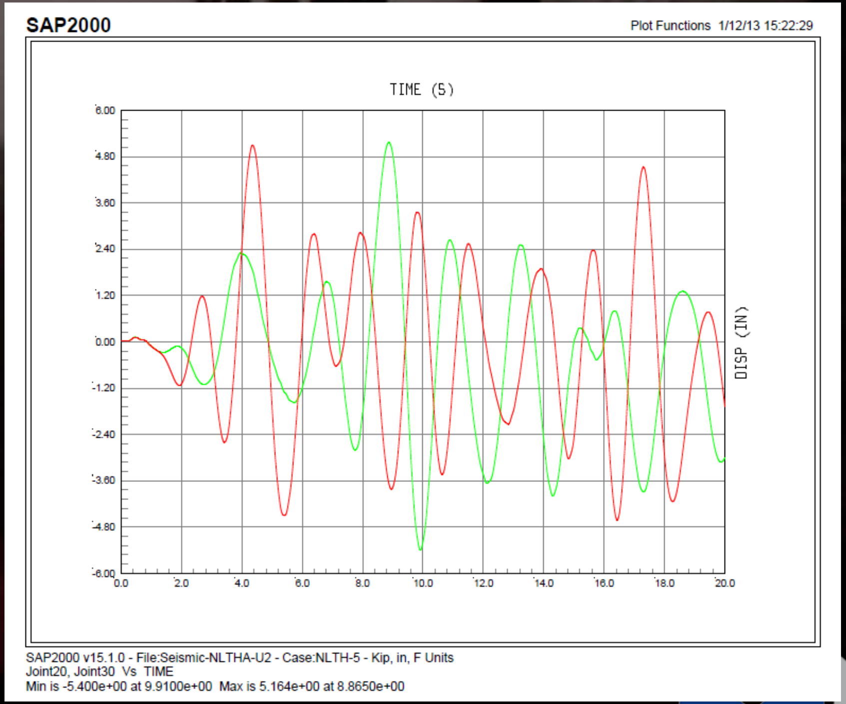
Non-Linear Time History Analysis by SAP 2000

- Groups 4 & 5 Transverse Displacement vs. Time at Top of Bents 7 & 8-U2 Direction





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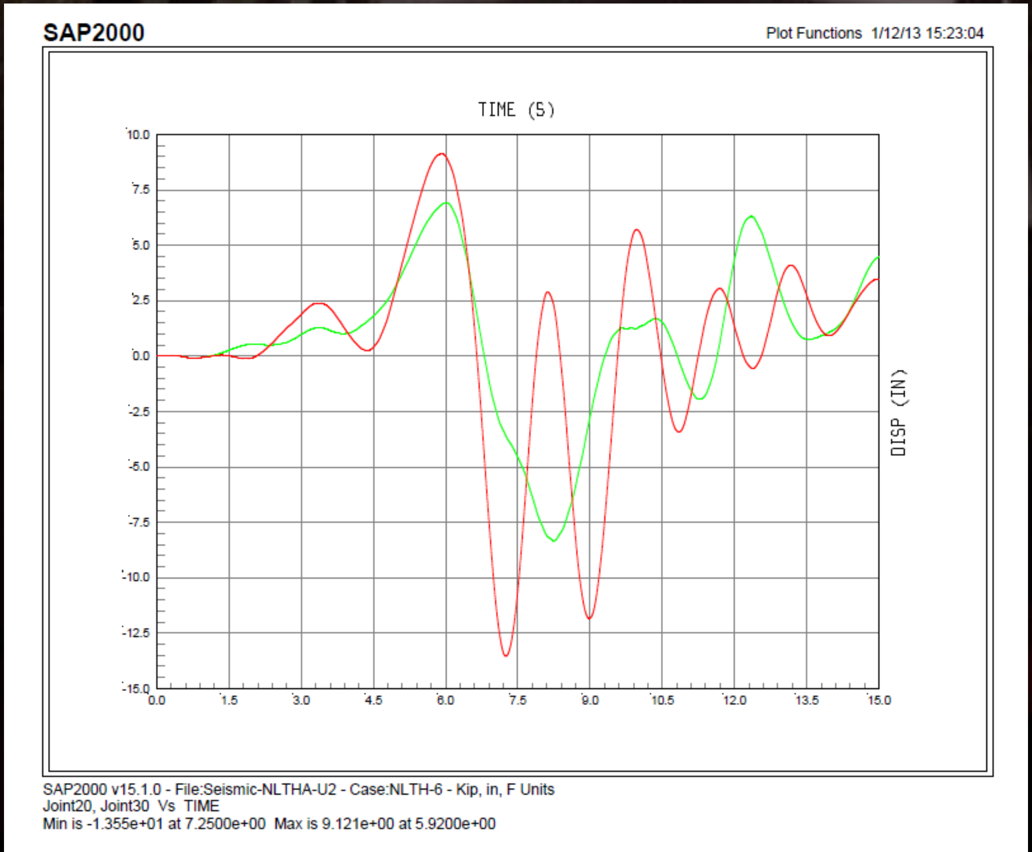
Non-Linear Time History Analysis by SAP 2000

