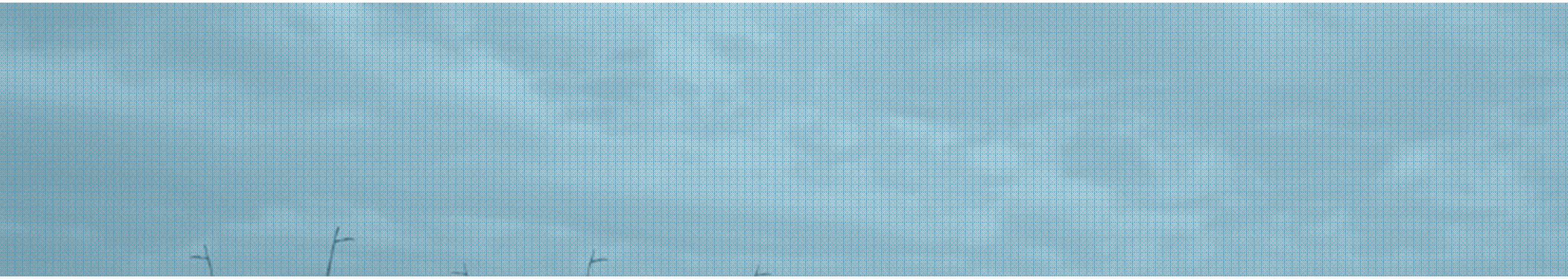

Seismic Design Challenges of the West Mission Bay Drive Bridge Replacement

2017 Western Bridge Engineers' Seminar

Kumar Ghosh, Ph.D., PE
Senior Bridge Engineer
T·Y·LIN INTERNATIONAL

Vicinity Map

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Location Map

- *US Fish and Wildlife*
- *Regional Water Board*
- *USACE*
- *Coastal Commission*
- *Parks and Recs*
- *City of San Diego*
- *Caltrans*

Why a new bridge?

Seismic Impacts on Bridge Foundation Design

Column-Pile Shaft Pin Details

Pile Shaft Optimization – Structure Performance and Cost

Agenda

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Why a New Bridge?

- Functionally Obsolete (FO) and Structurally Deficient (SD)

Existing Bridge Information

- Built in 1950
- Four 12' travel lanes (2 each direction)
- Current and future daily traffic volume on bridge exceeds current capacity
- Need to match desired lane configurations on both sides
- Barrier separated 5' sidewalks
- Existing foundation is not sufficient for seismic event - Concrete pier walls on timber piles (30'-45' in length)

