Western Bridge Engineers' Seminar

September 6–8, 2017

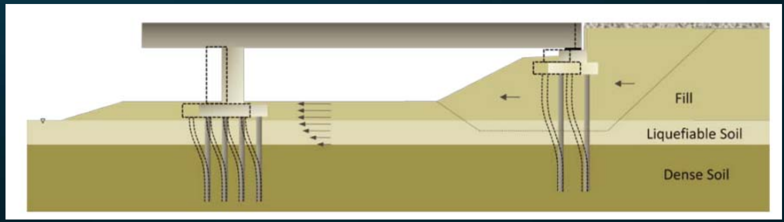
INNOVATIVE SOLUTIONS THAT STAND THE TEST OF TIME

Portland Marriott Downtown Waterfront
Portland, Oregon

Sept 7th, 2017

Foundation Restrained Liquefaction Induced Lateral Spreading Load Analysis of Bridge Structures

Restrained ?? Vs Unrestrained ??



By:

Ahilan Selladurai, P.E.,S.E.,PMP

Senior Bridge Engineer

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OUTLINE

- Introduction
- Unrestrained Ground Displacement
- Foundation Restrained Ground Displacement
- Analysis Procedures
- Example
- Conclusion

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- **Introduction**
- **Unrestrained Ground Displacement**
- **Foundation Restrained Ground Displacement**
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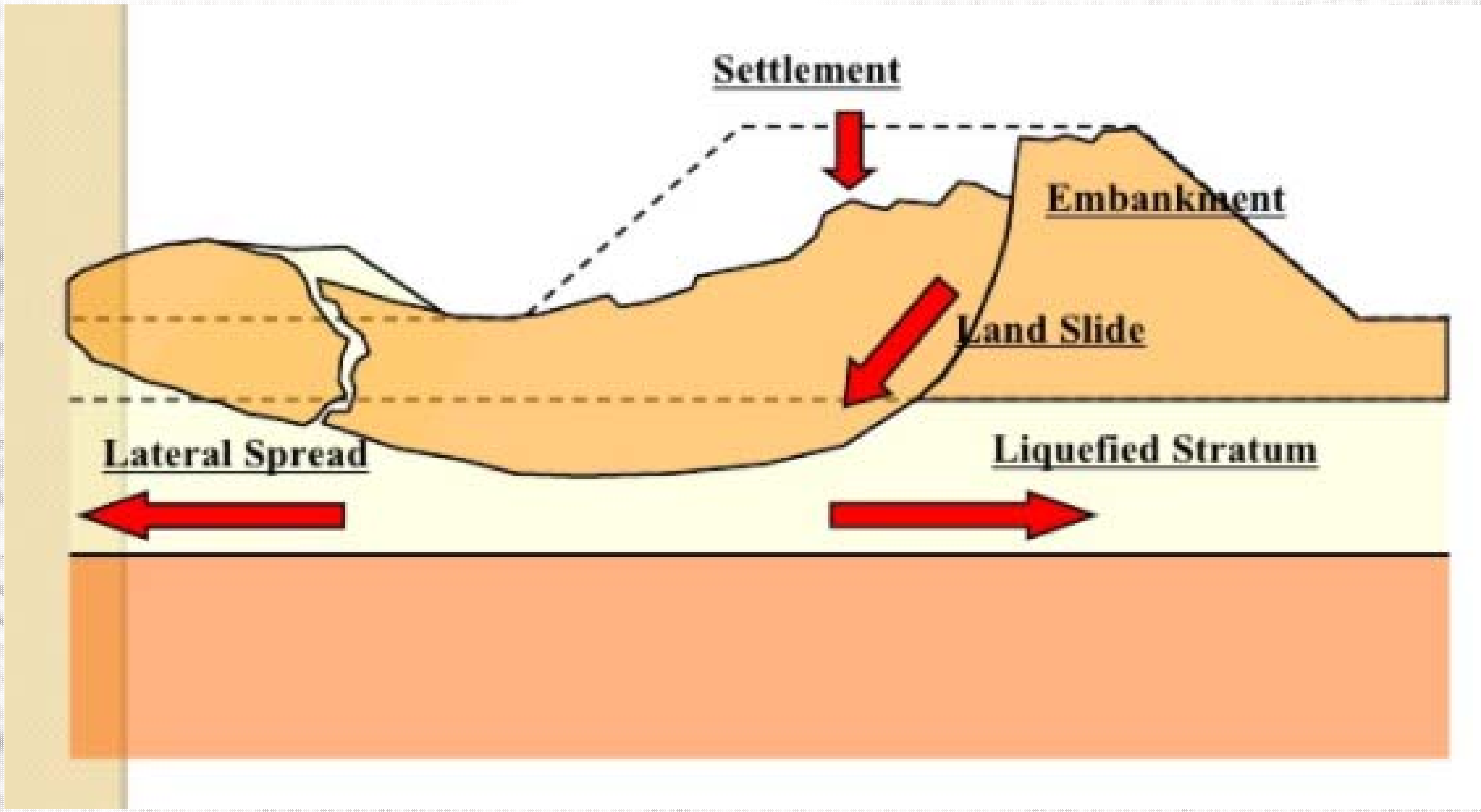
- **Example**
- **Conclusion**

INTRODUCTION



REF: Prof. Dr. J.N.Jha, Dept of Civil Eng, Guru Nanak Dev Engineering College, Ludhiana

Reference

Guidelines on Foundation Loading and Deformation Due to Liquefaction Induced Lateral Spreading

October, 2013

1 INTRODUCTION

Past earthquakes offer many examples of bridges that either collapsed or incurred severe damage resulting from lateral foundation movement caused by liquefaction induced lateral spreading. The following guidelines provide specific recommendations for the calculation of loads and deformation demands on bridge foundations and abutments resulting from liquefaction induced spreading ground. These procedures are based on recommendations given in Ashford et al. (2010) but occasionally go beyond these more general recommendations in an effort to provide as specific guidance as possible. The recommended approach relies on an equivalent nonlinear static analysis methodology. While this approach does not attempt the analytical rigor of a nonlinear dynamic analysis, it was developed through careful evaluation of a modest body of research performed in the centrifuge, small scale shake table, large scale shake table, and full size field tests. Where research results were insufficient to adequately address an issue, opinion of both researchers and industry experts was utilized. Since every project has unique aspects, these guidelines should not be used to constrain or replace engineering judgment. These guidelines present a framework for analysis that should be followed where possible, but with the freedom to extend them as needed to address unique circumstances.

Required Software

These guidelines were developed with the expectation that the reader has access to LPILE 5.0 to perform lateral pile analysis. Many programs are available that perform p-y curve based lateral pile analysis. The somewhat unique and critical feature incorporated in LPILE 5.0 is the ability to impose a free field soil displacement against the pile by adjusting the location of the base of the soil springs. Other codes that offer this capability should be sufficient to implement the recommended procedures. For projects that fall into the Foundation Restrained Displacement design case (defined in Section 2.2) use of a slope stability program will also be necessary. No special functionality will be required so most commercial slope stability programs will be suitable. For the evaluation of pile or shaft moment capacity, LPILE 5 can be used, though use of a program such as X-Section or XTRACT may offer some advantages as will be discussed in Section 2.3.

1

Ct LRFD

Memo to Designers 20-15 • November 2016

20-15 Lateral Spreading Analysis For New And Existing Bridges

Introduction

This memo describes a procedure to estimate the deformation demands (and capacities) of bridge foundations and abutments resulting from liquefaction induced spreading ground (i.e. horizontal ground displacement). Designers wishing to learn more about liquefaction can refer to Caltrans *Geotechnical Manual*, *Memo to Designers* (MTD) 20-14, and *Seismic Design Criteria* (SDC) Sections 2.2.5 and 6.1.2.

Lateral spreading is caused by the accumulation of incremental displacements that develop within liquefied soil under cyclic loading. Depending on the number and amplitude of stress pulses, lateral spreading can produce displacements that range from a few inches to tens of feet. For the purposes of this memo, the definition of lateral spreading is extended to the case of flow liquefaction. Flow liquefaction occurs when a slope becomes unstable under static loading due to strength loss caused by liquefaction. Flow liquefaction is characterized by slumping behavior and generally large deformation. The procedures described in this memo apply to both cyclic deformation and slumping behavior.

Excessive load or displacement demands caused by lateral spreading can be addressed using ground improvement techniques or structural enhancement of the bridge. Either option can be expensive. Generally, structural options are preferred but ground improvement options should be considered as well. Conservatism that might be appropriate in other design situations may come at an unacceptably high cost when applied to lateral spreading evaluation. The following evaluation procedure seeks to provide a best estimate of lateral soil displacement and the resulting displacement demand on the bridge.

New bridges in potentially spreading soil must be supported on ductile and strong foundations. Ductile piles and shafts are allowed to form two plastic hinges with allowable ductility demands up to five ($\mu_D \leq 5$). The recommended performance criteria reflect that SDC compliant bridges have the capacity to withstand large deformation demands without collapse. The performance criteria for existing bridges are described in the "Capacity Estimation" section of this memo.

The following sections outline the design procedure for evaluating lateral spreading. These sections provide the Geotechnical Designer (GD) and the Bridge Designer (BD) with the basic steps required to estimate the displacement demand on bridge members resulting from lateral spreading. Attachment 1 provides recommendations for the development of *p-y* curves and the construction of an equivalent single pile model.

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- **Unrestrained Ground Displacement**
- Foundation Restrained Ground Displacement
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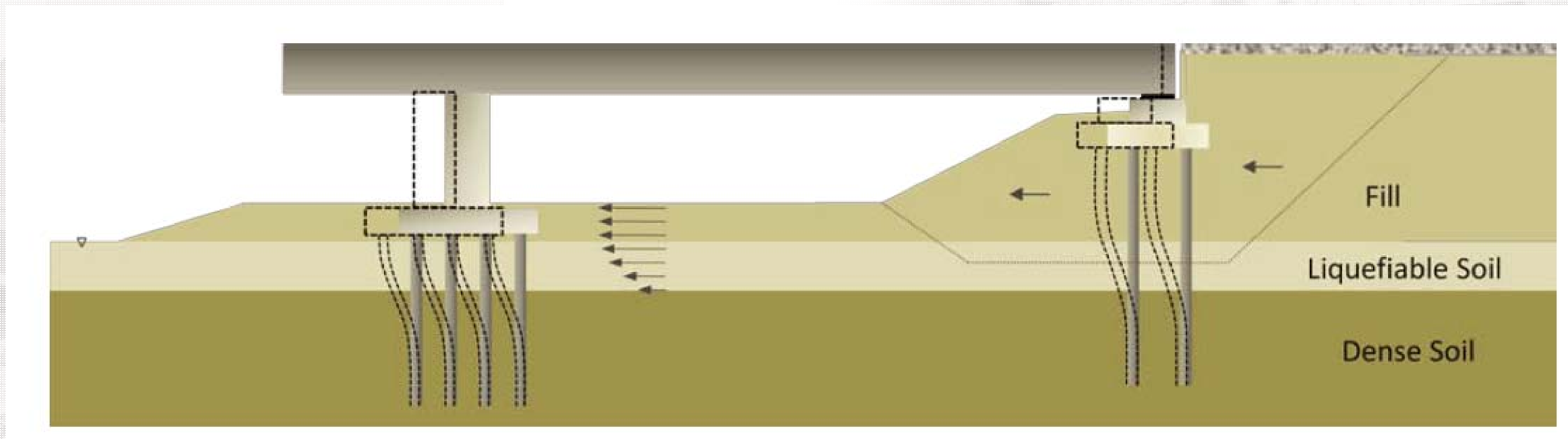
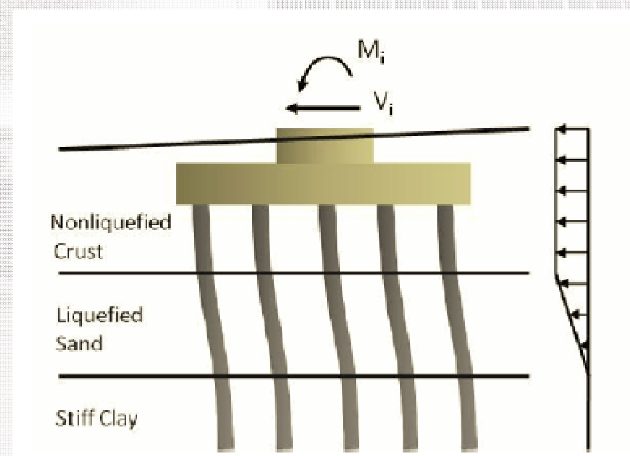
UNRESTRAINED GROUND DISPLACEMENT



- Larger Soil Mass Movement
- Foundation Displacement characterized "Unrestrained"
- Design Parameter is Estimated Crust movement



REF: Caltrans Design Guide

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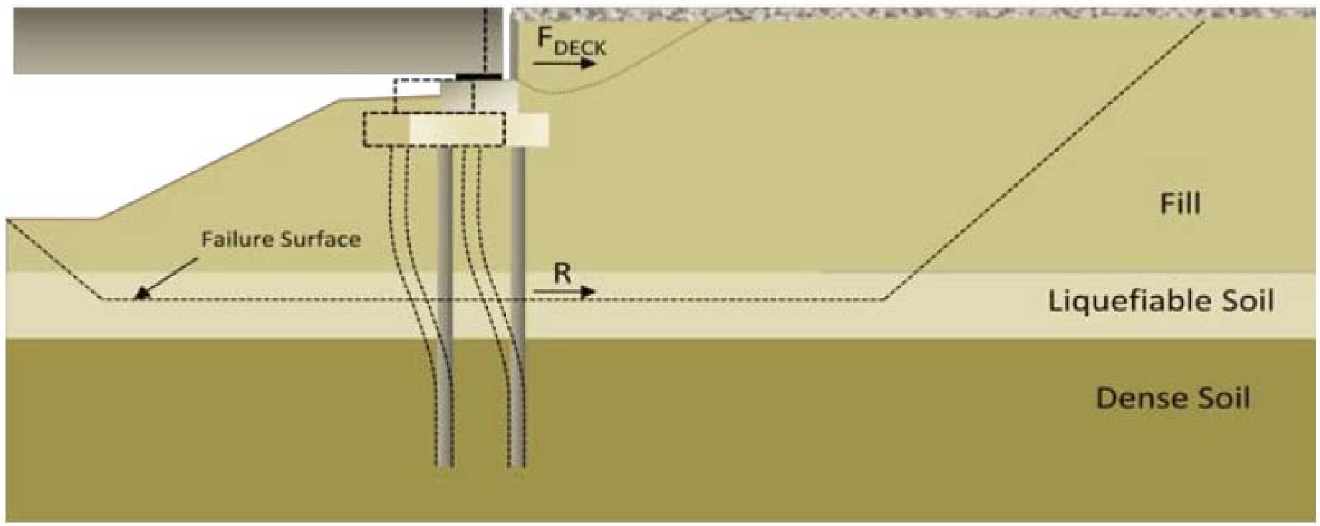
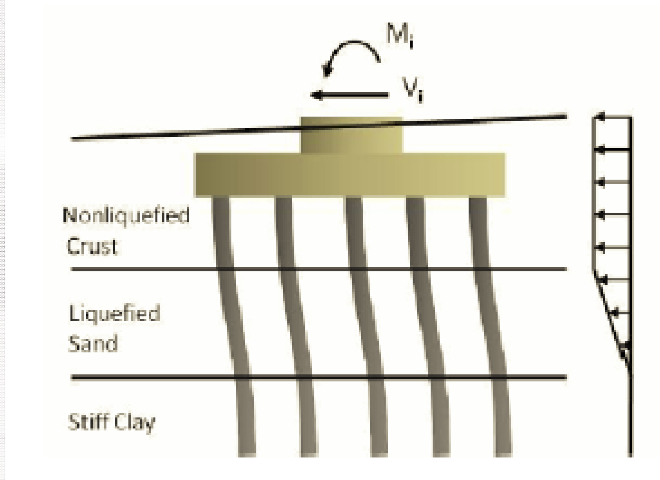
Restrained Ground Displacement

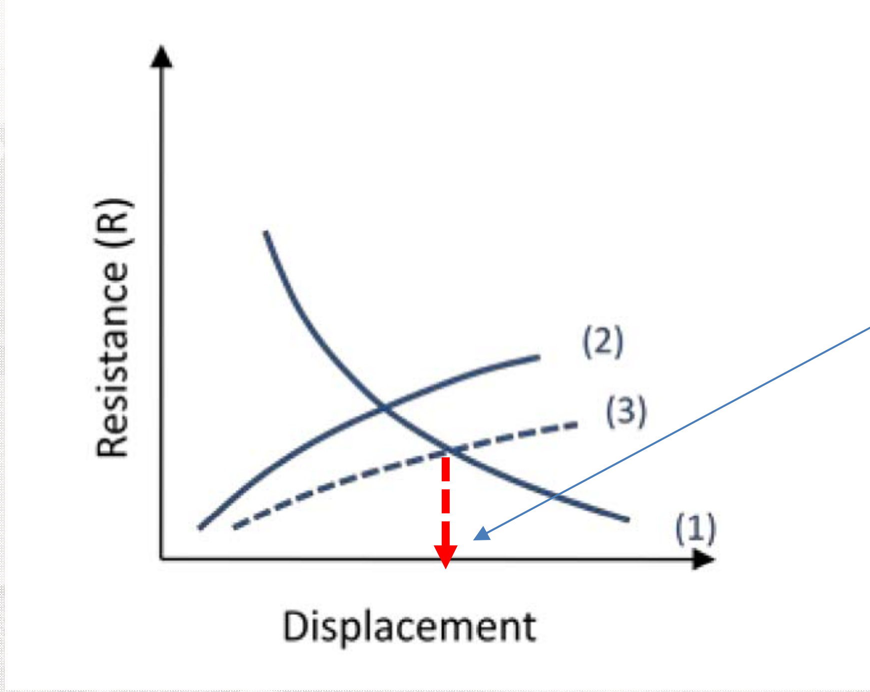


- **Partially Restrained By Foundation Elements**
- **Foundation Displacement characterized "Restrained"**
- **Determine Displacement of the sliding mass as function of the pile group resistance**