- Group 6 - Transverse Displacement vs. Time at Top of Bents 7 & 8-U2 Direction



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Non-Linear Time History Analysis by SAP 2000

- Summary of Non-linear Time History
  - Transverse Displacement

U1	Wps2	Wps3	Wps4	Wps5	Wps6
Bent 7 (Jt30)	38.2	36.0	34.0	10.3	31.5
Bent 8 (Jt 20)	38.6	33.6	34.6	8.7	27.6

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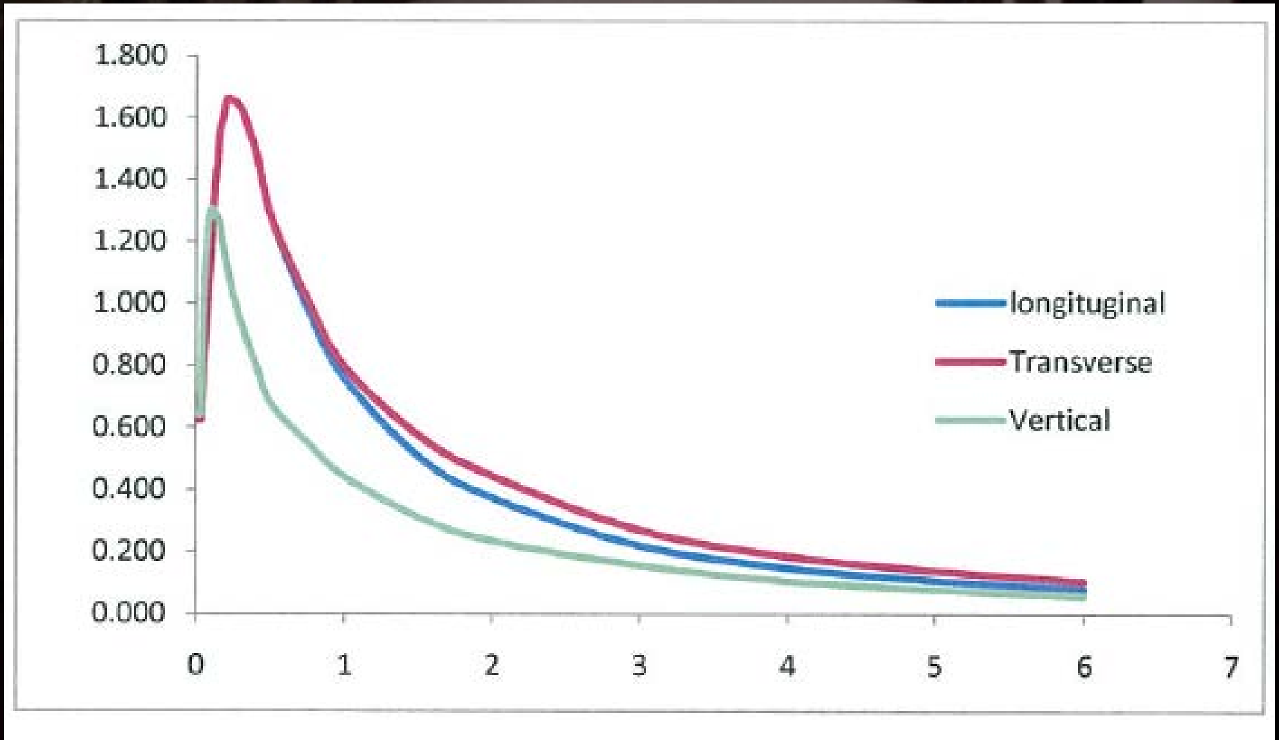
Non-Linear Time History Analysis by SAP 2000

- Summary of Non-linear Time History
  - ➢Longitudinal Displacement

U2	Wps2	Wps3	Wps4	Wps5	Wps6
Bent 7 (Jt30)	12.5	13.3	14.0	12.1	13.5
Bent 8 (Jt 20)	11.8	12.9	14.1	11.9	13.8

LINEAR ARS CURVE ANALYSIS by SAP 2000

- ARS Curve (SEE)-same as NLTHA
  - Combination 1: 100% Transv. + 30% Longit.+30% Vert
  - Combination 2: 100% Longi. + 30% Transv.+ 30% Vert.
  - Results will be compared in Table below.