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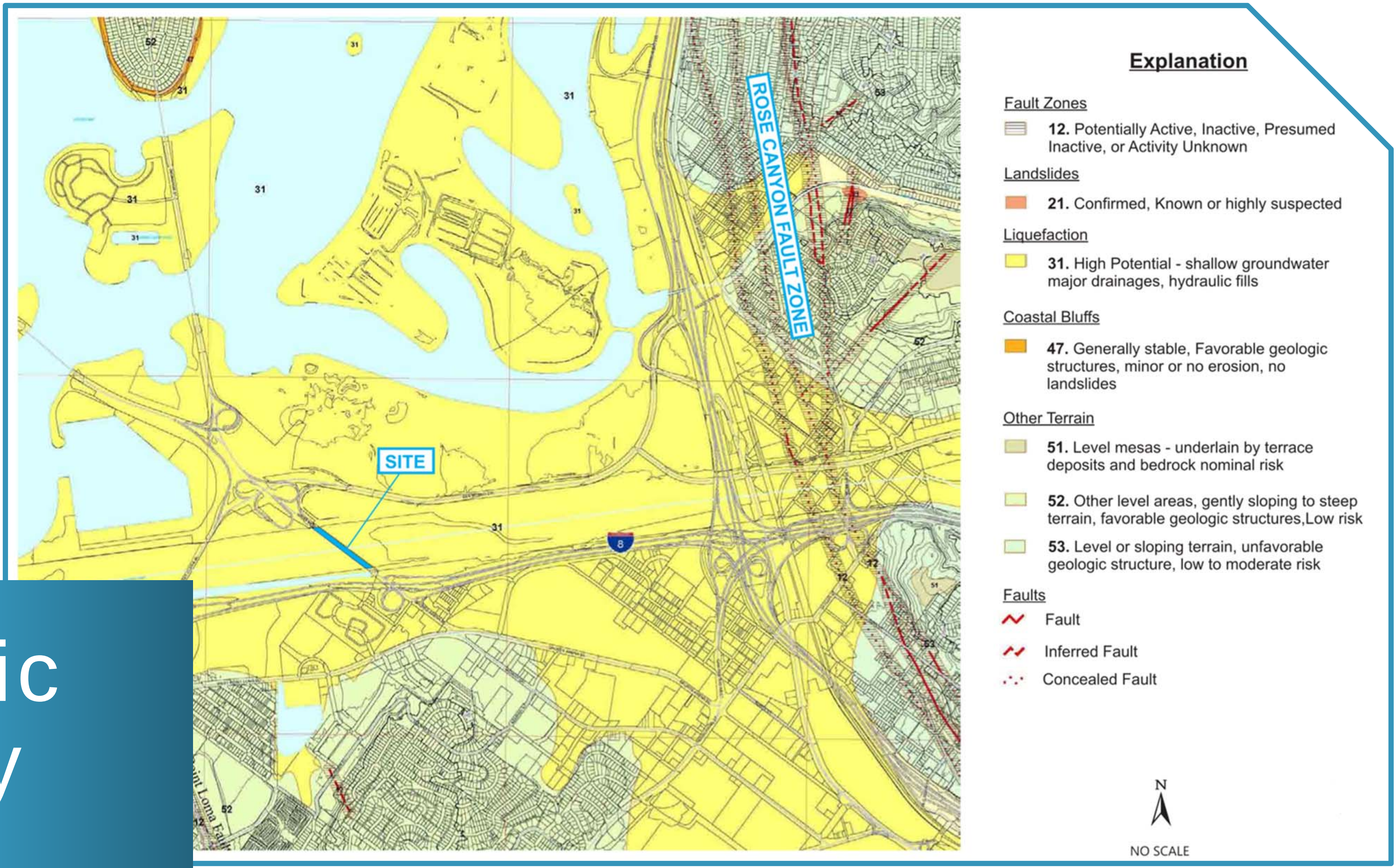
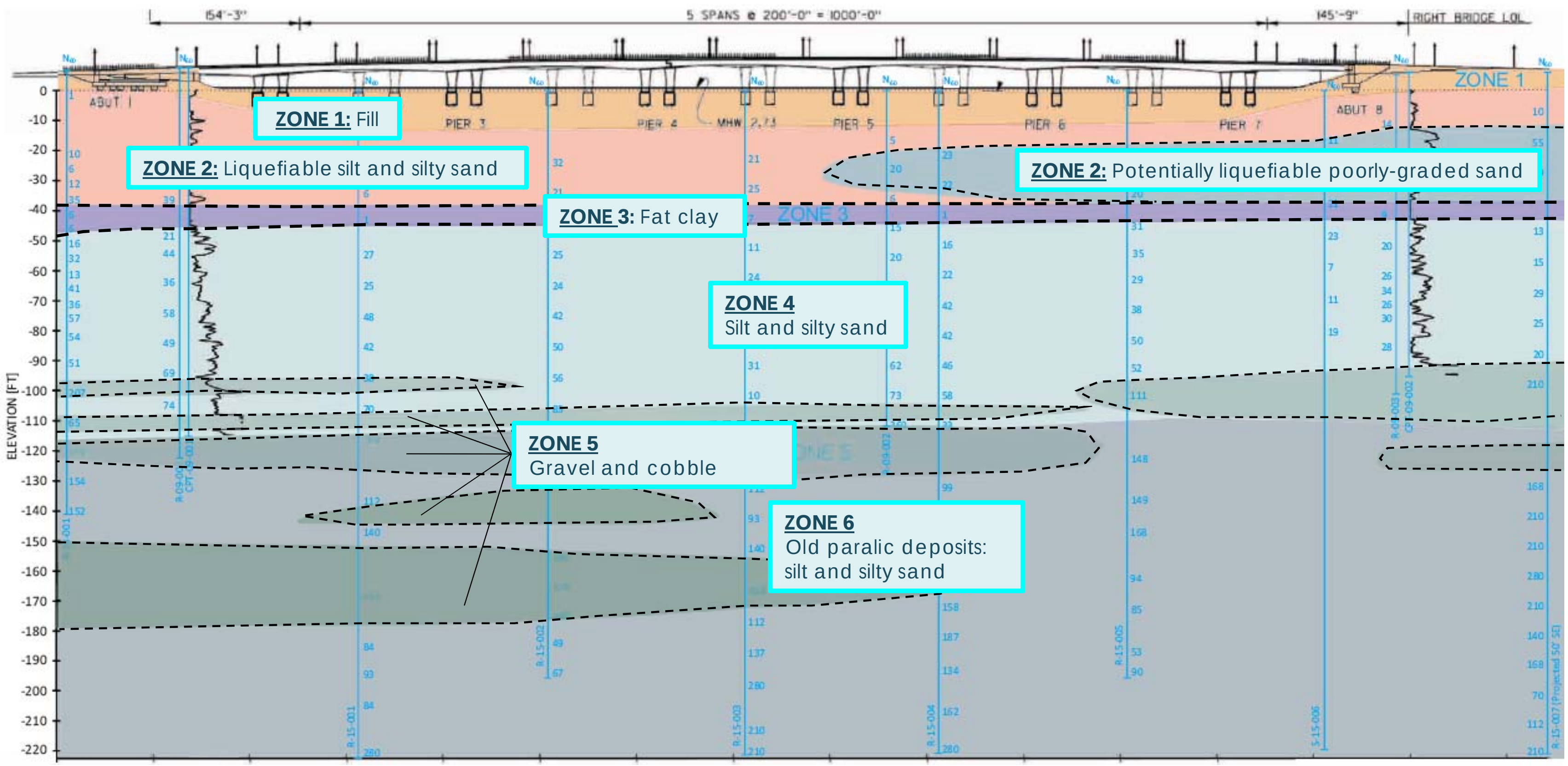