REF: Caltrans Design Guide

RESTRAINED GROUND DISPLACEMENT



Balanced Foundation Restrained Soil Movement

- **Curve (1) – Expected crustal displacement for given constant resistive force**
- **Curve (2) – Foundation resistive force corresponding to given crustal displacement**
- **Curve (3) "Running Average" of Foundation resistive force.**

REF: Caltrans Design Guide

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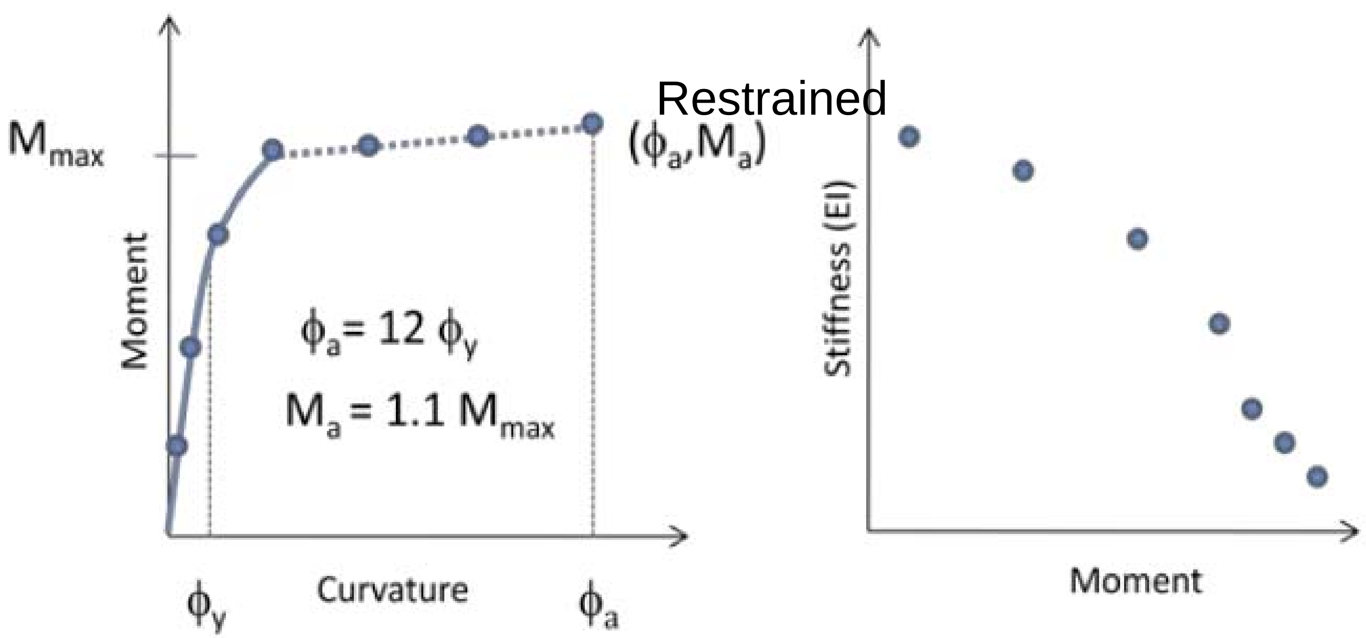
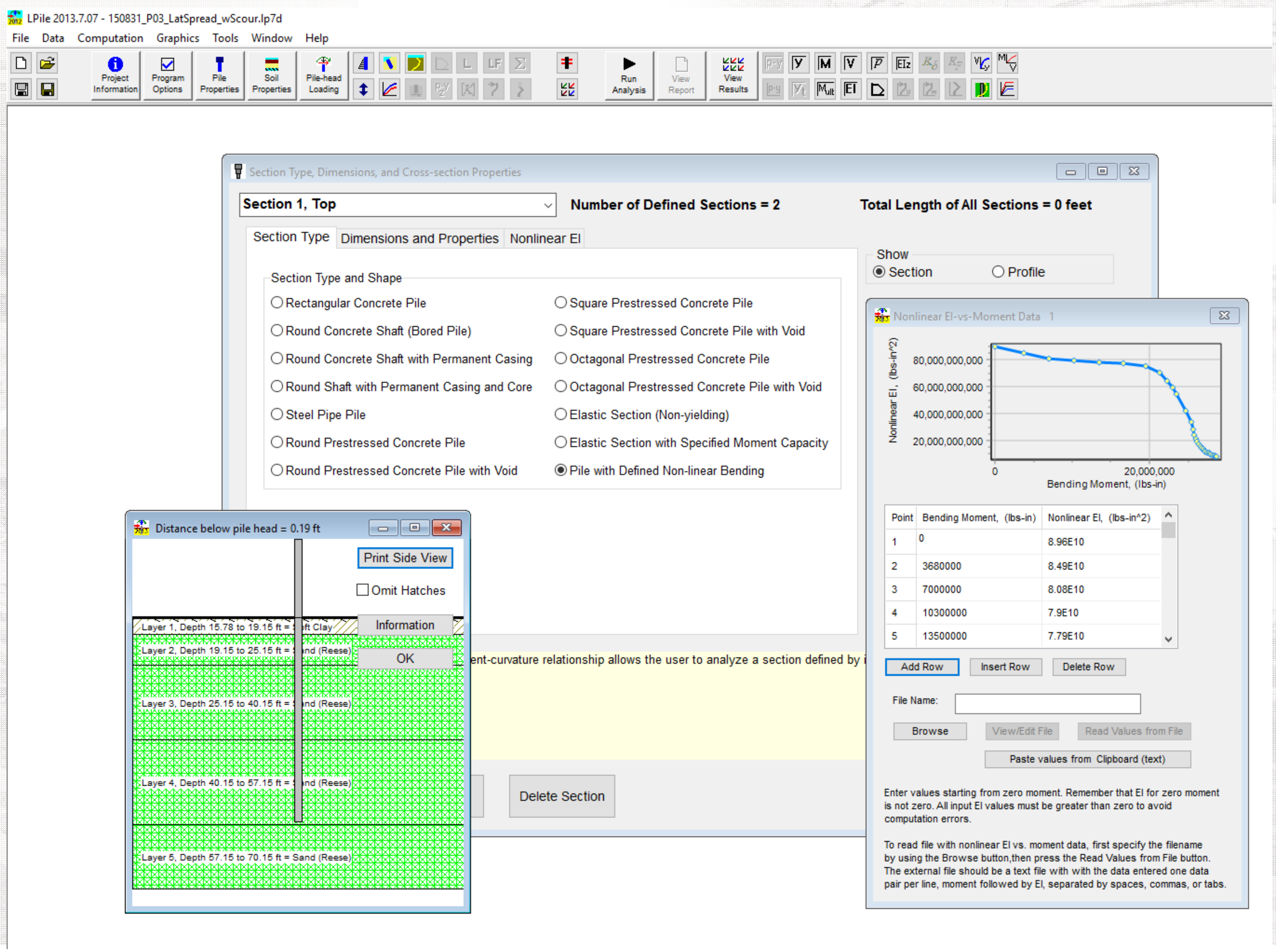
Analytical Framework
Modeling Piles

1. Develop a moment curvature curve for a single pile.
2. Scale the moment in the M-ϕ curve by the number of piles in the pile group.
3. Determine the yield curvature, ϕ_y, from the M-ϕ plot as shown in Figure Calculate the allowable curvature ϕ_a as $\phi_a = 12\ \phi_y$. Extend the M-ϕ curve to the point (ϕ_a , 1.1 M_{max}).
4. M-EI points are calculated at several points along the curve using the fact that EI = M/ϕ.

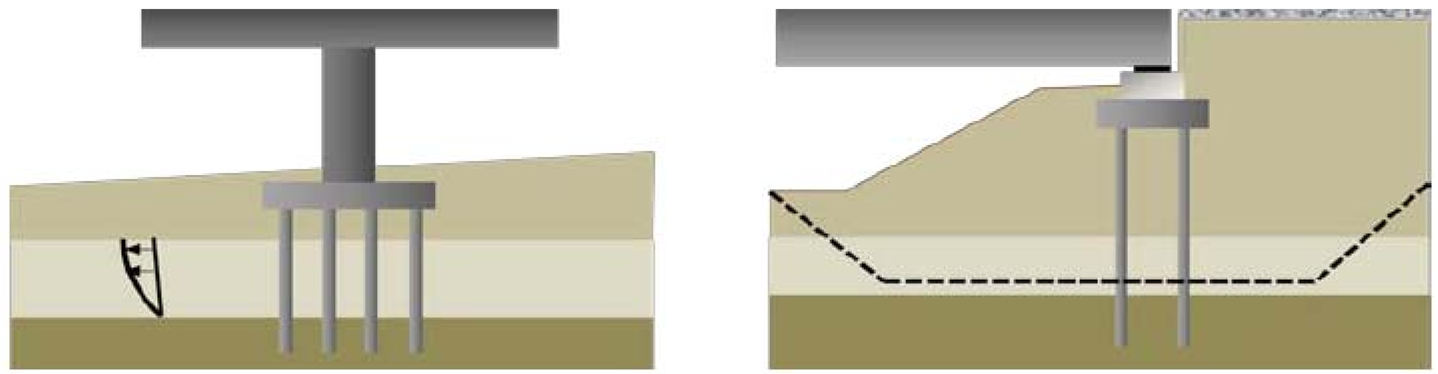


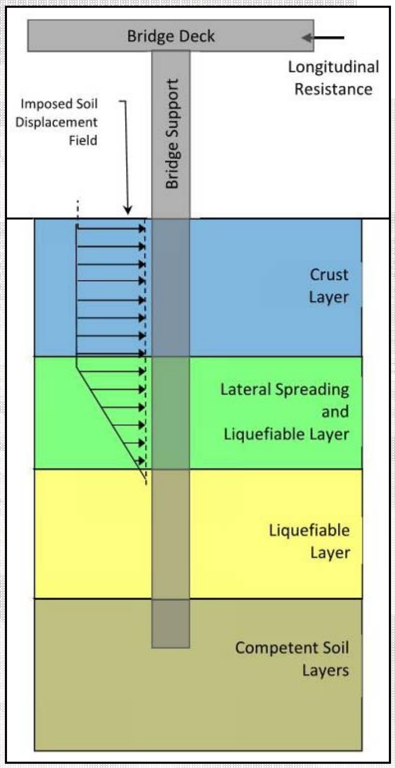
REF: Caltrans Design Guide

NON-LINEAR BENDING PROPERTIES @ LPILE



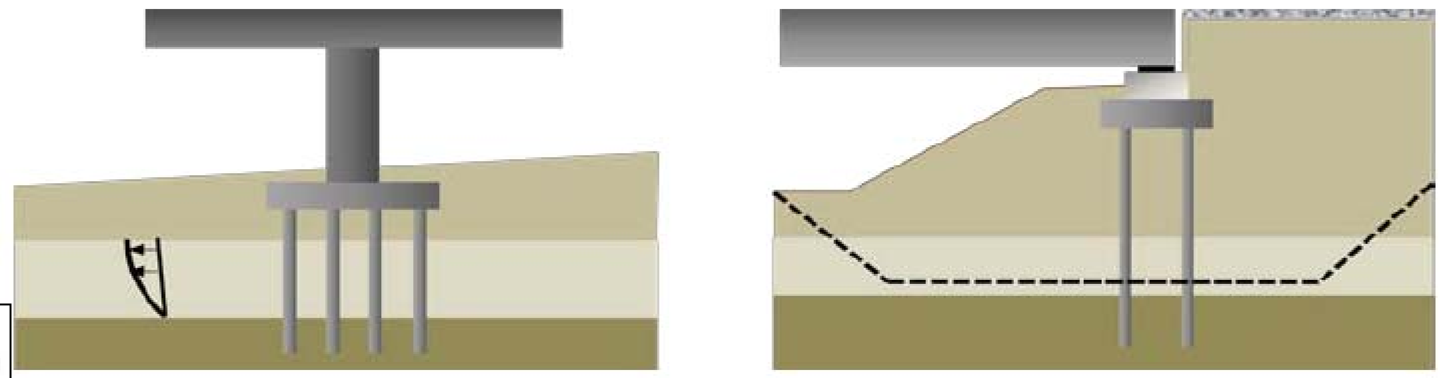
ESTIMATING CRUST MOVEMENT

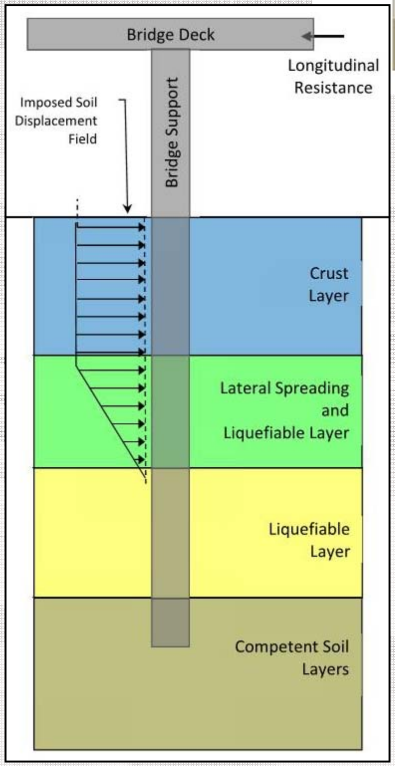




- The Bray and Travasarou method
- Faris (2006) Method
- Youd et al. 2002
- Bardet, Jean-Pierre, et al. 2002
- Zhang, G., et.al. 2004

ESTIMATING CRUST MOVEMENT





Two Recommended Methods

- **Bray and Travasarou (2007)**
- **Faris (2006)**

REF: Caltrans Design Guide

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Apply Crust Movement to Piles

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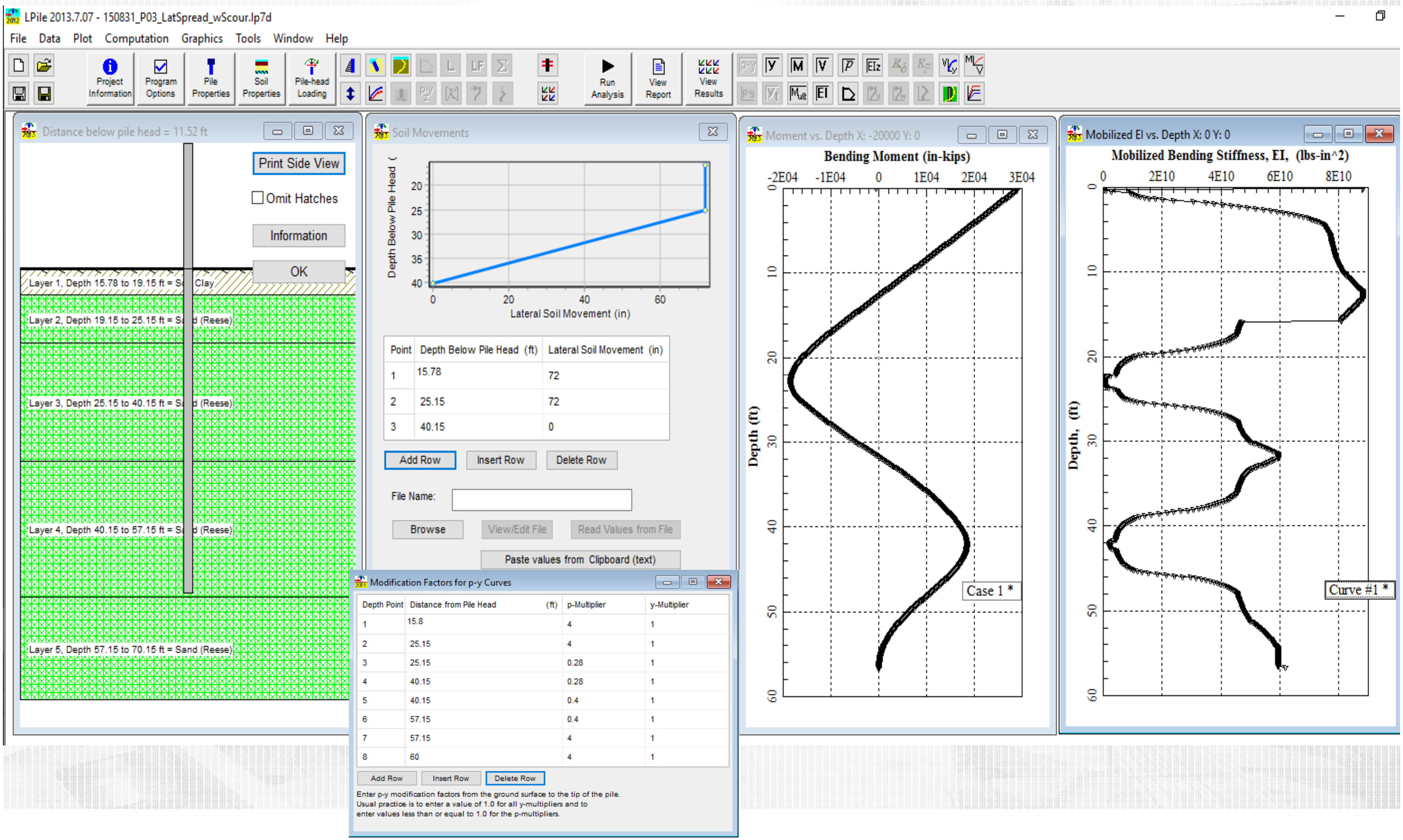