Non-LINEAR TIME HISTORY ANALYSIS by OPENSEES

- OPENSEEs
  - The Open System for Earthquake Engineering Simulation (OpenSEES)-developed by UC-Berkeley
  - The same load case, same structure, same hinges are used.
  - Results are list in the following table.

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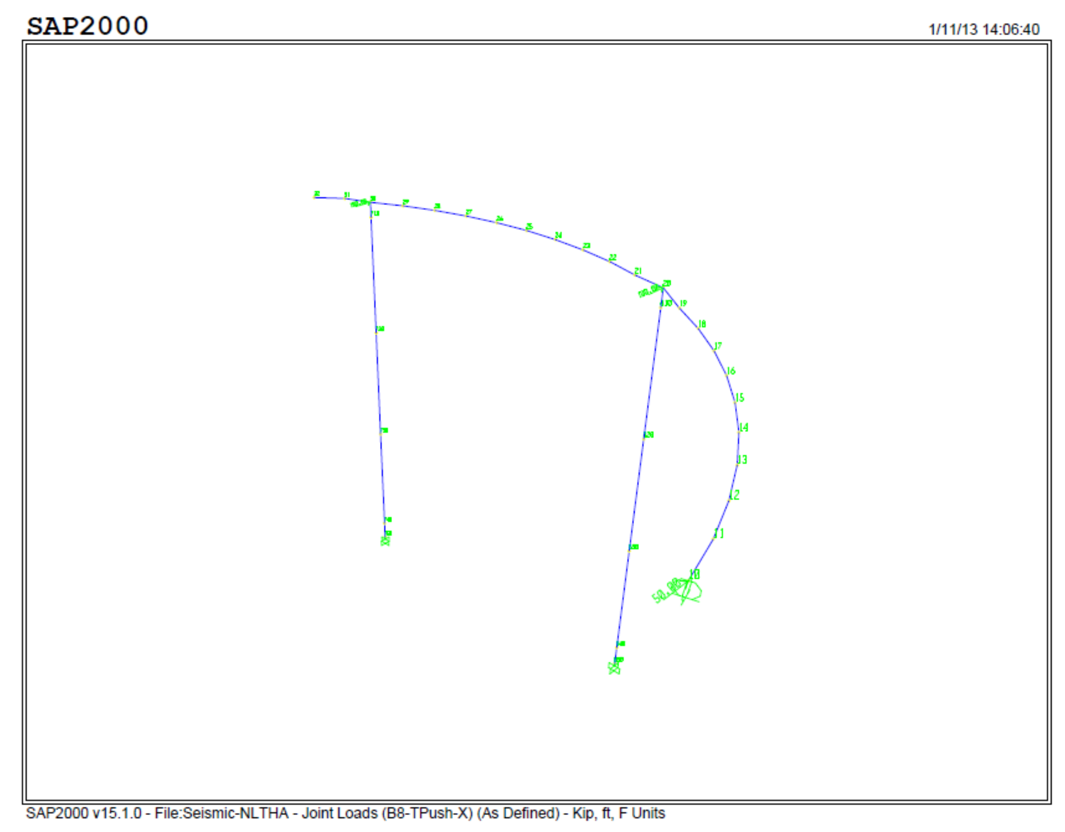
NON-LINEAR PUSH-OVER ANALYSIS by SAP 2000