Seismic Safety Map

Soil Characterization



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Project History

Project Timeline

WIDENING VS. REPLACEMENT

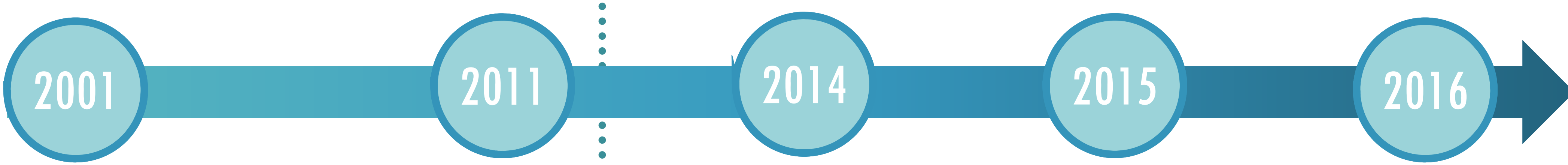
- Widen + Rehab
- ***Replacement***

ALIGNMENTS

- 1
- 2A
- 2B
- ***2C***
- 2D
- 3

HIGH-COST BRIDGE REPORT

- Cast-in-place box
- Steel girder
- Precast girder
- Sliced girder
- ***Haunched box***



TYPE SELECTION

- 5-span
- 6-span
- ***7-span***
- 9-span

FOUNDATION STUDY

- Type 1 Shaft F-F
- Type 1 Shaft P-F
- Type 2 Shaft F-F
- ***Type 2 Shaft F-P***
- Type 2 Shaft P-F

FINAL DESIGN

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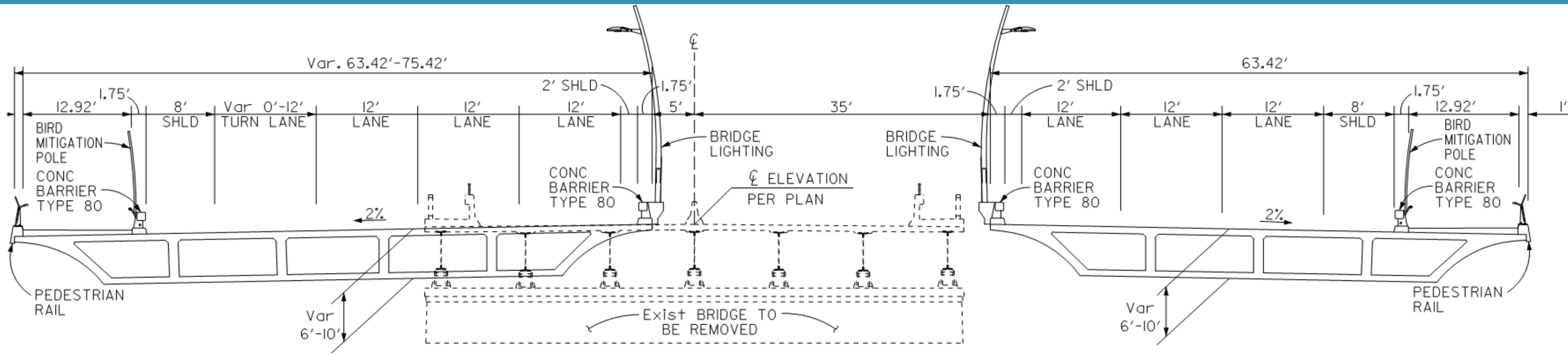
Stage Construction

WIDEN & REPLACE BRIDGE WITH SHIFT TO THE EAST (TWO STRUCTURES)



Bridge Configuration

Bridge Length	1,300’
Number of Spans	7
Number of Frames	2
Max Span Length	200’