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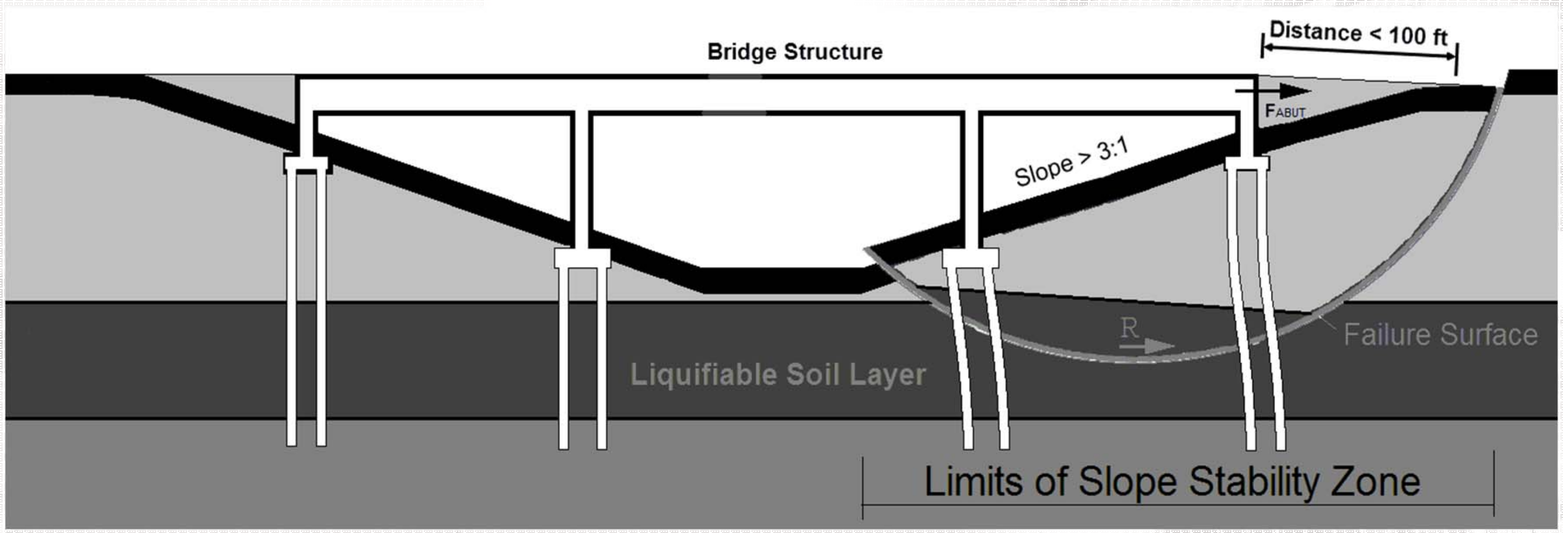
UNRESTRAINED CRUST DISPLACEMENT CASE PROCEDURES

- **Assess the Soil Profile using PGA based on 5% in 50 yrs Hazard. Liquefaction Evaluation Shall be Based on Youd et al. (2001)**
- **Assign Residual Strength of Liquefiable layers**
- **Find Crust Displacement**
- **Develop Foundation Model (Super Pile)**
- **Impose Soil Displacement Profile to Foundation Model**
- **Evaluate Foundation for Applied Lateral Spread Loads**

RESTRAINED CRUST DISPLACEMENT CASE PROCEDURES



- When Potential Sliding Mass is Limited in Size, Lateral Stiffness of the Foundation Can Impede its Movement
- Restraining Effect Can Result in Significant Economy Since Reduced Displacement Demand
- Accounting Foundation "Pinning" Effect

Restrained Crust Displacement Case Procedures

- Geotechnical Engineer Provide Unliquefied p-y Curves and 5% in 50 Year Design Spectrum to Bridge Designer
- Bridge Designer calculate Inertia Displacement Demand Using Unliqufied p-y Curves
- Geotechnical Engineer Assess the Soil Profile using PGA based on 5% in 50 yrs Hazard. Liquefaction Evaluation Shall be Based on Youd et al. (2001)
- Geotechnical Engineer Assign Residual Strength of Liquefiable layers
- Bridge Designer Update Liquefiable p-y Curves to Soil Layers

Restrained Crust Displacement Case Procedures

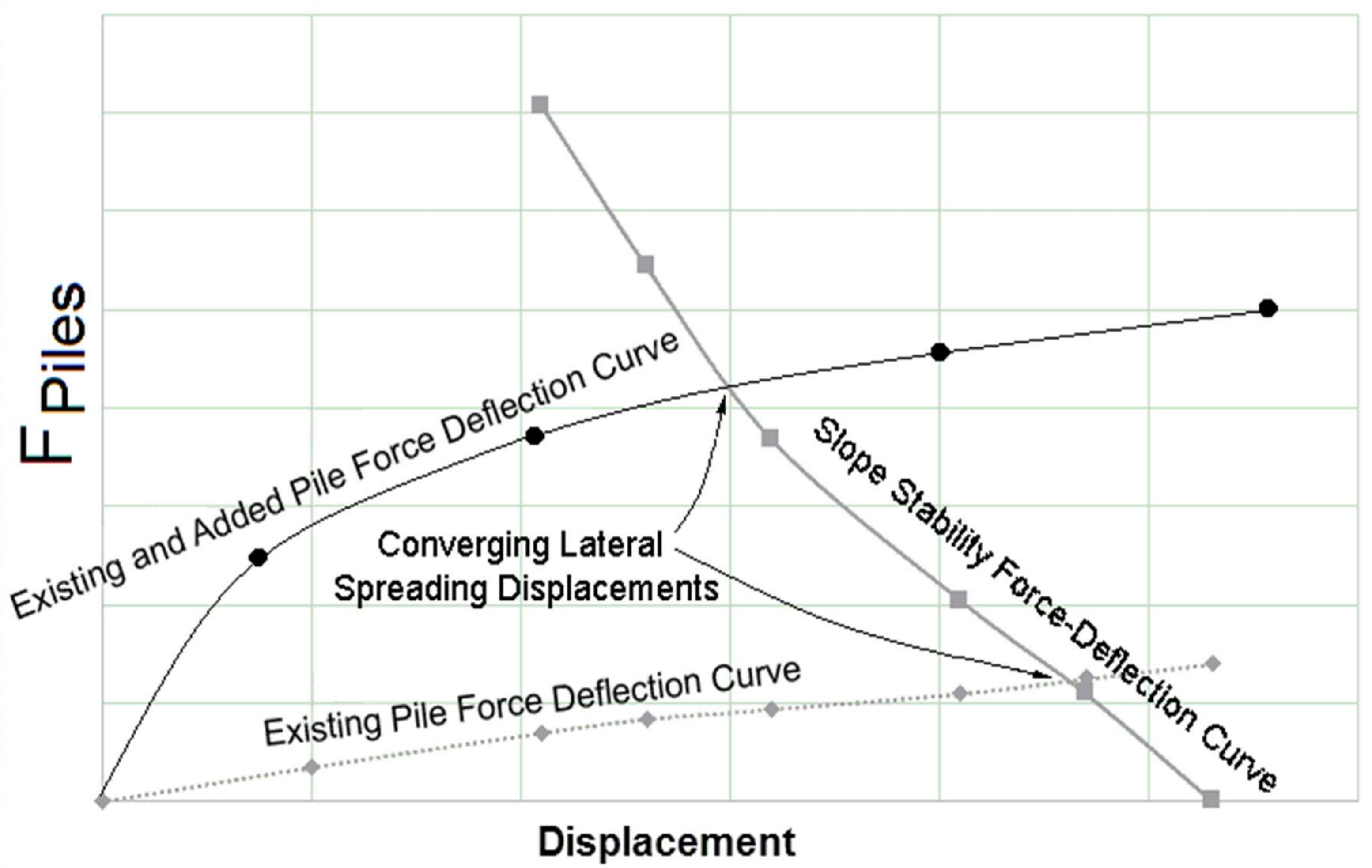
- **Bridge Designer Calculate Inertial Displacement Demand Using Unliqufied p-y Curves**

- **Bridge Designer Calculates Resisting Force (F_{ABUT}) Using Full Height of the Abutment and the Passive Resistance Pressure**

- **Geotechnical Engineer Perform Slope Stability Analysis Accounting Abutment Resisting Force (F_{ABUT}) and Provide Force-Deflection Curve**

- **Bridge Designer Derives the Force -Deflection Curve For Existing / Existing +Retrofit Piles (Allow Multiple Plastic Hinges to it's Full Capacity**

Restrained Crust Displacement Case Procedures

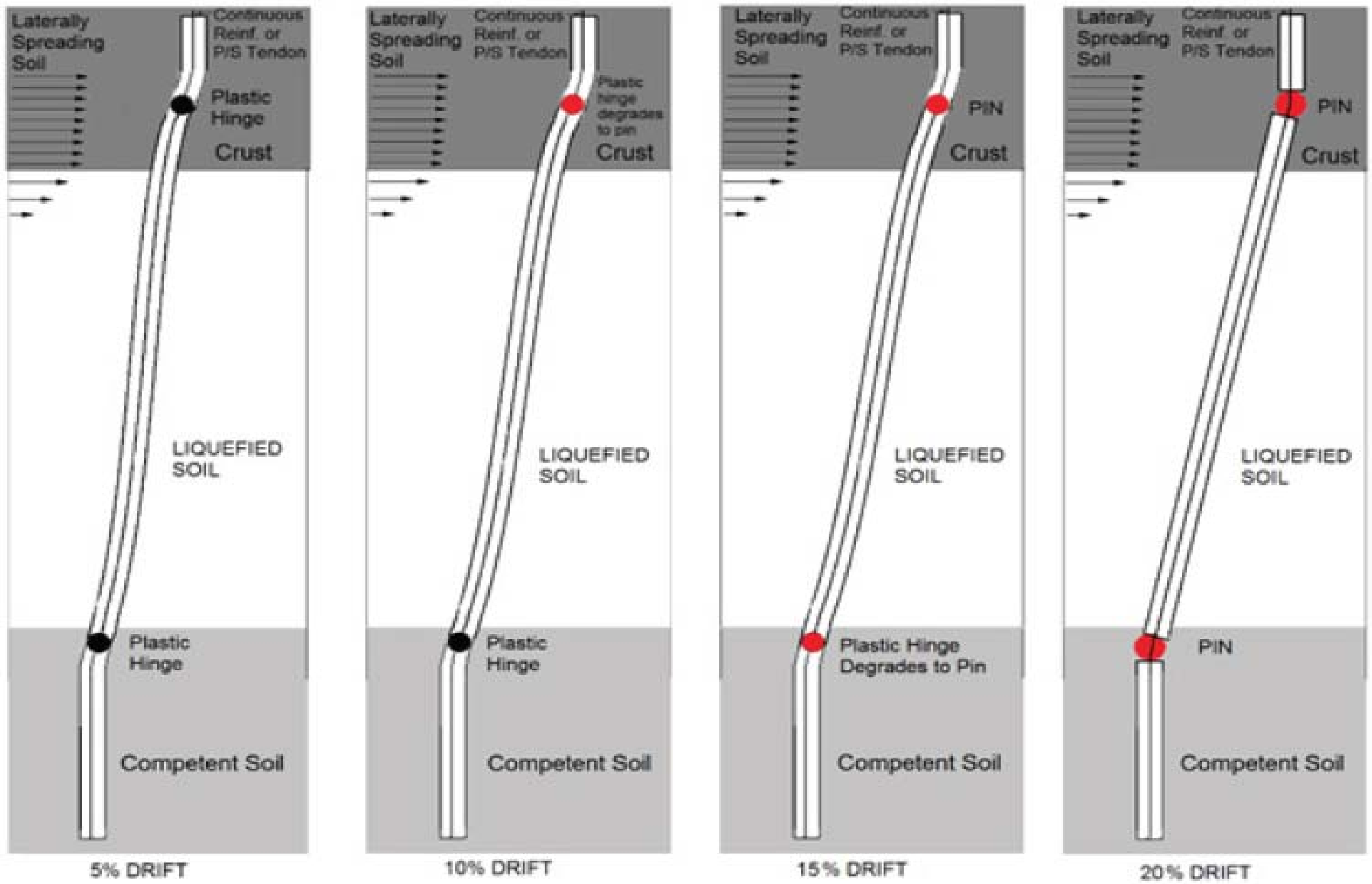


Determining Displacement for Restrained Lateral Spreading

RESTRAINED CRUST DISPLACEMENT CASE PROCEDURES

- **Case – I**
  100% (Kinematic) + 50% (Inertial) -> Peak Pile Cap Displacement
- **Case – II**
  50% (Kinematic) + 100% (Inertial) -> Peak Pile Moment & Shear

PILE CAPACITY – EMBEDDED PILES



Lateral spreading of existing piles showing evolution from plastic hinges to pins

Pile Capacity – Embedded Piles

- New Piles
  - Allowed to form 2 plastic Hinges
  - $\frac{\Delta_{demand}}{\Delta_{yield}}$ up to 5
- Existing Piles
  - Allowed to be damaged or even to pin as long as drift does not exceeds the values shown in the following table

Element	Drift Ratio	Comments
Step Tapered in Steel Shell Piles	0.05	Larger capacity allowed through analysis
CIDH Piles with reinforcement only in top 10 ft of pile	0.05	Larger capacity allowed through analysis
Timber Piles	0.20	-
Driven Precast Piles	0.20	-
Steel Pipe Piles	0.20	Larger capacity allowed through analysis
Steel H Piles	0.20	Larger capacity allowed through analysis

REF: Caltrans Design Guide

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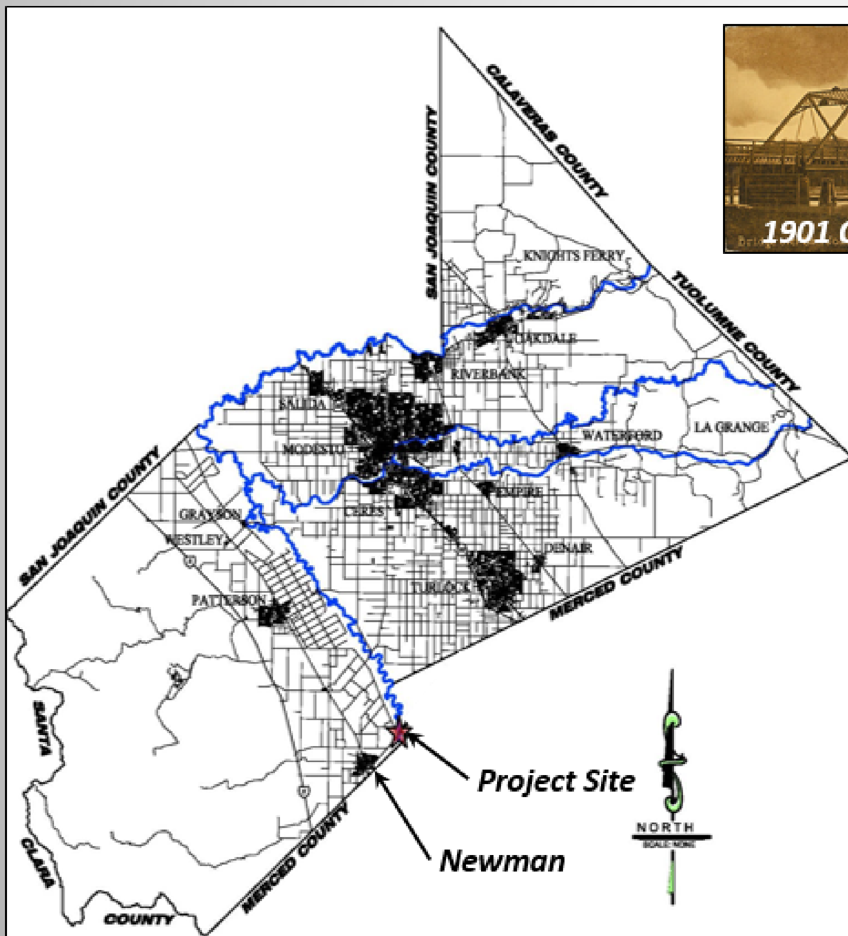
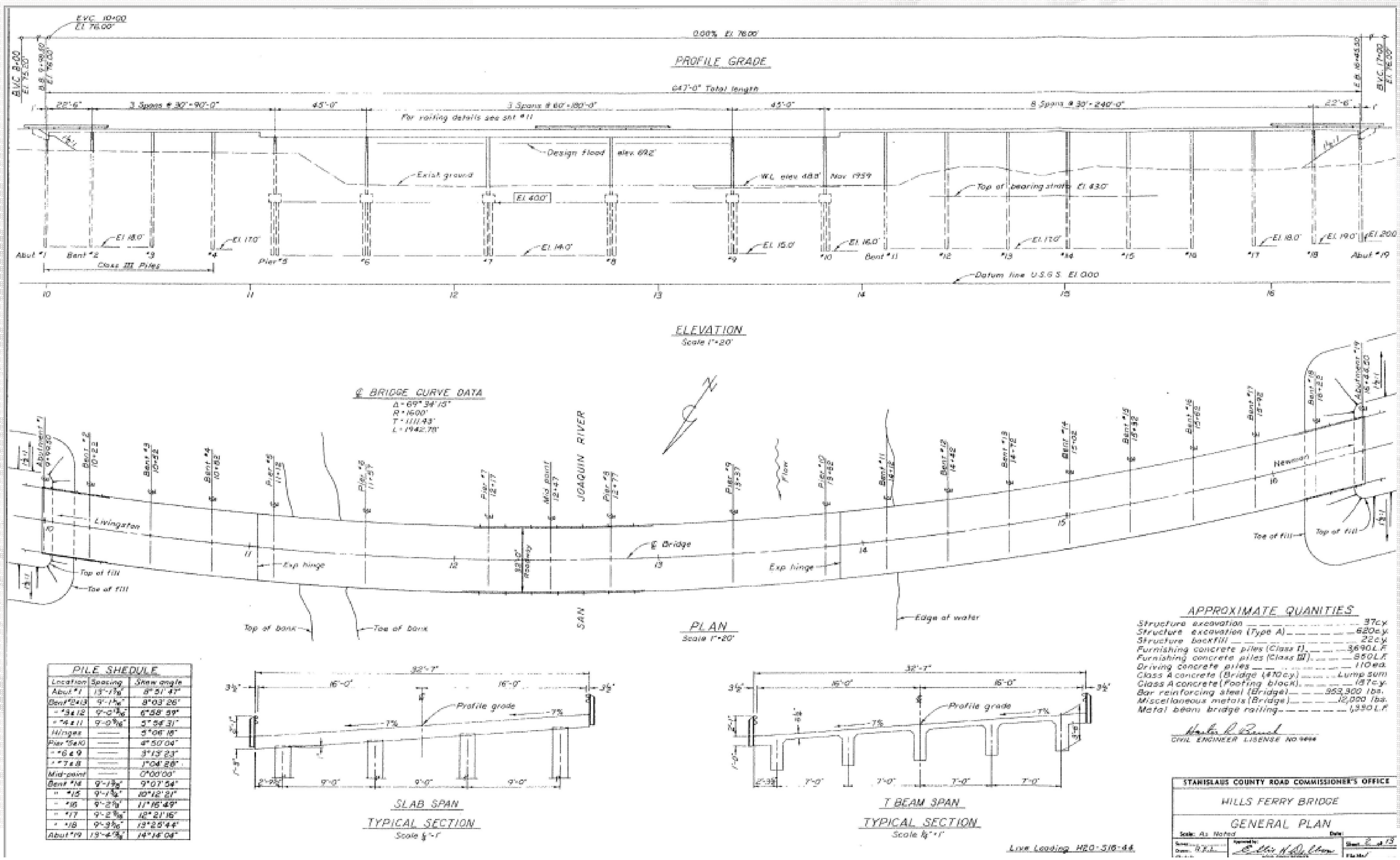
Hill Ferry Road Seismic Retrofit
Project Location