- Push-over model-Forces are proportional to DL



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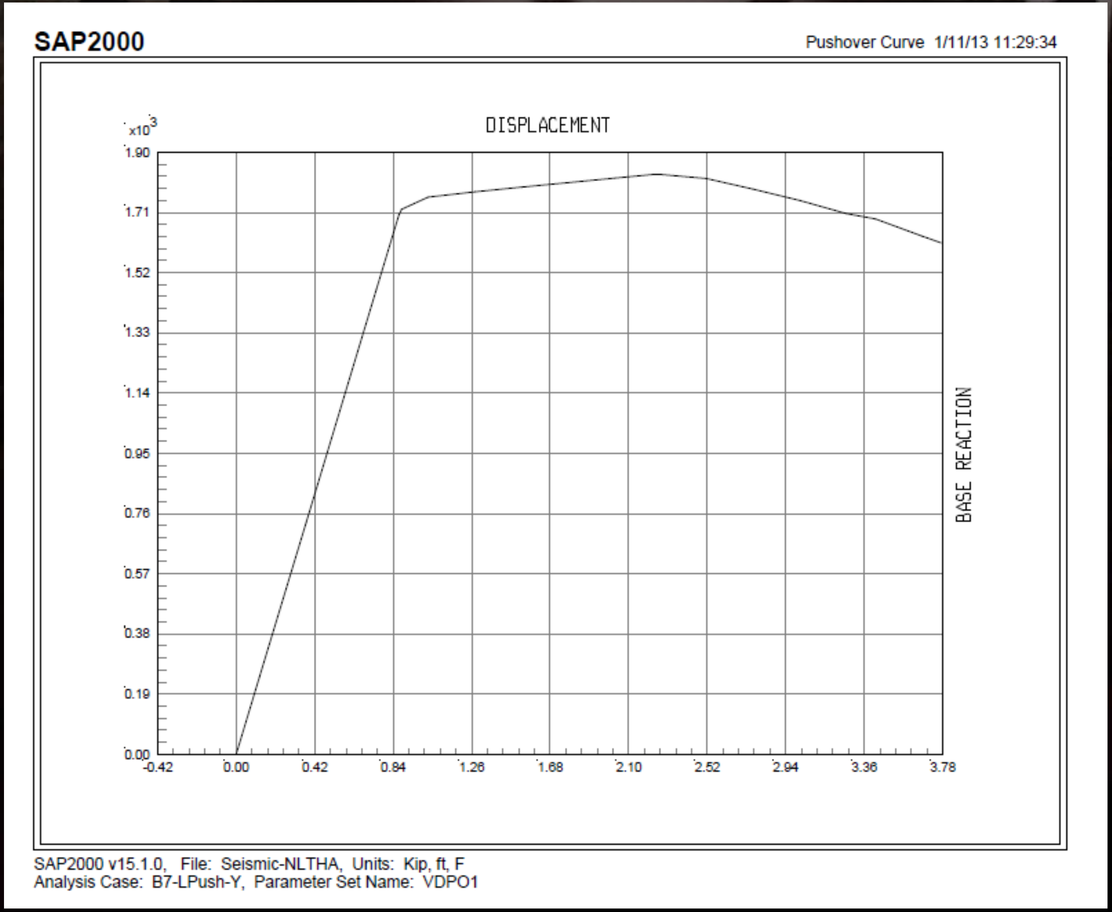
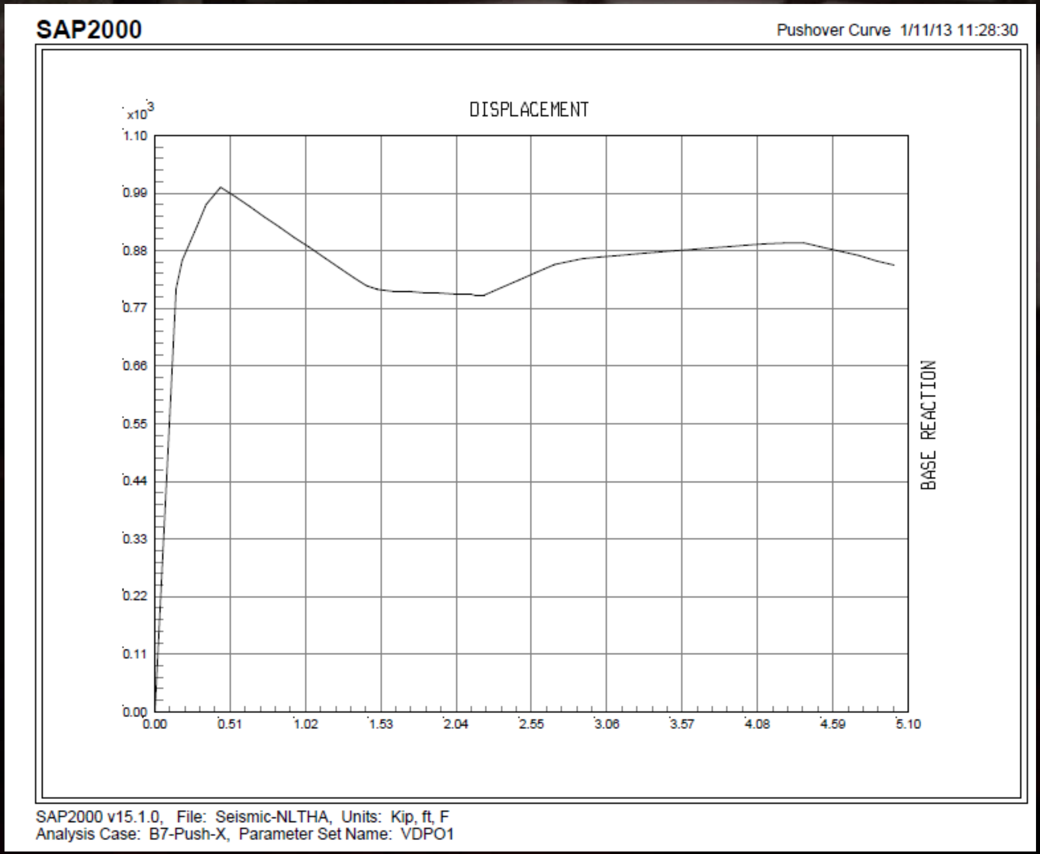
NON-LINEAR PUSH-OVER ANALYSIS by SAP 2000