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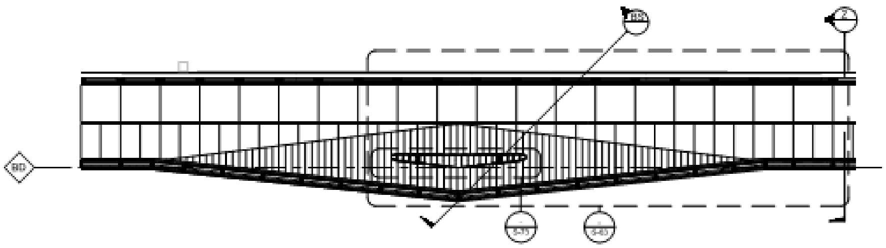
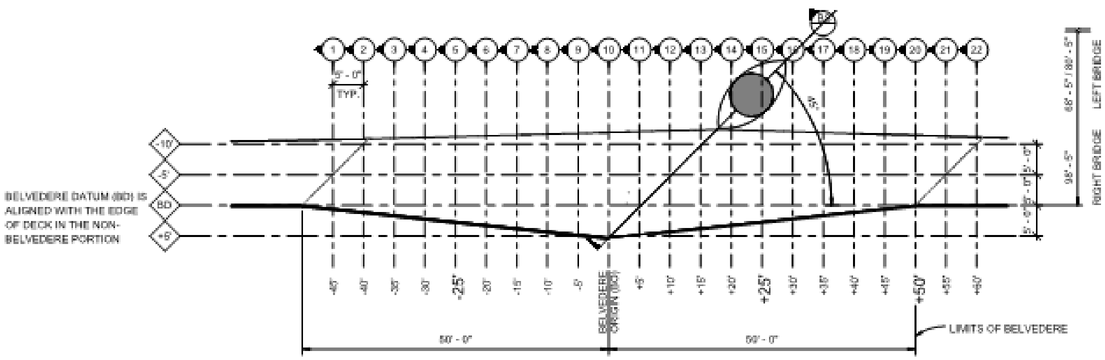
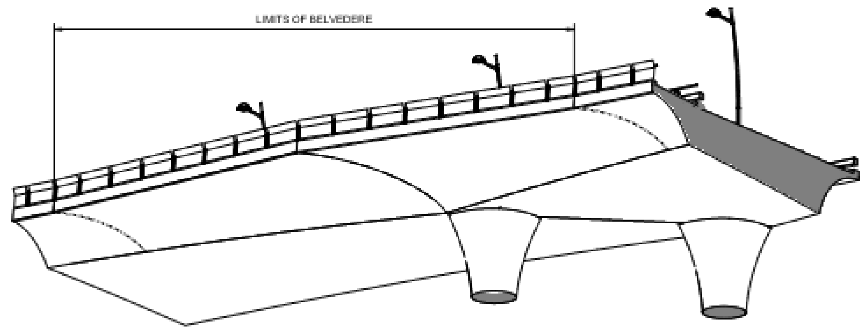


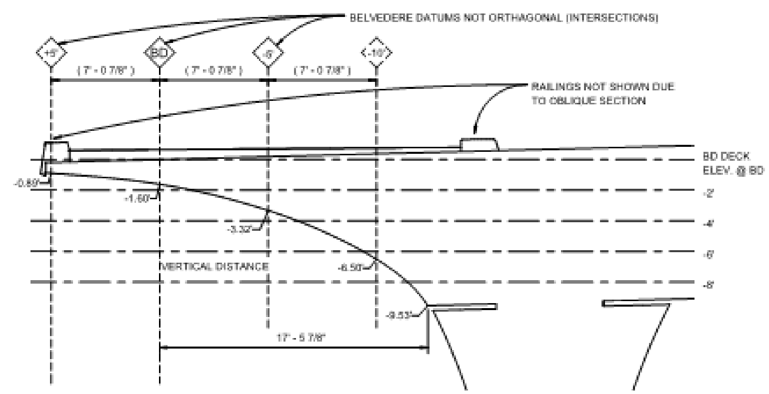
PLAN



BELVEDERE SOFFIT (RCP)
1" = 10'-0"



LIMITS OF BELVEDERE



BELVEDERE SEAM SECTION (BS)
1/4" = 1'-0"

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Why a new bridge?

Seismic Impacts on Bridge Foundation Design

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Pile Shaft Optimization – Structure Performance and Cost

Agenda

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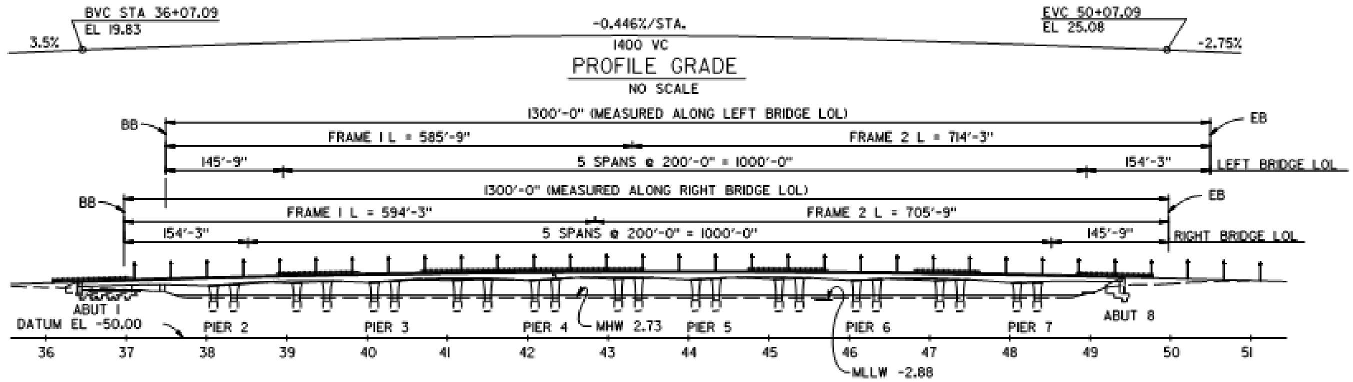
Seismic Challenges