Vicinity Map

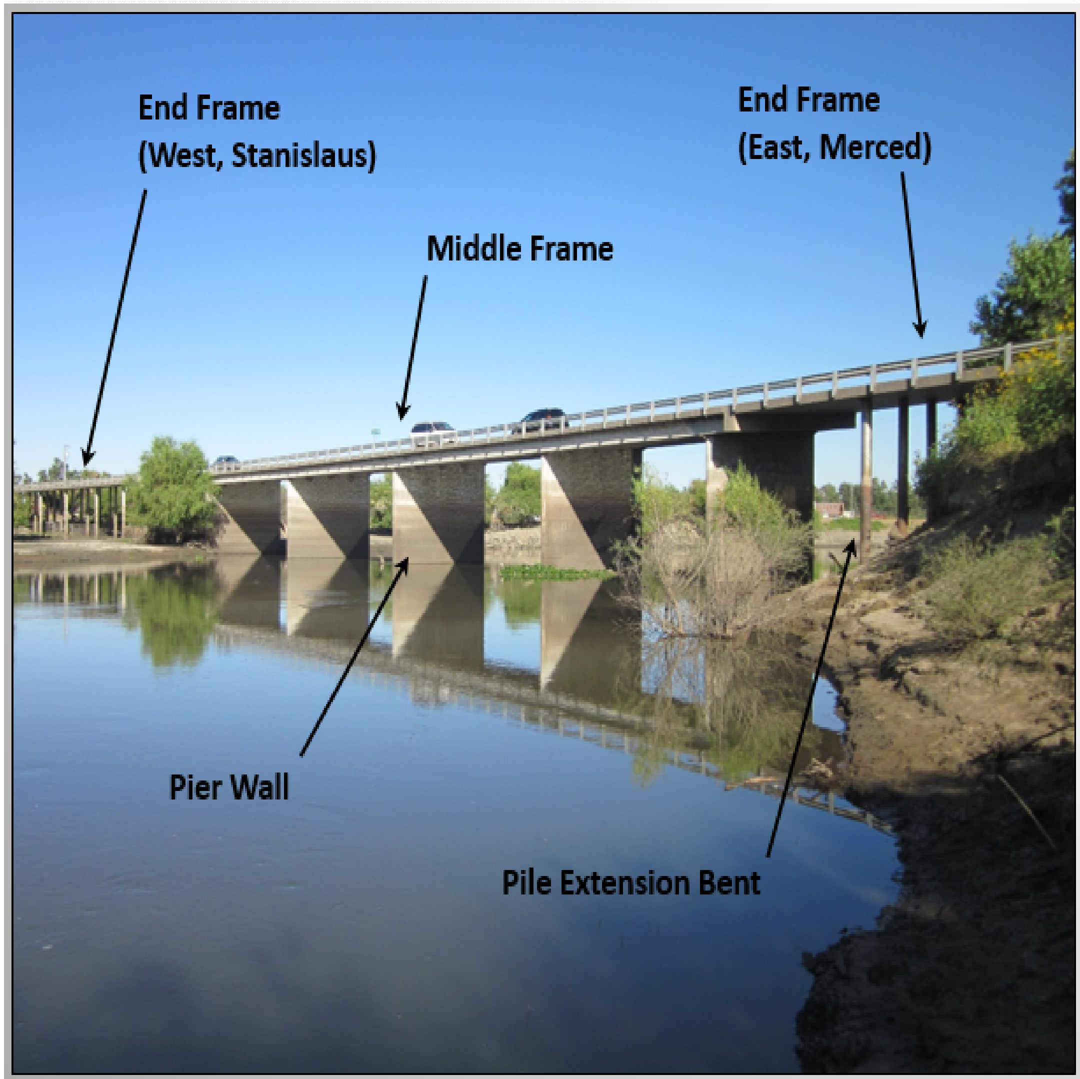


Location Aerial

Hill Ferry Road Seismic Retrofit
Bridge Plan & Elevation



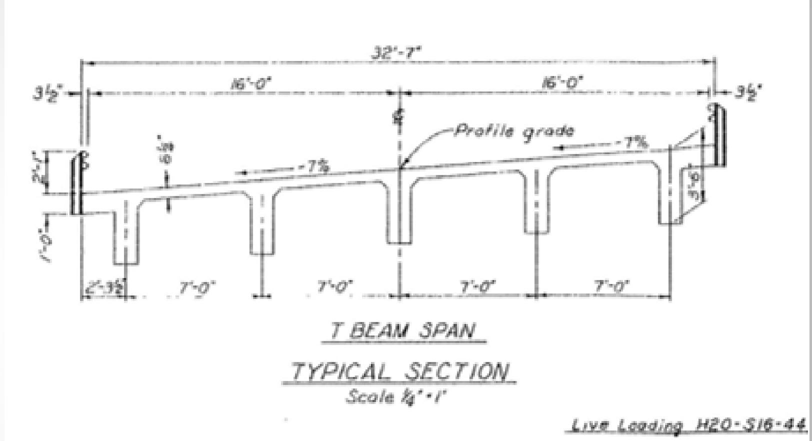
Hill Ferry Road Seismic Retrofit Project Photos



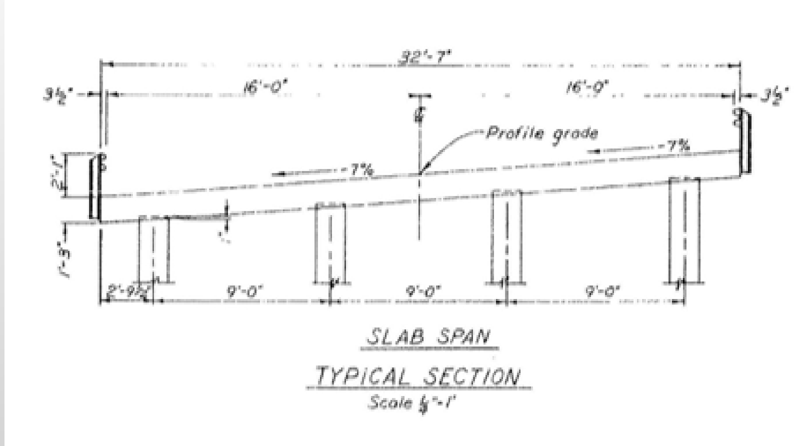
Hill Ferry Road Seismic Retrofit
Bridge Summary

- **Existing Bridge, 39C0001 (1961)**
  - L = 647'-0"; W = 32'-7"
  - 3 Frames, 18 Spans
    - End Frames: Slab spans on pile extensions
    - Middle Frame: T-Beam spans with pier walls on piles foundations
  - Diaphragm abutments on piles on embankment fills
- **Roadway (Major Collector)**
  - Posted Speed = 55 mph
  - ADT = 4,471

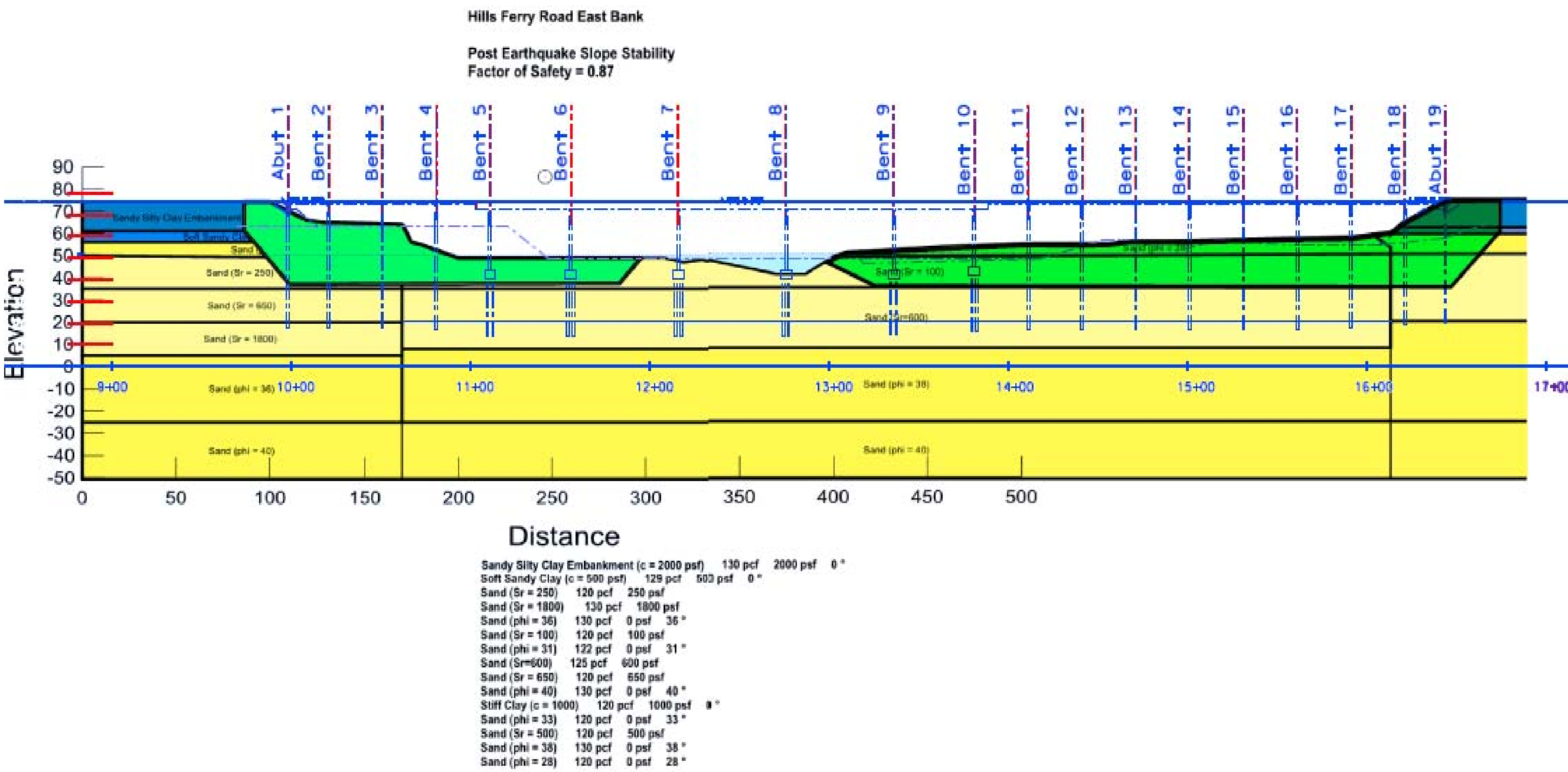
Middle Frame: CIP/RC T-Beam



End Frames: CIP/RC Slab

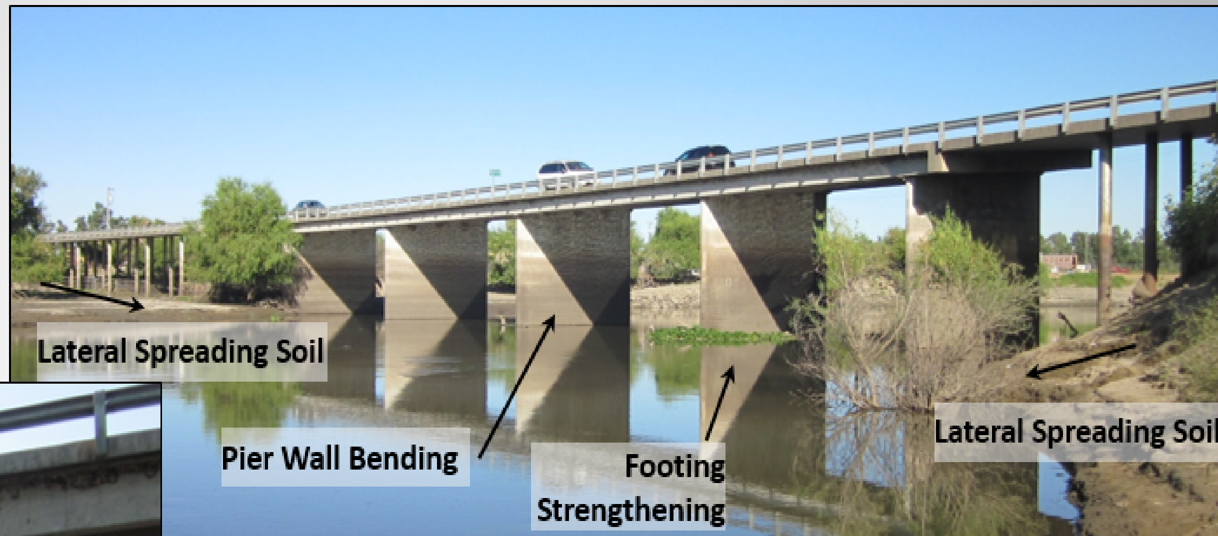


HILL FERRY ROAD SEISMIC RETROFIT
LATERAL SLIDING SURFACE



HILL FERRY ROAD SEISMIC RETROFIT VULNERABILITIES

- **Vulnerabilities**



HILL FERRY ROAD SEISMIC RETROFIT
HISTORIC CHANNEL MIGRATION

- **Historic Channel Migration**

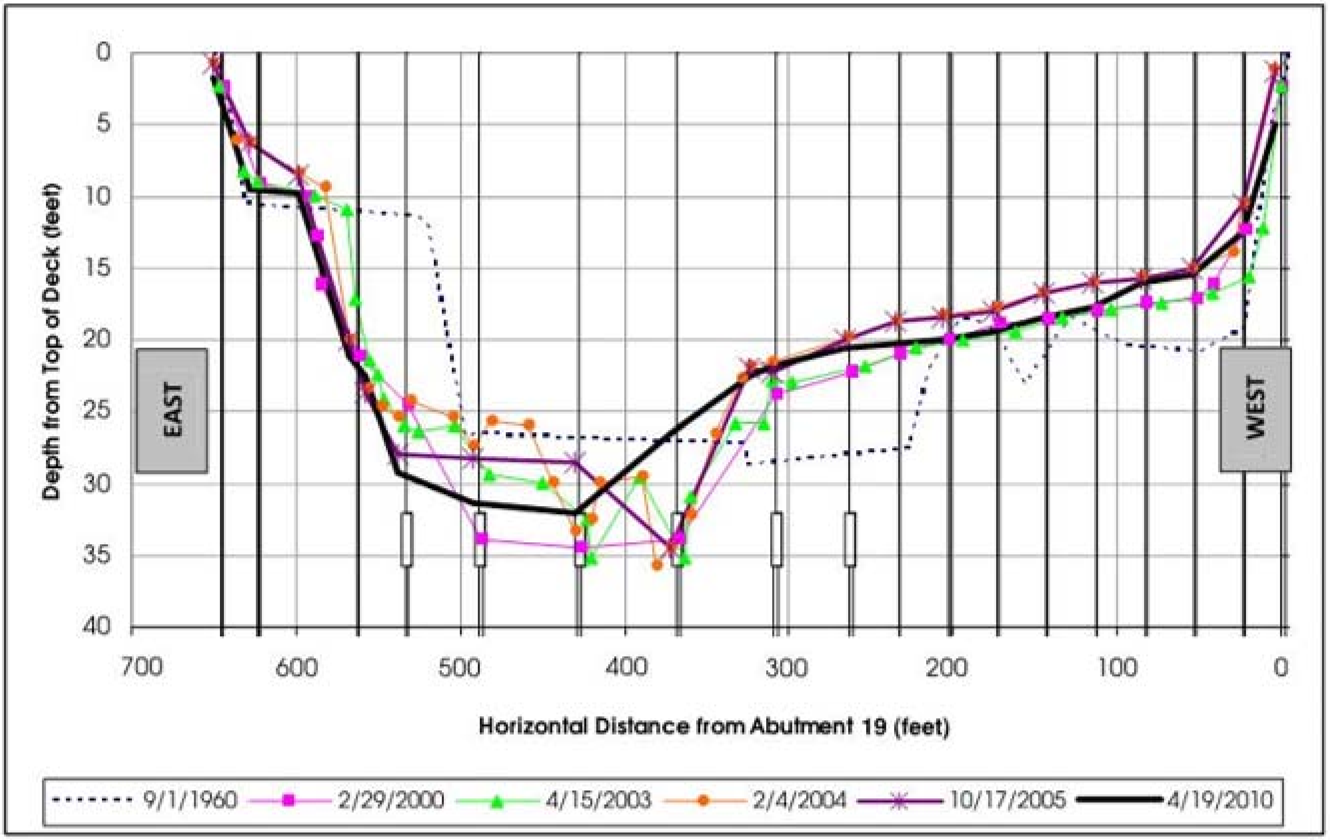


Figure 1. Channel Cross Sectional Measurements at Upstream (Southern) Face of Existing Hills Ferry Road Bridge over San Joaquin River

Source: Channel Measurements Based on Data from Caltrans BIRs, 1960 through 2010

Hill Ferry Road Seismic Retrofit Project Background

- **Previous Studies – 1993 - 2004**
  - 1993 Seismic Evaluation & Strategy (Force Based)
  - 1999 Liquefaction & Lateral Spread Study
  - 2002 Channel Migration (Historic 1961 to 2001)
  - 2001-2004 Revised Seismic Evaluation & Strategy (Force & Displacement Based)