- Transverse Pushover Curve at Bent 7



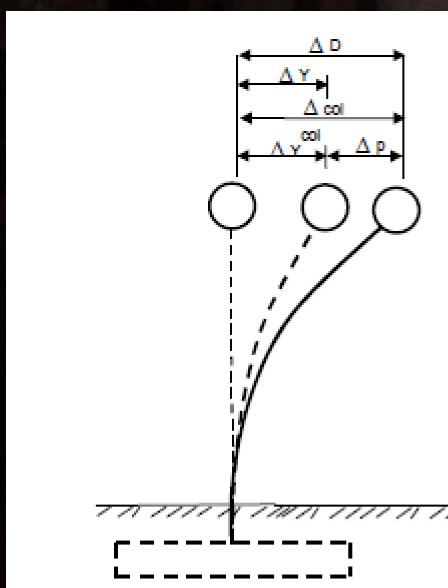
NON-LINEAR PUSH-OVER ANALYSIS by SAP 2000

- Longitudinal Pushover Curve at Bent 7



CALTRANS SDC CAPACITY

- Caltrans Seismic Design Criteria (Caltrans SDC)
  - ➢Caltrans SDC Equations are based on idealized Structure-Transverse



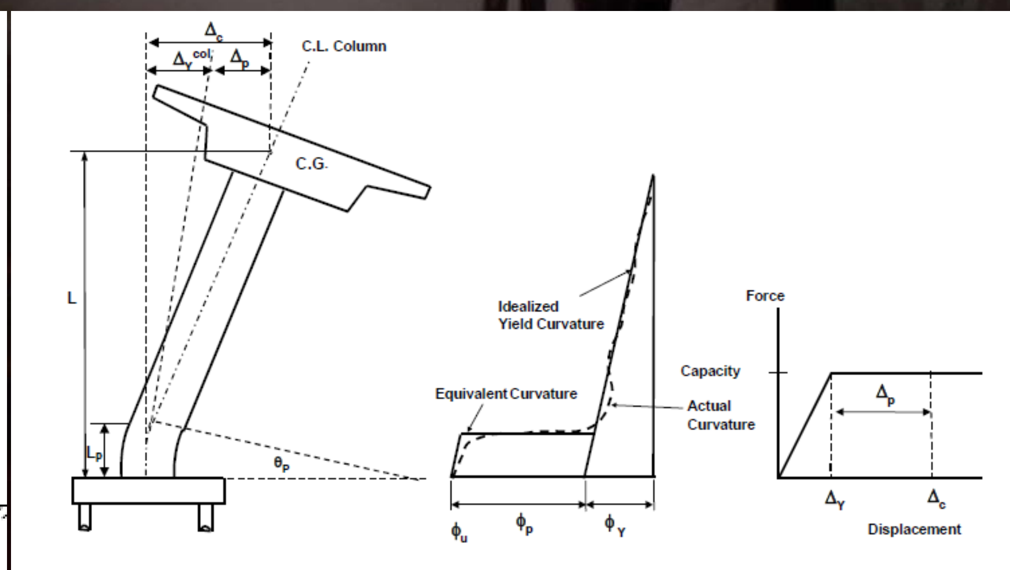


Figure 3.1 Local Displacement Capacity – Cantilever Column w/Fixed Base

CALTRANS SDC CAPACITY

- Caltrans Seismic Design Criteria (Caltrans SDC)
  - Caltrans SDC Equations are based on idealized Structure-Longitudinal or Multi-column bents at transverse

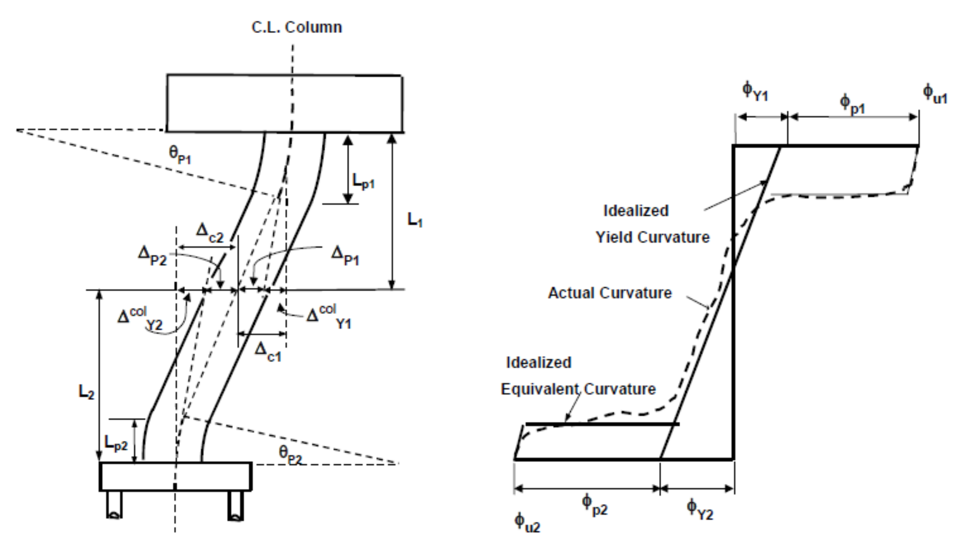


Figure 3.2 Local Displacement Capacity – Framed Column, assumed as fixed-fixed

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COMPARISON OF RESULTS

- Transverse

Category	Top of Bent 7 (Jt 30)	Top of Bent 8 (Jt 20)
NLTHA-SAP 2000	38.2	38.6
NLTHA-OpenSees	41.1	42.6
ARS Linear Analysis	23.4	17.6
Caltrans SDC, Dy	21.5	18.7
Non-Linear Push-over, Dy	10.2	9.0
Caltrans SDC, Du	79.3	68.6
Non-Linear Push-over, Du	45.5	45.0

COMPARISON OF RESULTS

- Longitudinal

Category	Top of Bent 7 (Jt 30)	Top of Bent 8 (Jt 20)
NLTHA-SAP 2000	14.0	14.1
NLTHA-OpenSees	15.1	15.8
ARS Linear Analysis	17.8	17.4
Caltrans SDC, Dy	10.5	9.7
Non-Linear Push-over, Dy	5.5	13.0
Caltrans SDC, Du	41.3	38.4
Non-Linear Push-over, Du	48.4	44.0

DISCUSSIONS & CONCLUSIONS

- NLTHA: SAP 2000 vs. OpenSEES
  - SAP 2000 provide more convenient input
  - OpenSEES can provide multiple support earthquake excitations input options
  - OpenSEES usually provides higher demands than SAP 2000
  - ARS Curve analysis is good for elastic or lightly – non-elastic performance analysis

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DISCUSSIONS & CONCLUSIONS

- NL Capacity: SDC vs. Push-over
  - Caltrans SDC provides convenient theoretical calculations
  - For Straight Structures, especially pre-stressed concrete box girder, superstructure is much stiffer than columns, SDC can provide acceptable results
  - For horizontally curved bridge, SDC is about 30% to 50% off from push-over results, push-over analysis is strongly recommended.