- **Restart Project: 2011-Current**
  - Test Case for 1000's of bridges in CA
  - Retrofit Validation Study: 12/2011 - 7/2014
    - Compare 2004 Approved Retrofit Strategy against current seismic design principles (Displacement & Ductility Based)
    - Previous "approved" strategy inadequate
  - Comprehensive Retrofit Study: 8/2014 – 11/2016
    - Restart with As-Built Assessment
    - Develop new retrofit strategy
    - Reach consensus with Caltrans
    - Strategy approval

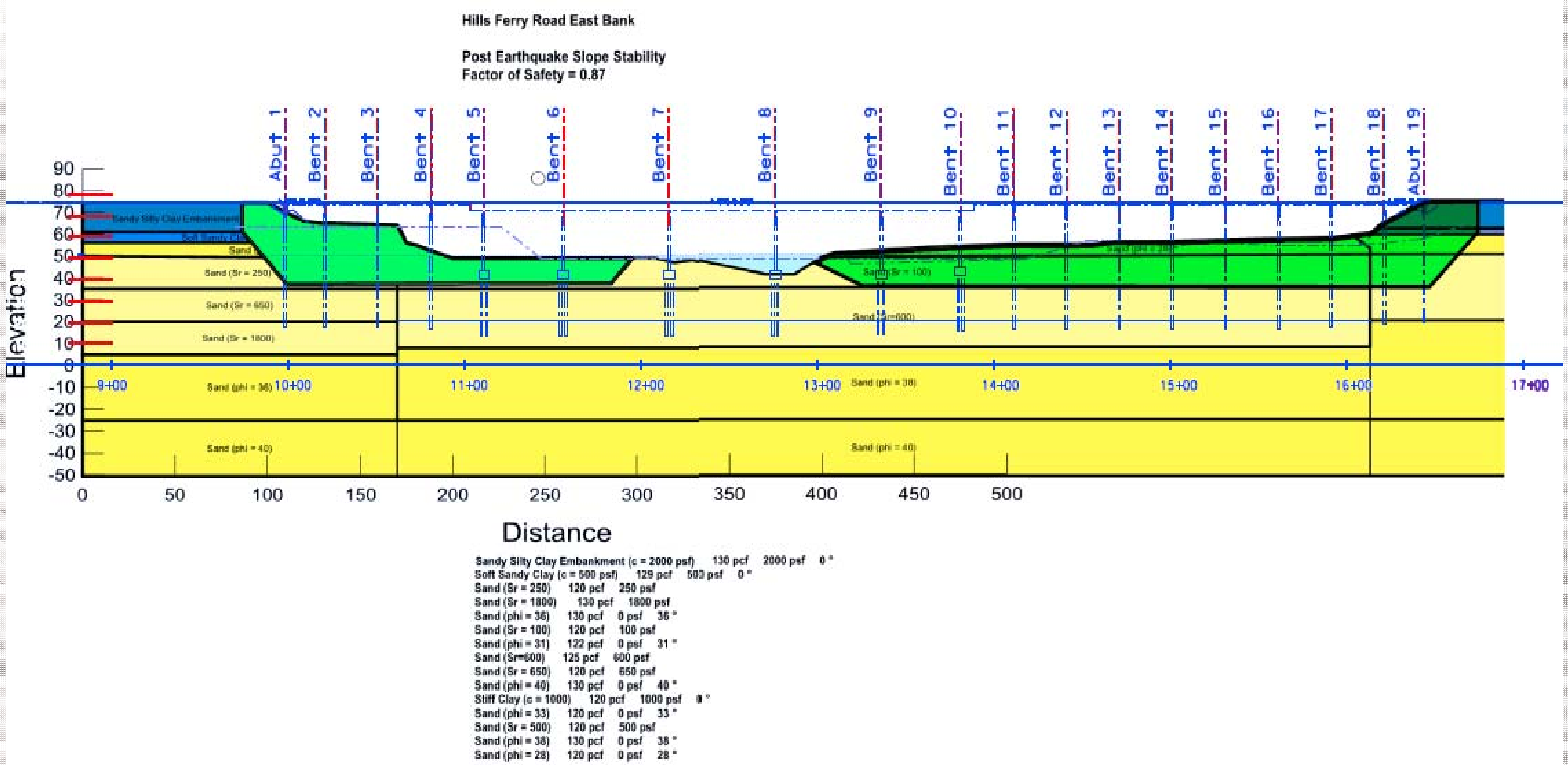
HILL FERRY ROAD SEISMIC RETROFIT PROJECT ASPECT & GOAL

- **Retrofitting Project Goal**
  - Upgrade seismic safety of the bridge - No Collapse, Life Safety
    - *"Provide minimum structural solution satisfying all requirements"*

- **Seismic Retrofit Project Process**

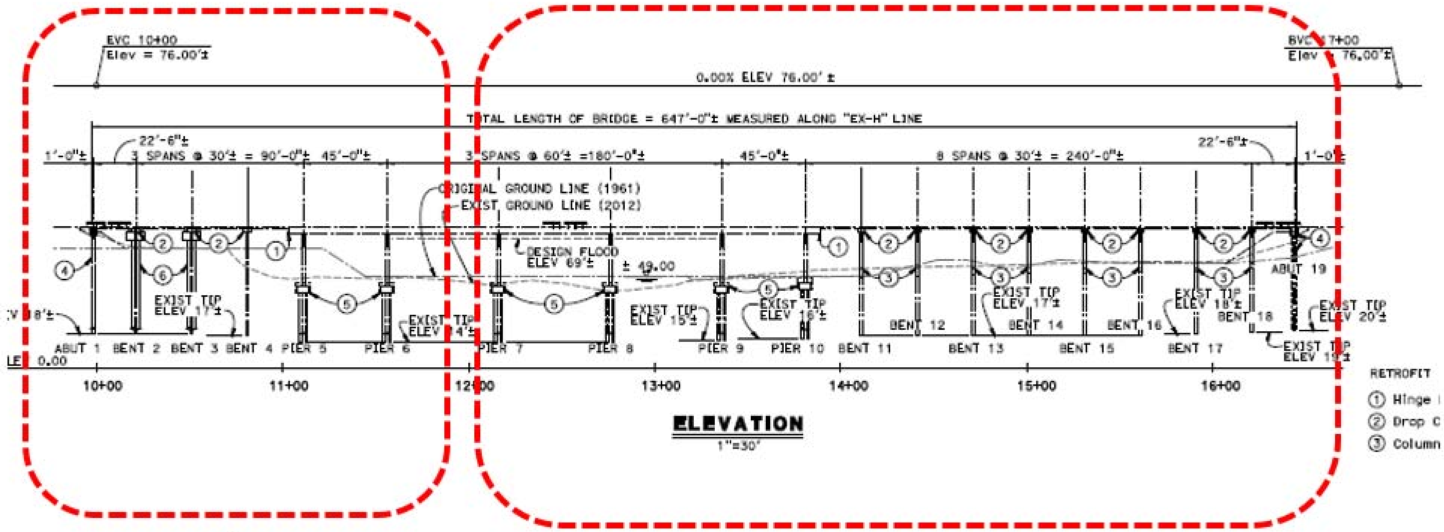
As-Built (Existing) Bridge Assessment	=	*What's Wrong?*
Retrofit Strategy Development and Cost Estimate (Draft Report)	=	*How do we fix it? How much is that going to cost?*
Strategy Meeting (Approved Strategy)	=	*Does Caltrans agree?*
Finalize Approved Strategy (Final Report)	=	*Any additional concerns?*
Environmental Docs & Final Design (PS&E)	=	*Let's permit, design, and build it!*

Hill Ferry Road Seismic Retrofit
Possible Analysis Cases – Frame-1

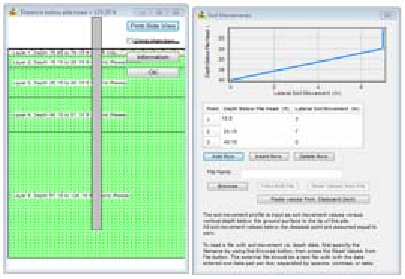


Hill Ferry Road Seismic Retrofit
Possible Analysis Cases – Frame-1

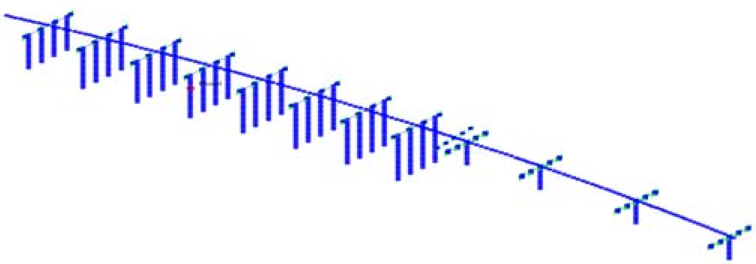
EAST BANK 100% LATERAL SPREAD + BENT 7 to Abut 19 ELASTIC



LPILE ANALYSIS

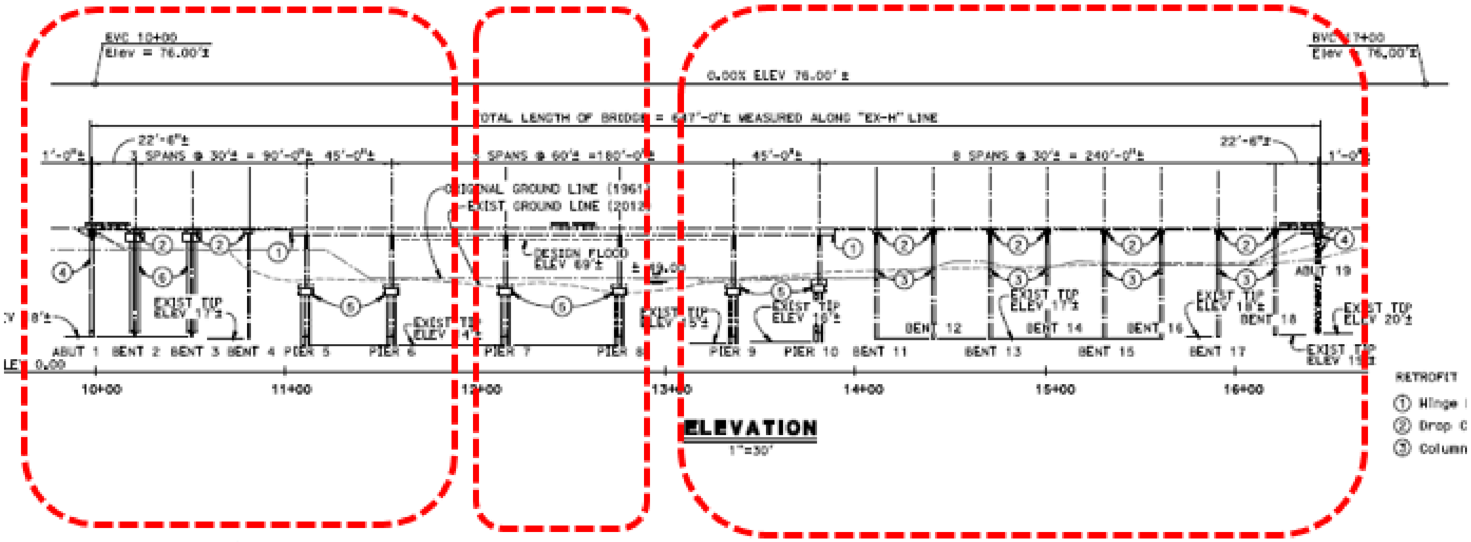


CSi BRIDGE ANALYSIS – FOR STIFFNESS

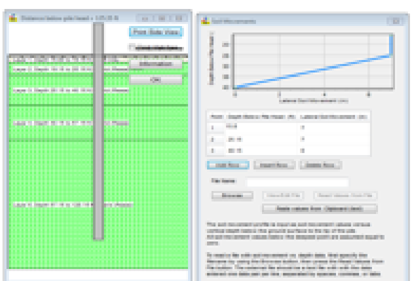


Hill Ferry Road Seismic Retrofit
Possible Analysis Cases – Frame-1

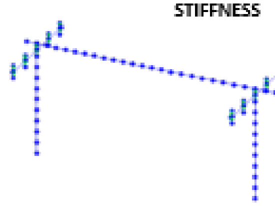
EAST BANK 100% LATERAL SPREAD + Bent 7 & 8 – ELASTIC + WEST BANK 100% LATERAL SPREAD



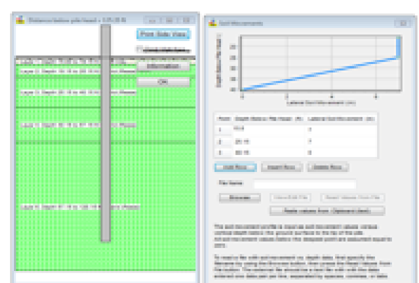
LPILE ANALYSIS



CSi BRIDGE ANALYSIS – FOR STIFFNESS



LPILE ANALYSIS



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HILL FERRY ROAD SEISMIC RETROFIT
BALANCED FRAME DISPLACEMENTS

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JOB NO. 710072
SHEET NO.
MADE BY Ahilan.S DATE 2/9/2016
CHECKED BY DATE

JOB DESCRIPTION Hills Ferry Road Bridge over the San Joaquin River
CALCULATION FOR Global Analysis Model - Applied Lateral Spreading Demands - Restrained Model - 12 Inch LS Load

EAST BANK SLIDE (LPILE ANALYSIS) + REACTION FROM P7 to A19 & EAST BANK SLIDE (LPILE ANALYSIS) + REACTION FROM P7 to P8 + WEST BANK SLIDES (LPILE ANALYSIS)

EAST BANK SLIDE (LPILE ANALYSIS) + REACTION FROM P7 to P8 + WEST BANK SLIDES (LPILE ANALYSIS)

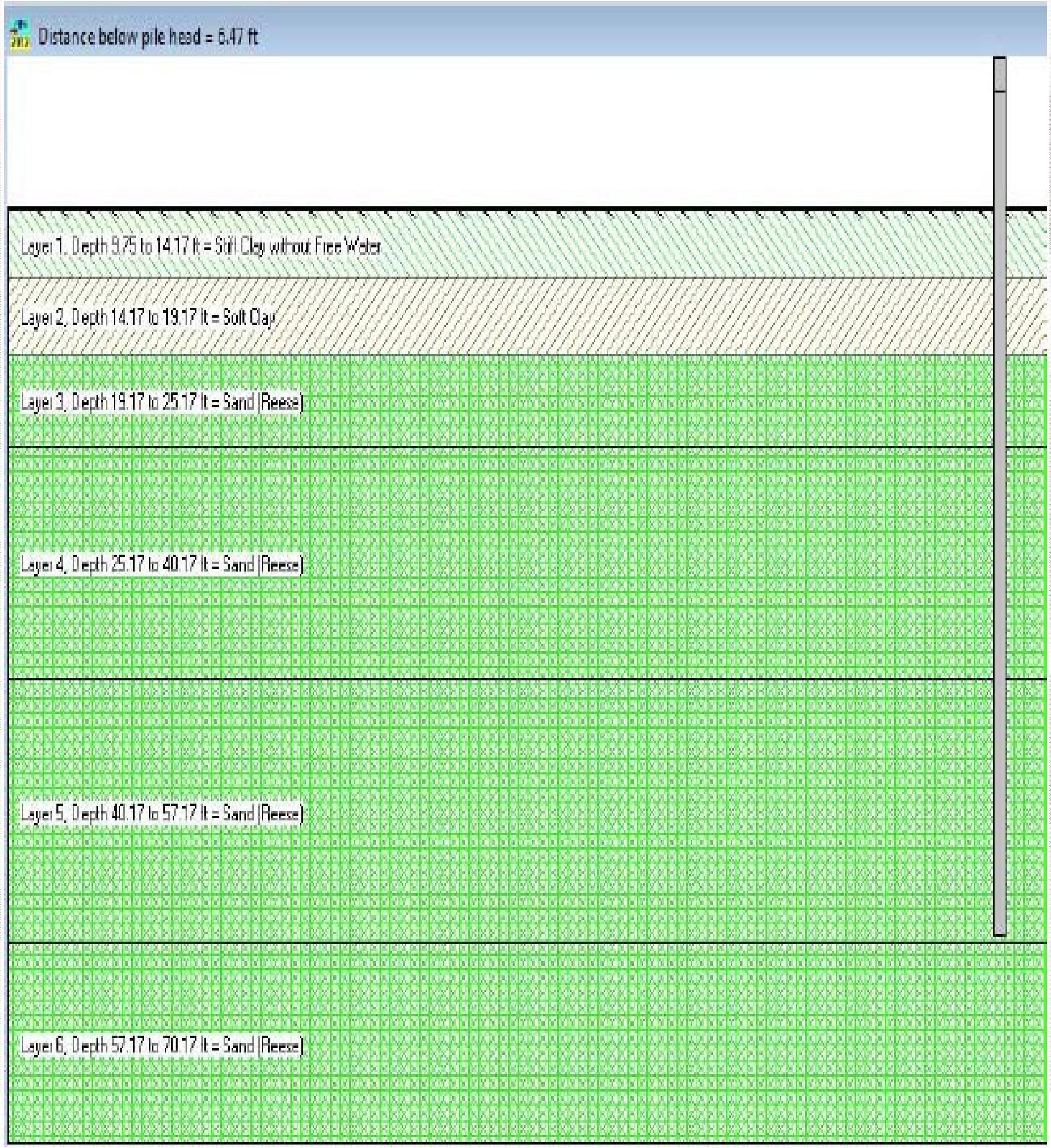
Folder: P:\710072 - Hills Ferry\Engineering\Bridge\2016-02-Restrained Model-AS\CSi Bridge

P:	1000	kips
D:	34.95	in
K:	28.6123	kip/in
P net:	0	lbs
Δ:	0	in

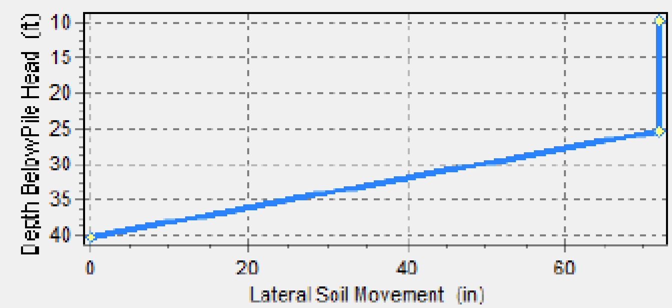
	EAST BANK						PIER 7 & 8			WEST BANK										
	1	2	3	4	5	6	7	8		9	10	11	12	13	14	15	16	17	18	19
Δ Lpile (in)		1.20	1.20	1.20	1.20	1.20				-1.20	-1.20	-1.20	-1.20	-1.20	-1.20	-1.20	-1.20	-1.20	-1.20	
Shear	-180000	-166354	-166386	-18102	-71386	-71386				-183007	-183007	-8072.95	-8651.09	-8651.09	-8651.09	-8651.09	-8651.09	-14526	-41243	-180000
Total Shear						-673614	P net:	20502.58	lbs											-653111
Reaction Frame Δ							Δ:	0.716565	in											
Δ Lpile (in)		1.00	1.00	1.00	1.00	1.00				-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	
Shear	180000	-166500	-166528	-18873	-73110	-71386				-183093	-183093	-7282.13	-7866.22	-7866.22	-7866.22	-7866.22	-7866.22	-13773	-40696	180000
Total Shear						-316397	P net:	29128.79	lbs											-287268
Reaction Frame Δ							Δ:	1.018051	in											
Δ Lpile (in)		1.00	1.00	1.00	1.00	1.00				-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	
Shear	180000	-166500	-166528	-18873	-73110	-71386				-183093	-183093	-7282.13	-7866.22	-7866.22	-7866.22	-7866.22	-7866.22	-13773	-40696	180000
Total Shear						-316397	P net:	29128.79	lbs											-287268
Reaction Frame Δ							Δ:	1.018051	in											

	1	2	3	4	5	6
Shear (Mid LQ Soil)	180000	165356	165395	17453	144611	144611
Shear (Bott LQ Soil)	180000	59995	59940	54361	282969	282969
Retrofit Pile Shear		275954	296429		31567	31567
Total (Mid LQ Soil)	180000	441310	461824	17453	176178	176178

HILL FERRY ROAD SEISMIC RETROFIT
LPILE ANALYSIS



Soil Movements



Point	Depth Below Pile Head (ft)	Lateral Soil Movement (in)
1	9.75	72
2	25.17	72
3	40.17	0

Add Row | Insert Row | Delete Row

File Name:

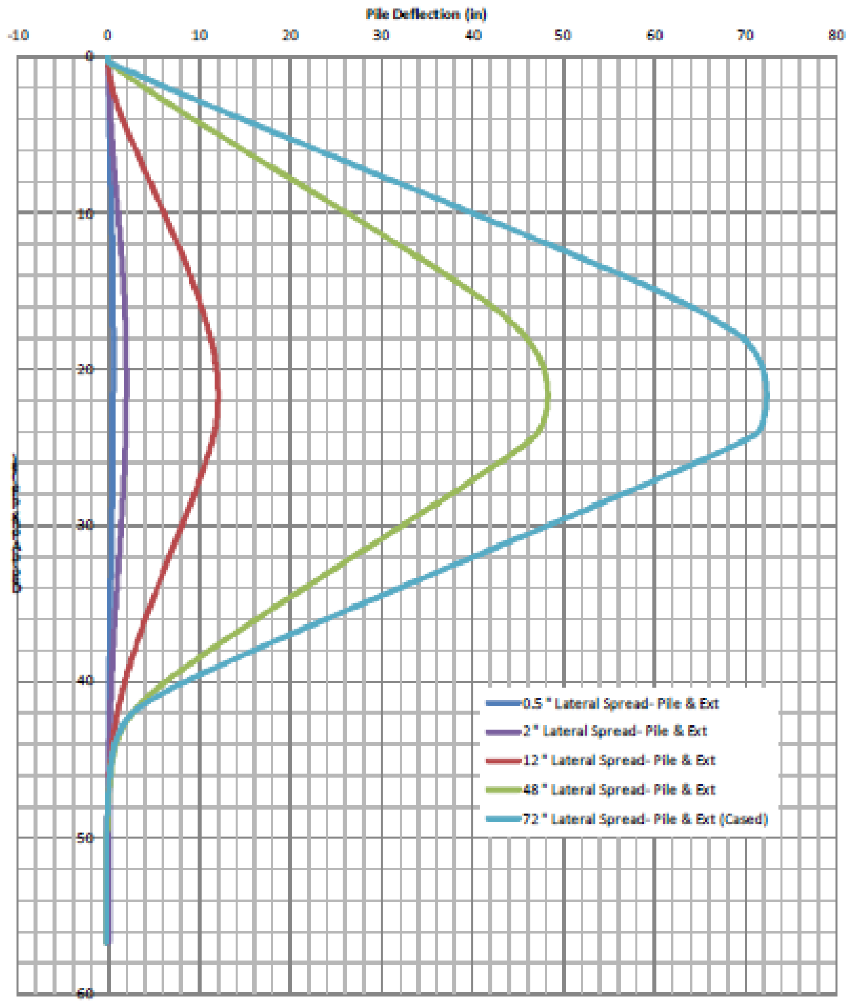
Browse | View/Edit File | Read Values from File

Paste values from Clipboard (text)

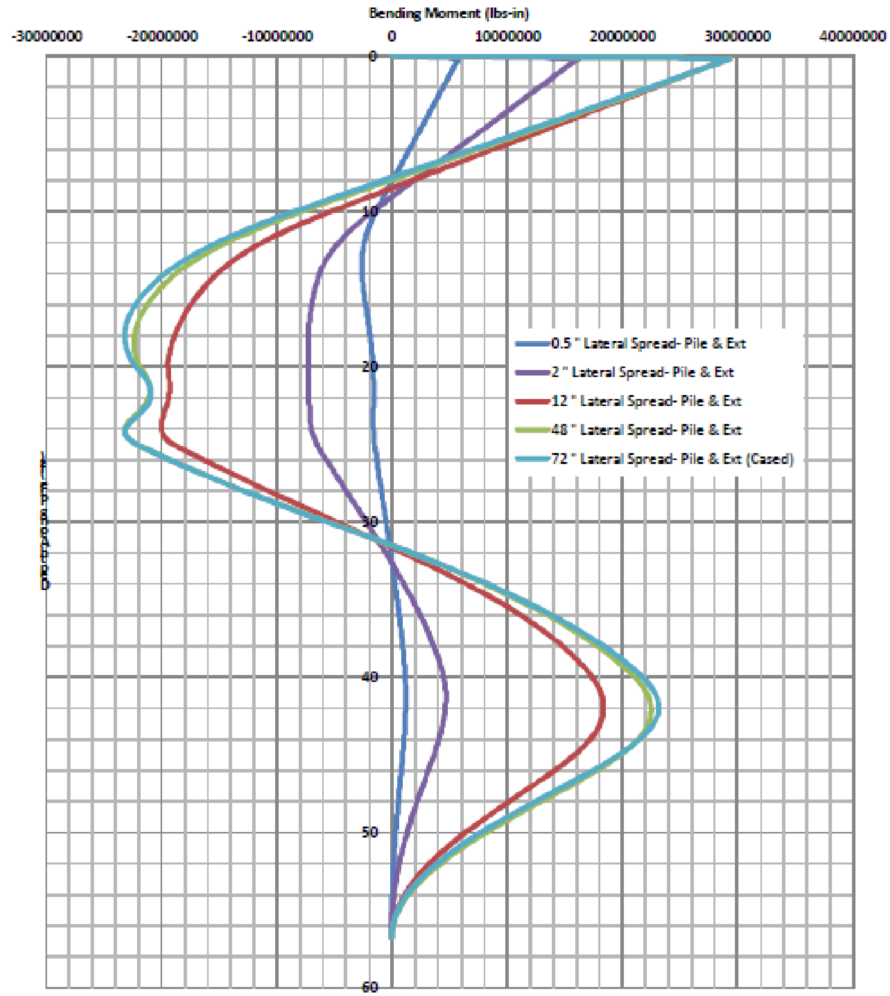
The soil movement profile is input as soil movement values versus vertical depth below the ground surface to the tip of the pile.
All soil movement values below the deepest point are assumed equal to zero.

To read a file with soil movement vs. depth data, first specify the filename by using the Browse button,then press the Read Values from File button.
The external file should be a text file with with the data entered one data pair per line, separated by spaces, commas, or tabs.

Hill Ferry Road Seismic Retrofit
Unrestrained Analysis

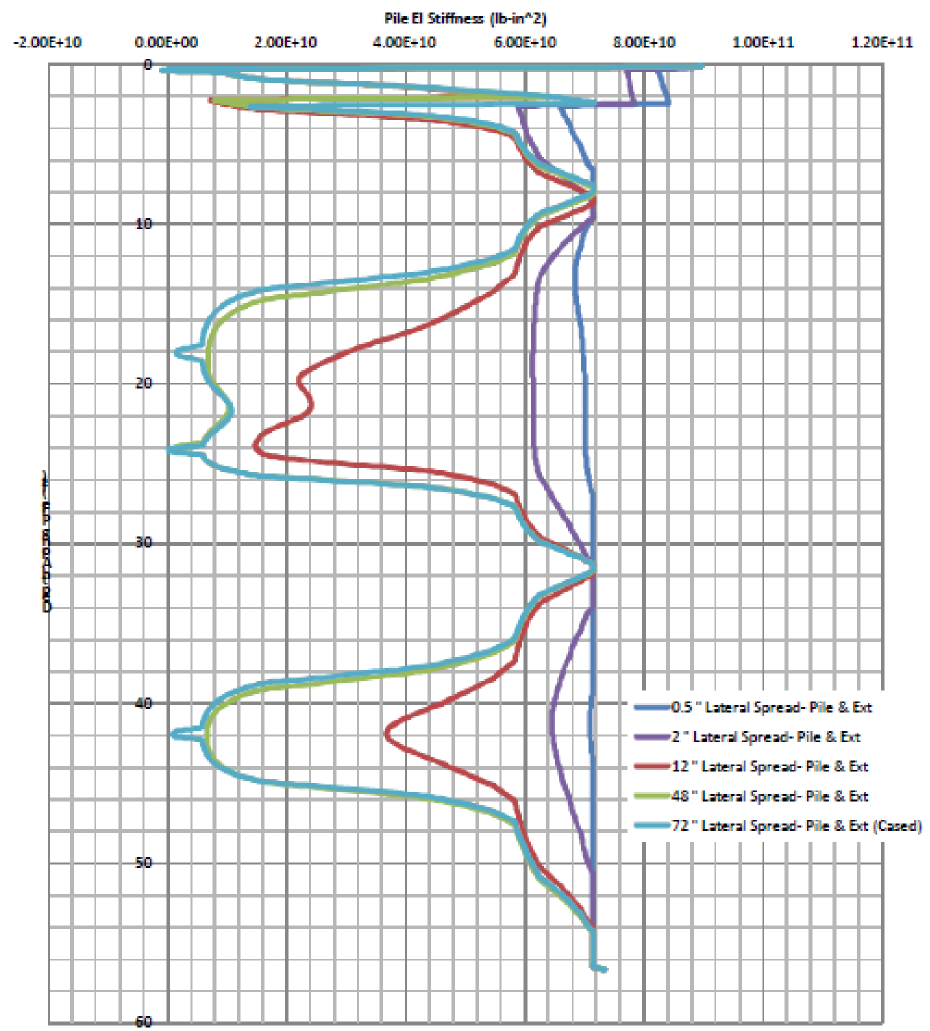


Pier 2-4 - Lateral Spread Displacement (no corrosion)

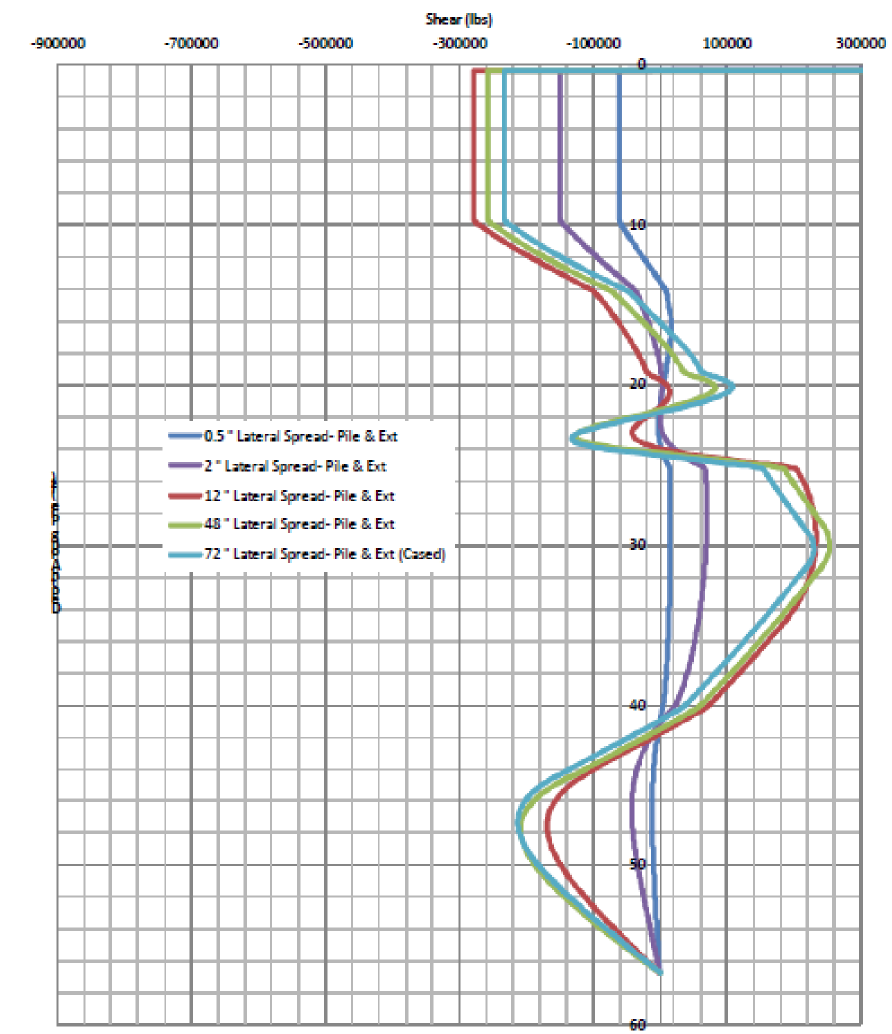


Pier 2-4 - Bending Moment (no corrosion)

Hill Ferry Road Seismic Retrofit
LPILE Results

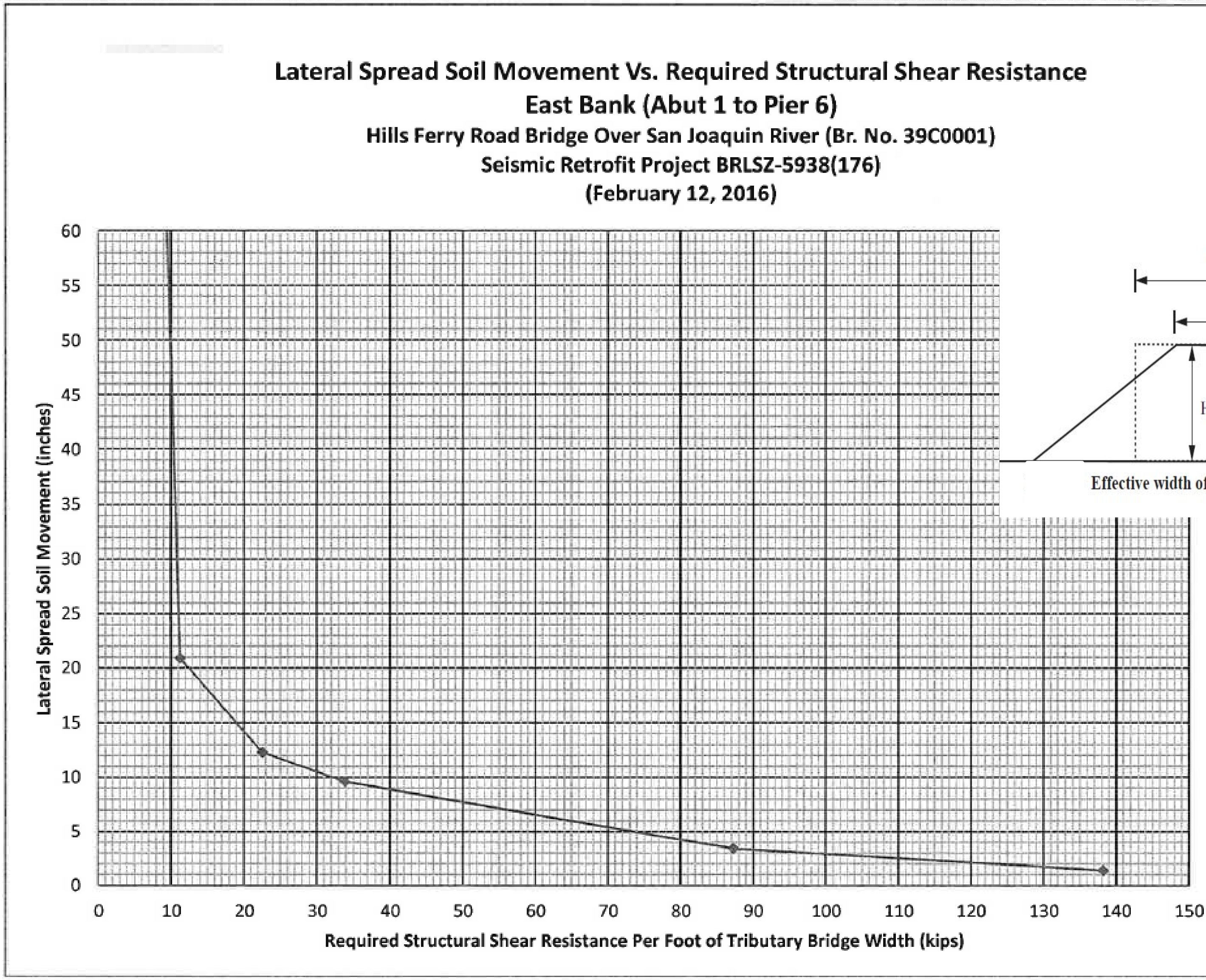


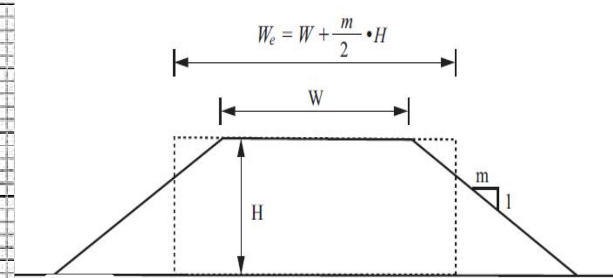
Pier 2-4 - Bending Stiffness (no corrosion)