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DISCUSSIONS & CONCLUSIONS

- SAP 2000 and OpenSEES provide reasonable results for non-linear time history analysis
- SAP 2000 is easier for input
- OpenSEES provides more options for earthquake excitation input as you write proper programs. This option is good for Long bridges.
- It is strongly recommended performing 3-D pushover and structural analyses for horizontally curved bridges.

FURTHER STUDY

- Different Curvatures analysis.
- RM Bridge and other programs (tools) possible for NLTHA.
- Further Investigate OpenSees Programs for NLTHA for most commonly used bridge structures

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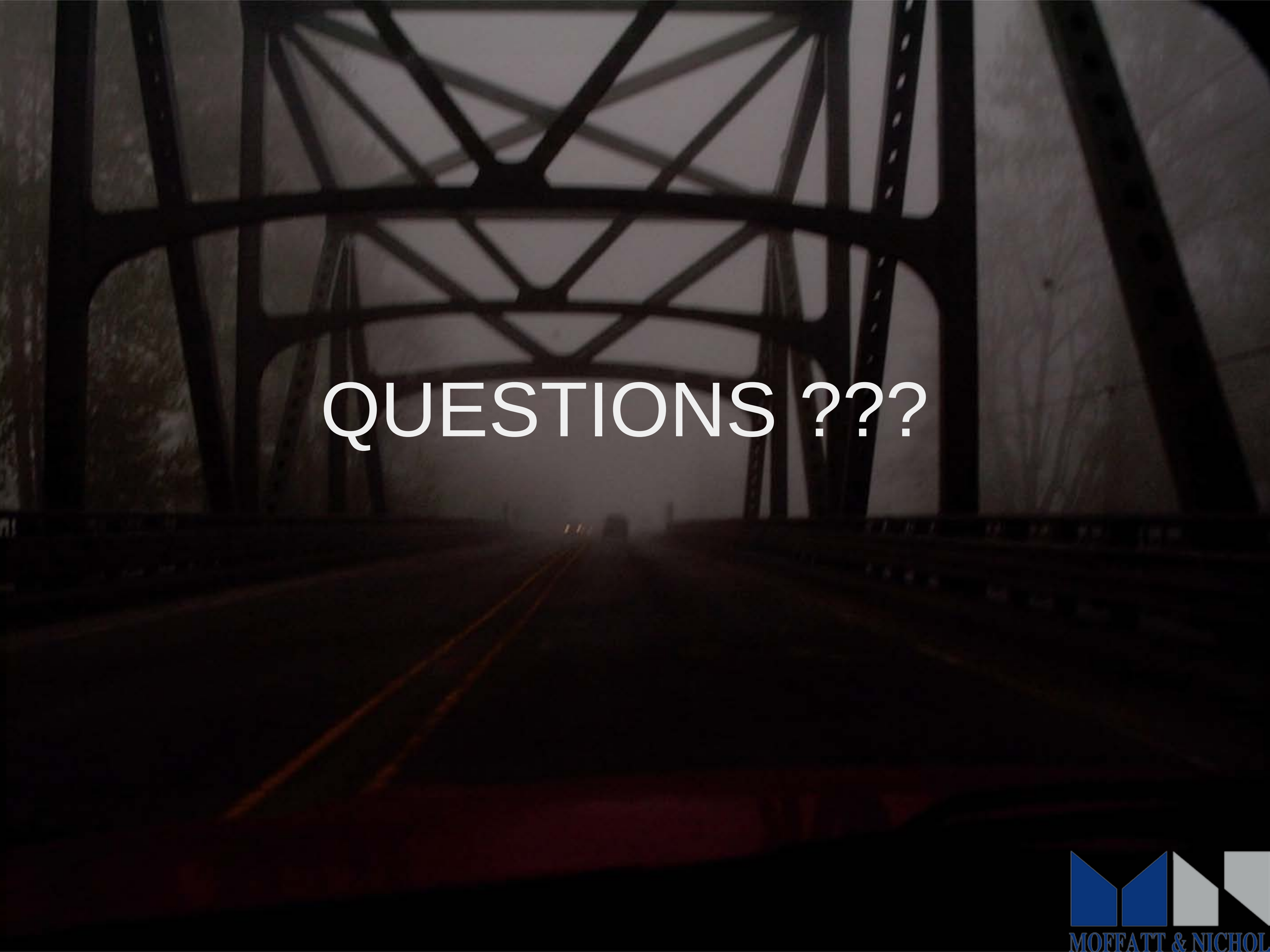
QUESTIONS ???
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