Pier 2-4 - Shear (no corrosion)

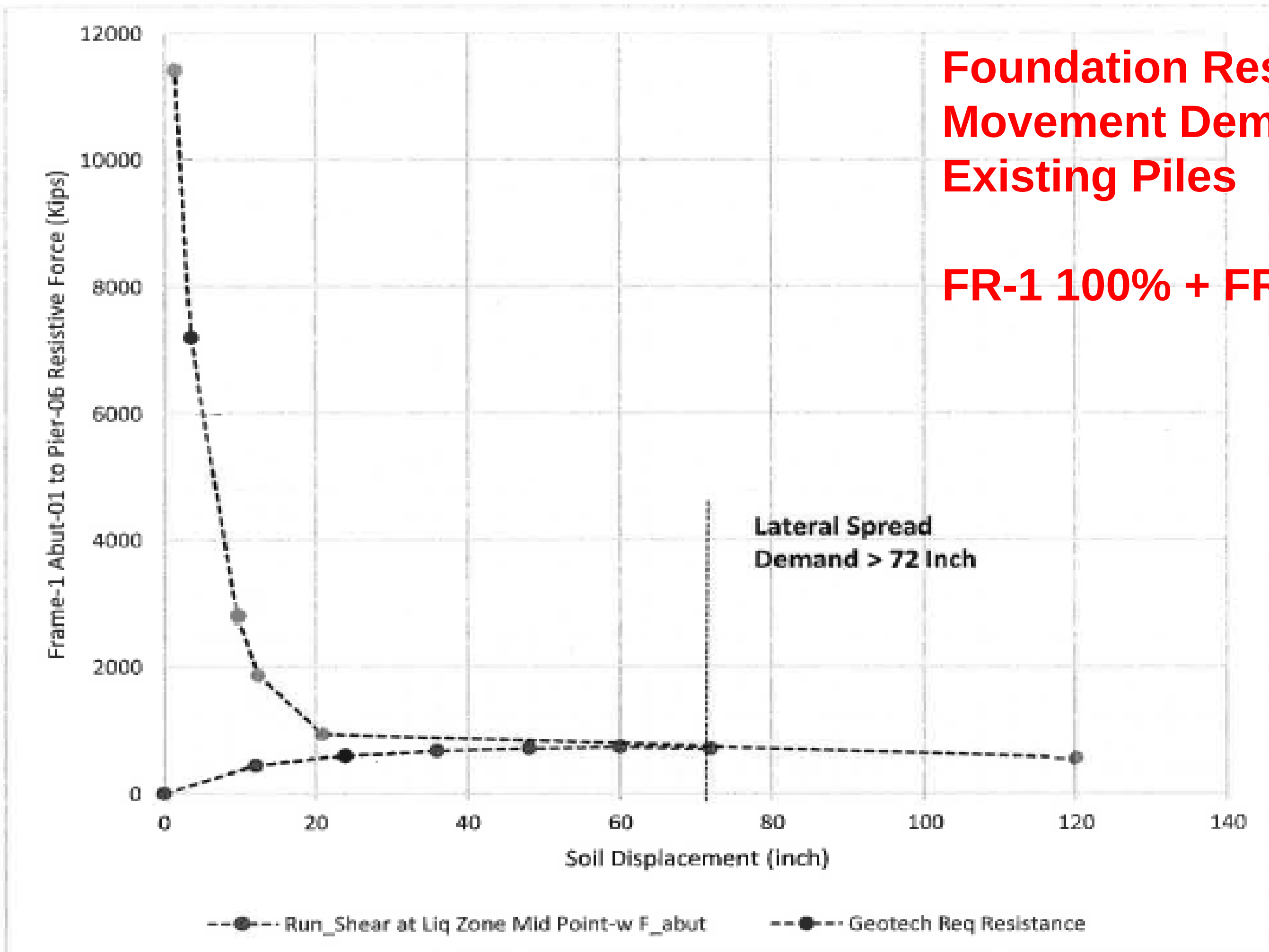
Hill Ferry Road Seismic Retrofit Restrained Analysis -





Effective width of embankment mass for abutment loading

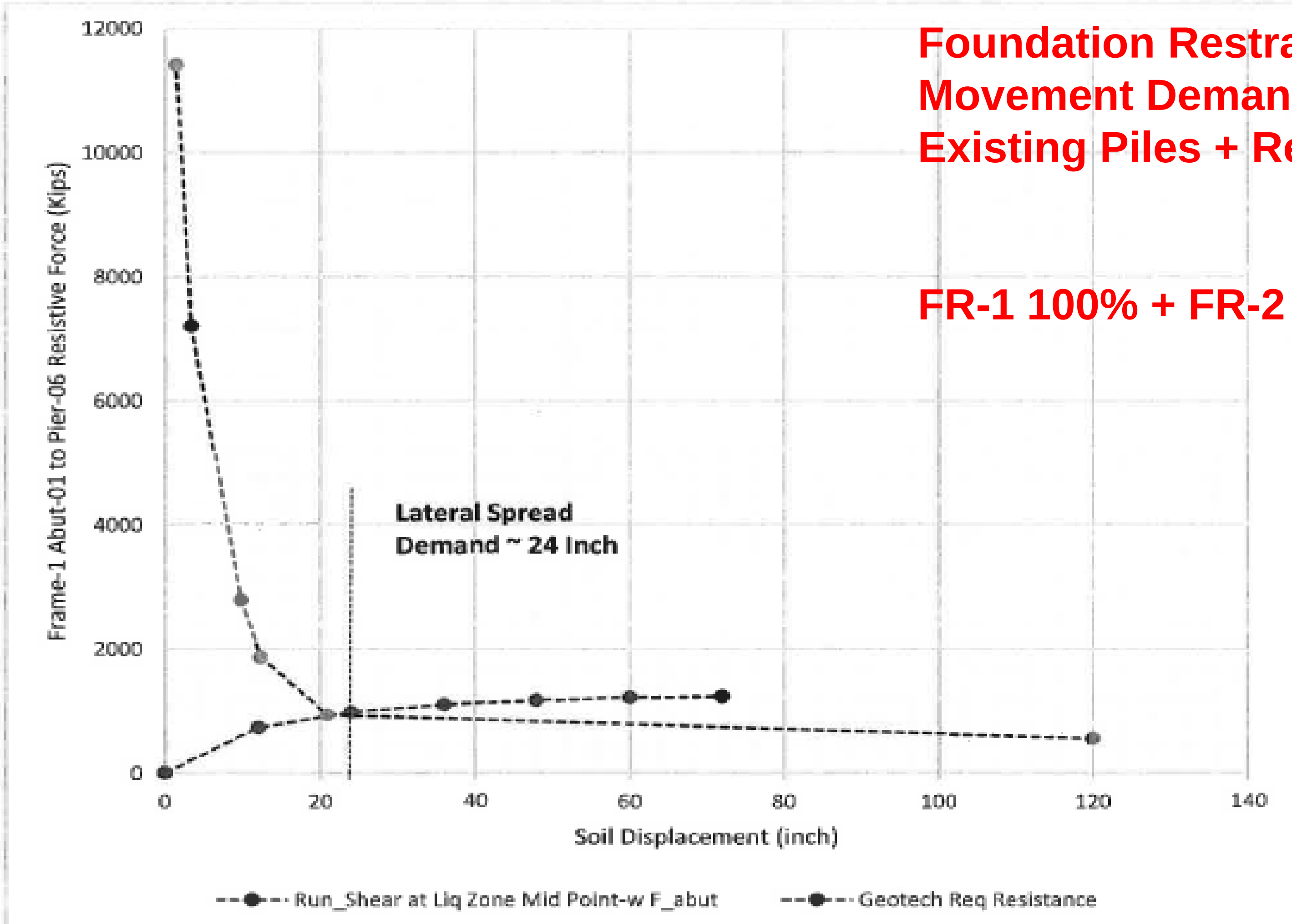
HILL FERRY ROAD SEISMIC RETROFIT
RESTRAINED ANALYSIS



Foundation Restrained Soil Movement Demand – With Existing Piles

FR-1 100% + FR-2 & 3 Elastic

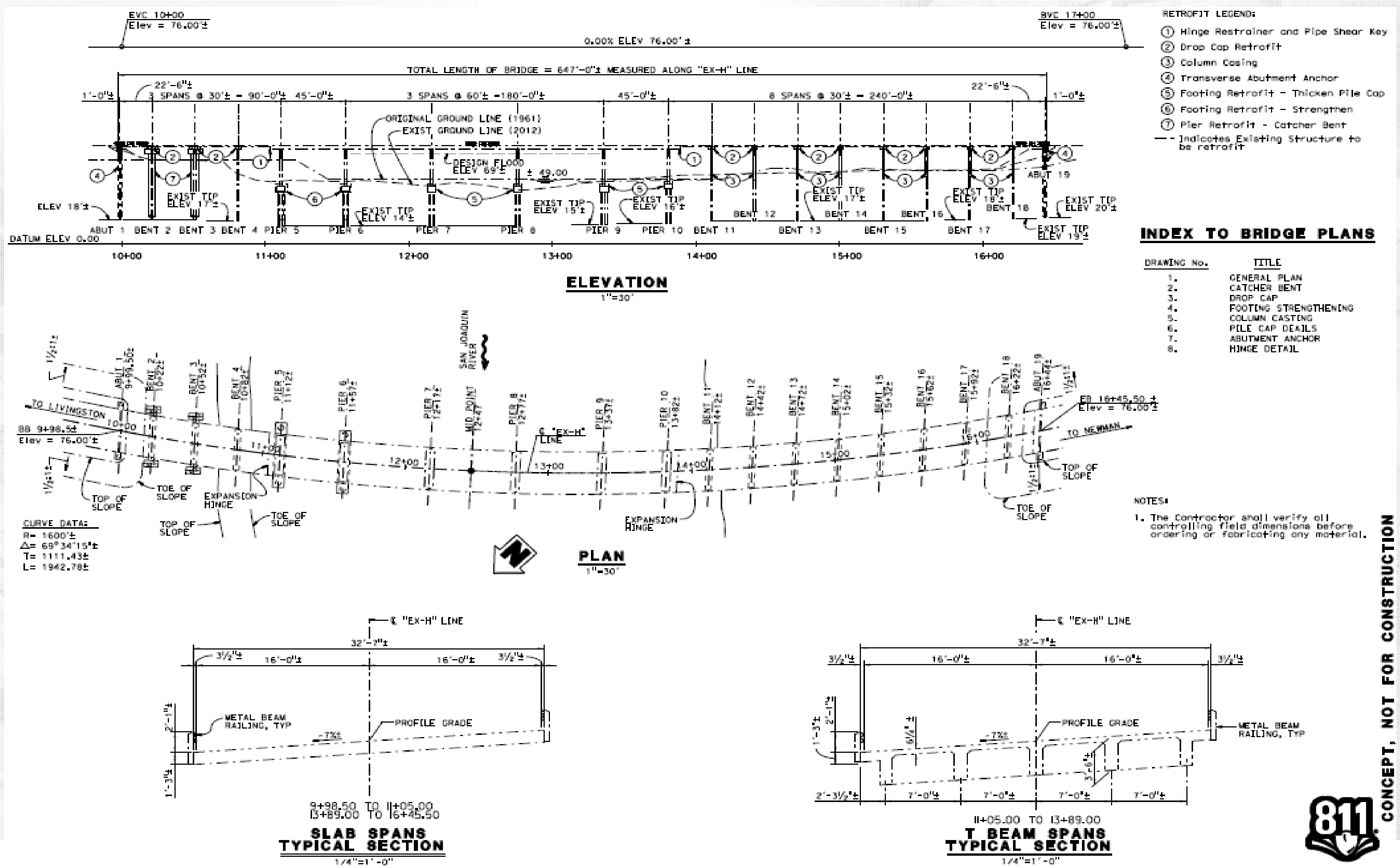
Hill Ferry Road Seismic Retrofit Restrained Analysis



Foundation Restrained Soil Movement Demand – With Existing Piles + Retrofit Piles

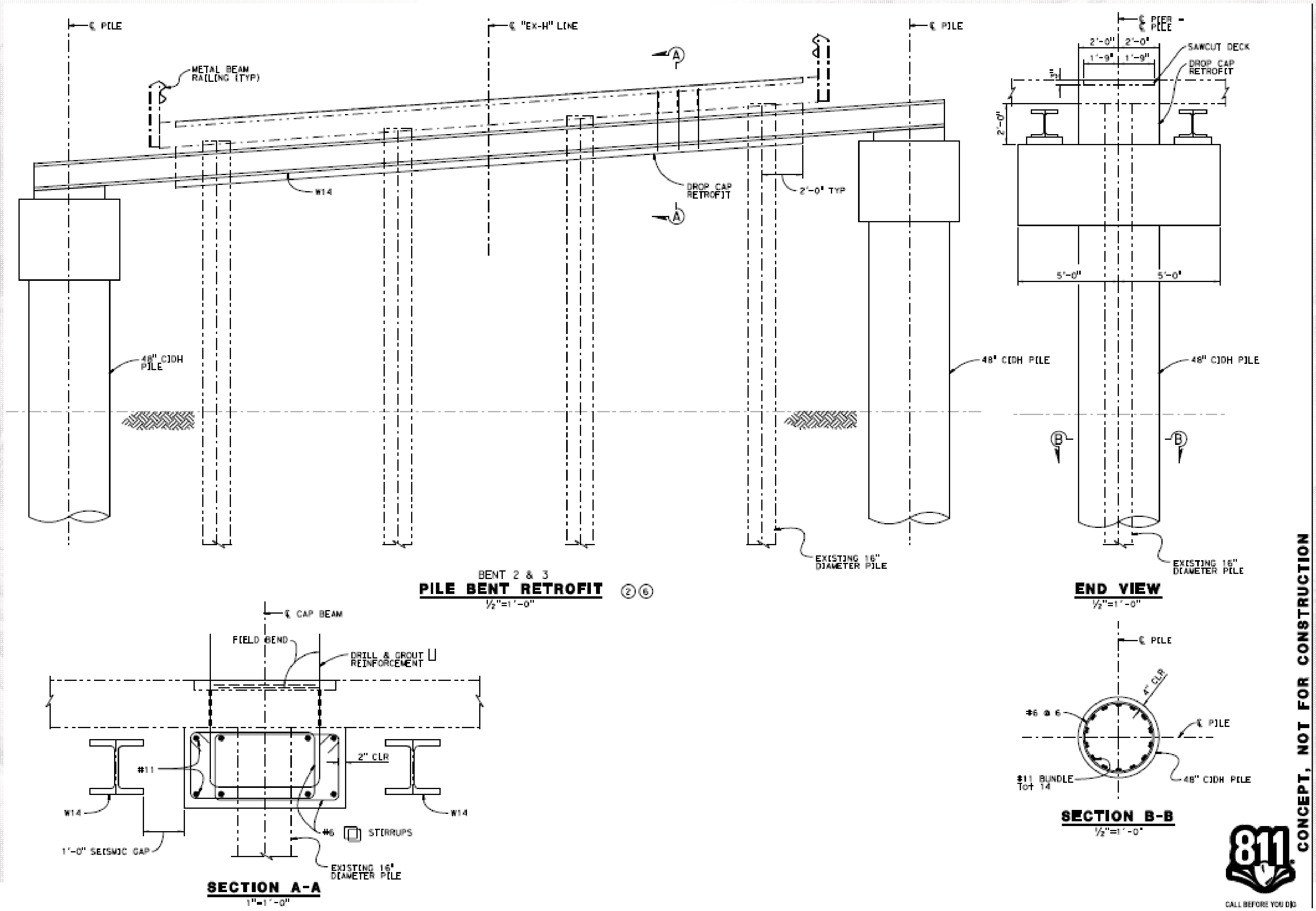
FR-1 100% + FR-2 & 3 Elastic

Hill Ferry Road Seismic Retrofit
Preliminary Retrofit Details



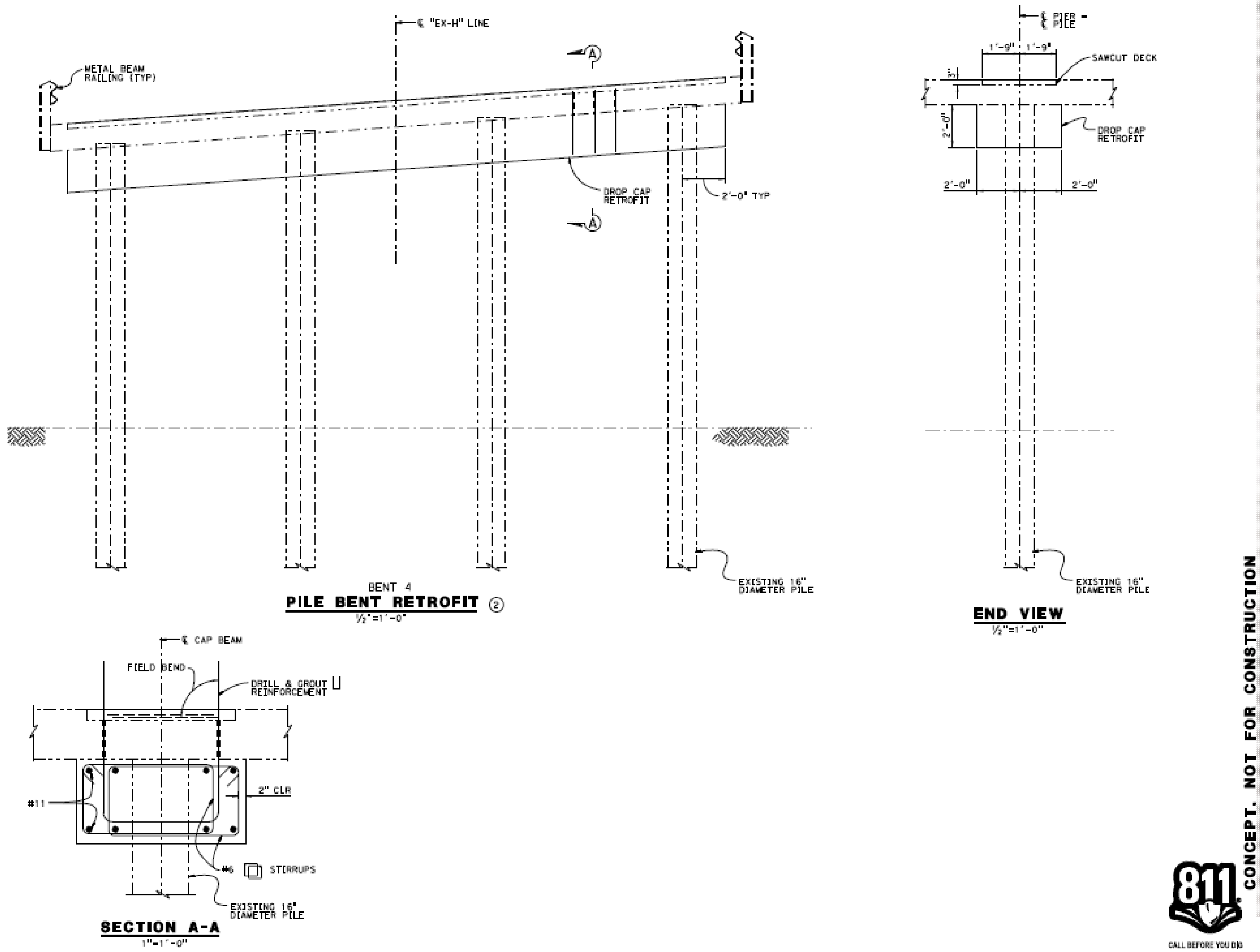
HILL FERRY ROAD SEISMIC RETROFIT

PRELIMINARY RETROFIT DETAILS – BENT 2 & 3



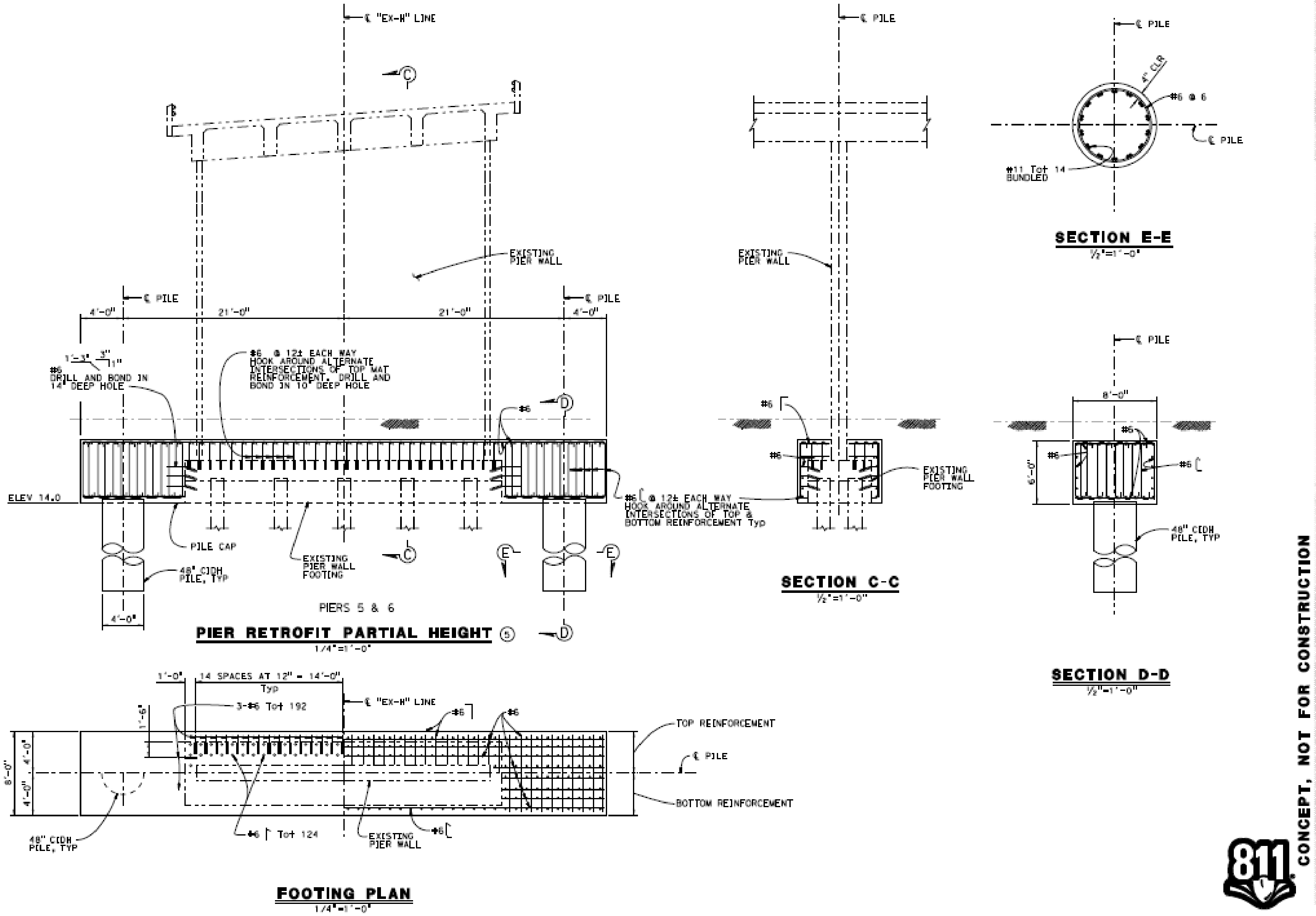
HILL FERRY ROAD SEISMIC RETROFIT

PRELIMINARY RETROFIT DETAILS – BENT 4



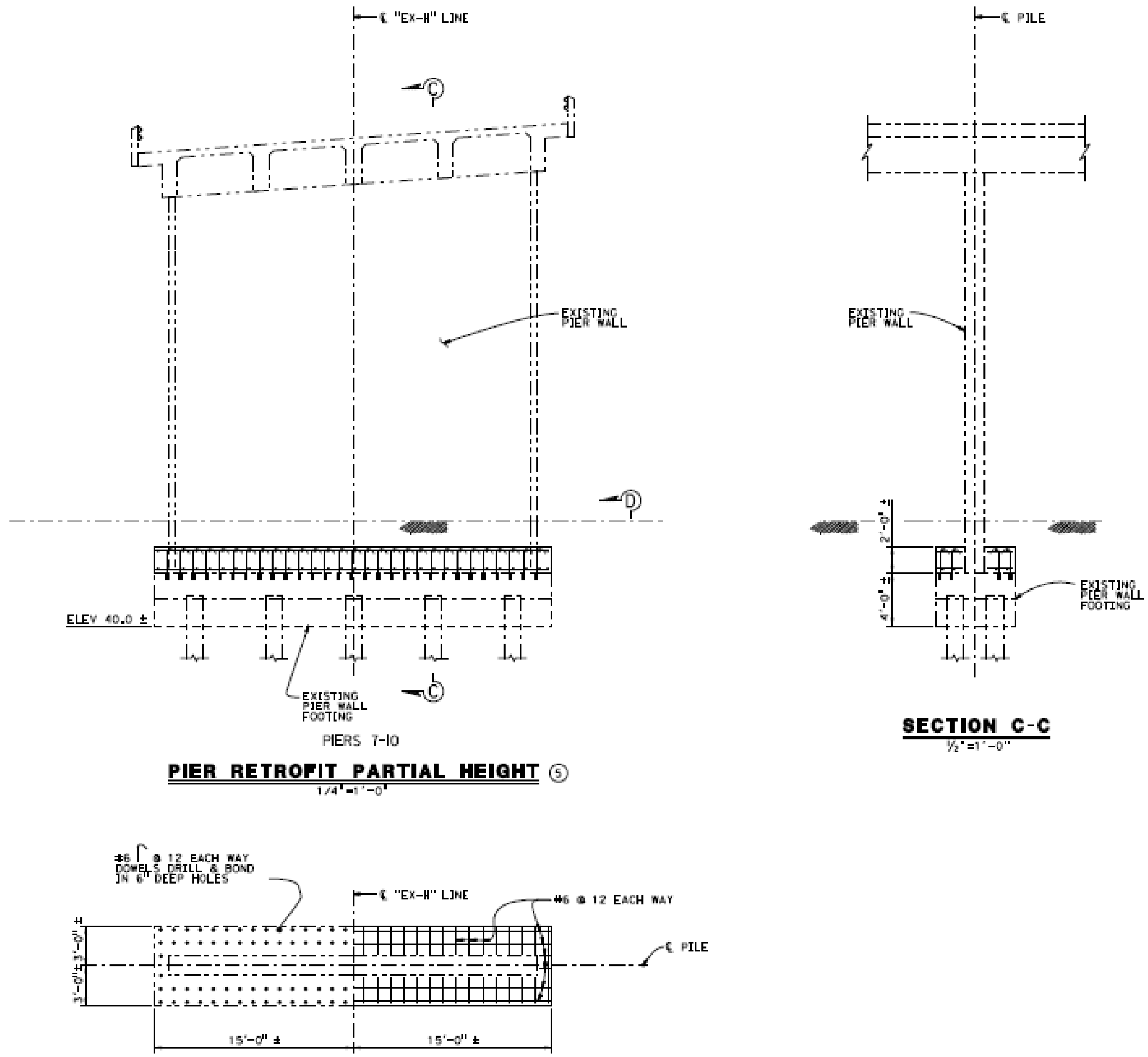
HILL FERRY ROAD SEISMIC RETROFIT

PRELIMINARY RETROFIT DETAILS – PIER 5 & 6



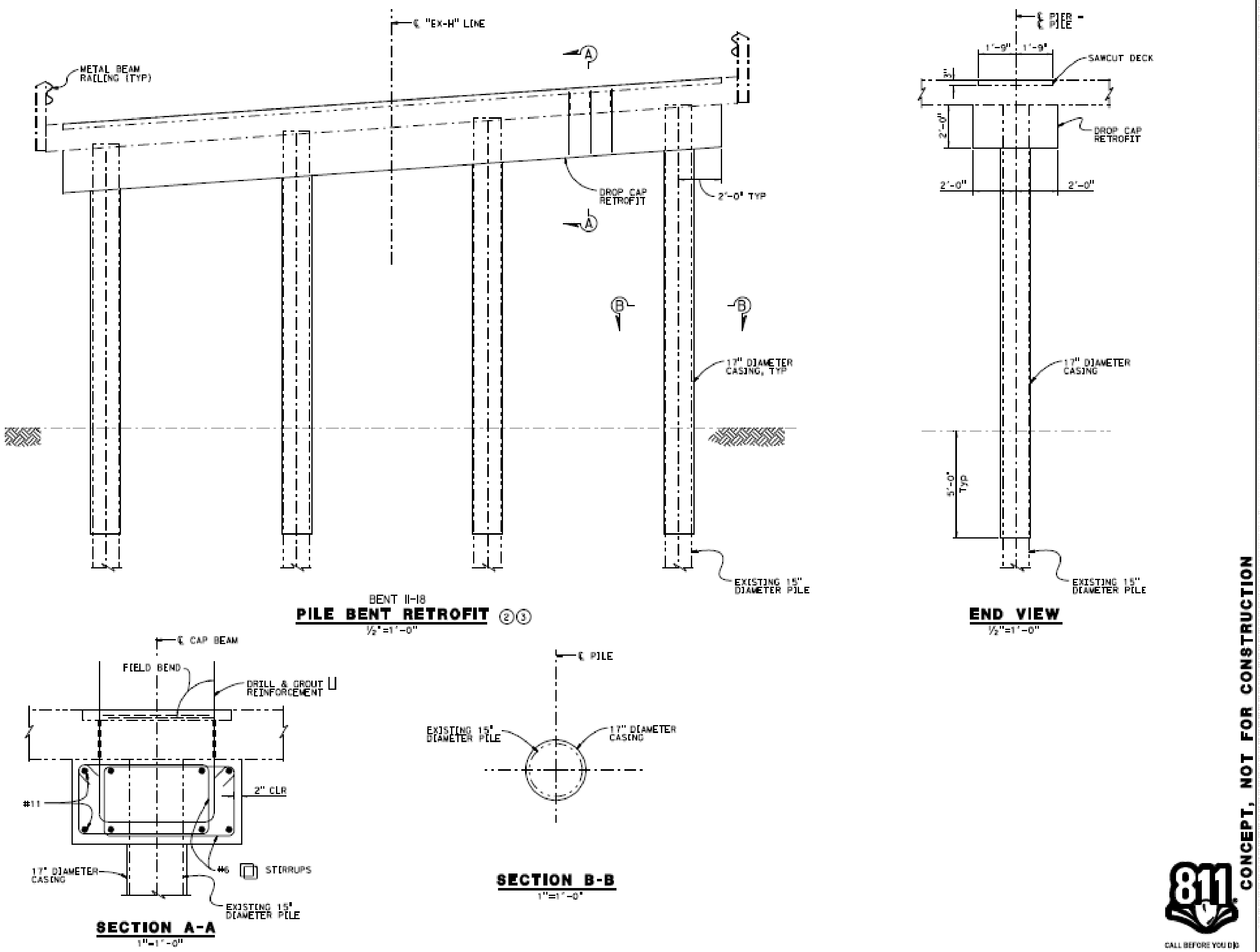
Hill Ferry Road Seismic Retrofit

Preliminary Retrofit Details – Pier 7-10



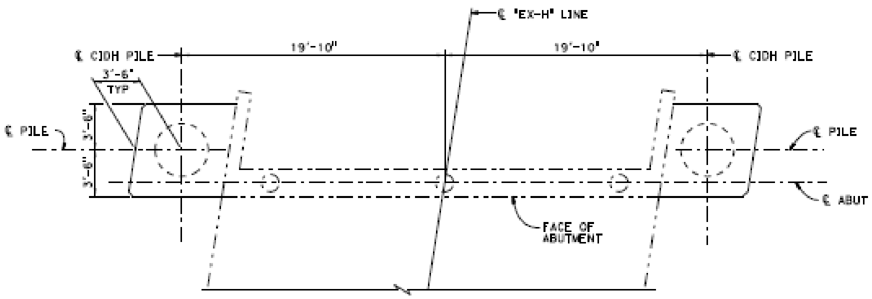
HILL FERRY ROAD SEISMIC RETROFIT

PRELIMINARY RETROFIT DETAILS – BENT 11 – 18

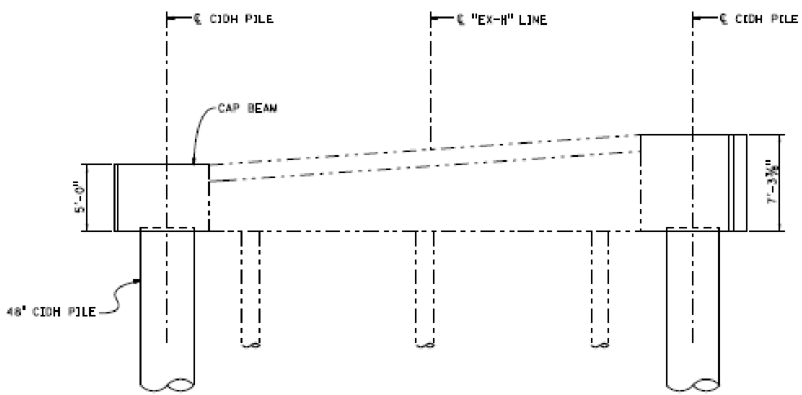


Hill Ferry Road Seismic Retrofit

Preliminary Retrofit Details – Abut 1 & 19

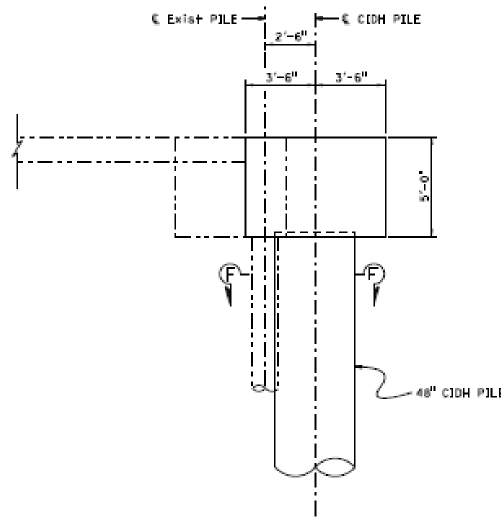


PLAN
¼"=1'-0"

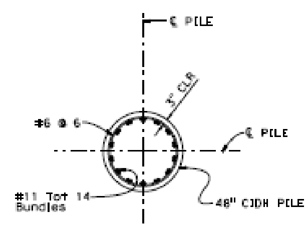


ABUTMENT RETROFIT - ELEVATION (4)
¼"=1'-0"

NOTE:
1. ABUTMENT 1 SHOWN, ABUTMENT 19 SIMILAR.



END VIEW
⅜"=1'-0"



SECTION F-F
⅜"=1'-0"

OUTLINE

- Introduction
- Unrestrained Ground Displacement
- Foundation Restrained Ground Displacement
- Analysis Procedures
- Example
- **Conclusion**

CONCLUSION

- **Conservatism when designing or Retrofitting Bridges in Liquefiable / Lateral Spreading Soil Can Result in Unnecessary Cost**
- **Well- Designed Bridges May Experience Damage Due to Soil Liquefaction During The Earthquake But They Are Not Expected To Collapse.**
- **Restrained Analysis Case, Bridge plays Major Role In Reducing Displacement**
- **Refined Analysis Reduce Conservatism**

QUESTIONS & ANSWERS

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