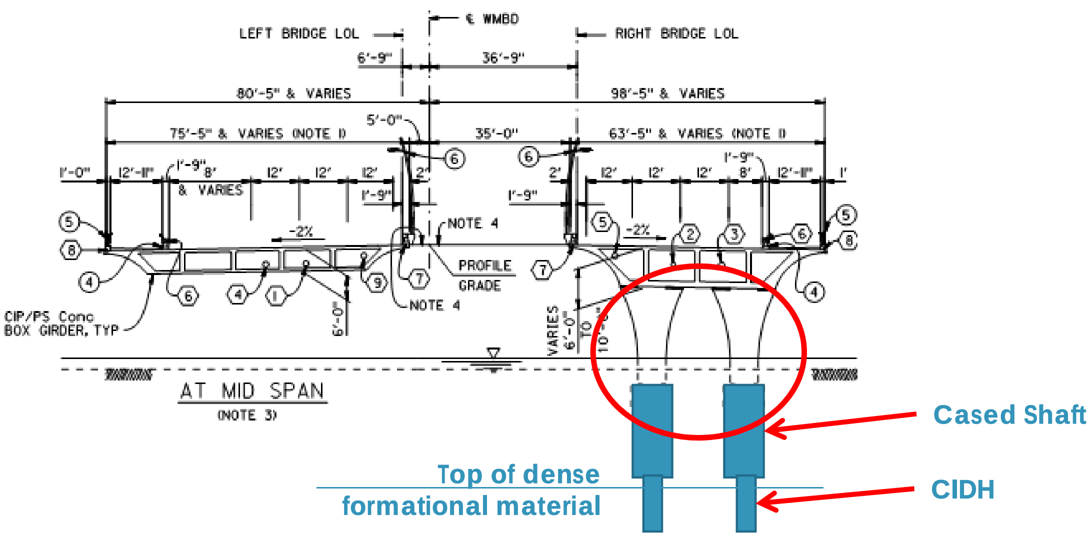
1. Design substructure for both liquefied and non-liquefied soil layers (shear critical short column for non-liquefied and flexure critical tall column for liquefied condition)
2. Design abutment for lateral spreading
3. Develop pin details between column and pile shaft
4. Satisfy all Caltrans MTD and SDC requirements – including new code updates

Geometry & Site Constraints

BRIDGE ELEVATION



BRIDGE SECTION



- Actual column height varies from 19’ to 27’ for non-liquefied soil conditions – does not satisfy height/diameter ratio of > than 4.0 (MTD 20-18 Draft) for fixed-fixed condition
- $P_{DL}/fc'Ag < 0.1$
- 30’ of liquefiable soil results in a longer effective column for liquefied condition – high moment demand on the pile shaft and design governed by lateral stability – requires permanent casing
- Axial resistance provided by the CIDH portion of shaft only – longer pile length

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Foundation Design: CIDH Piles with Permanent Steel Casing

PERMANENT STEEL CASING

- **Oscillator** or rotator recommended
- For constructability in loose caving soil
- For added structural bending strength
- Axial resistance ignored

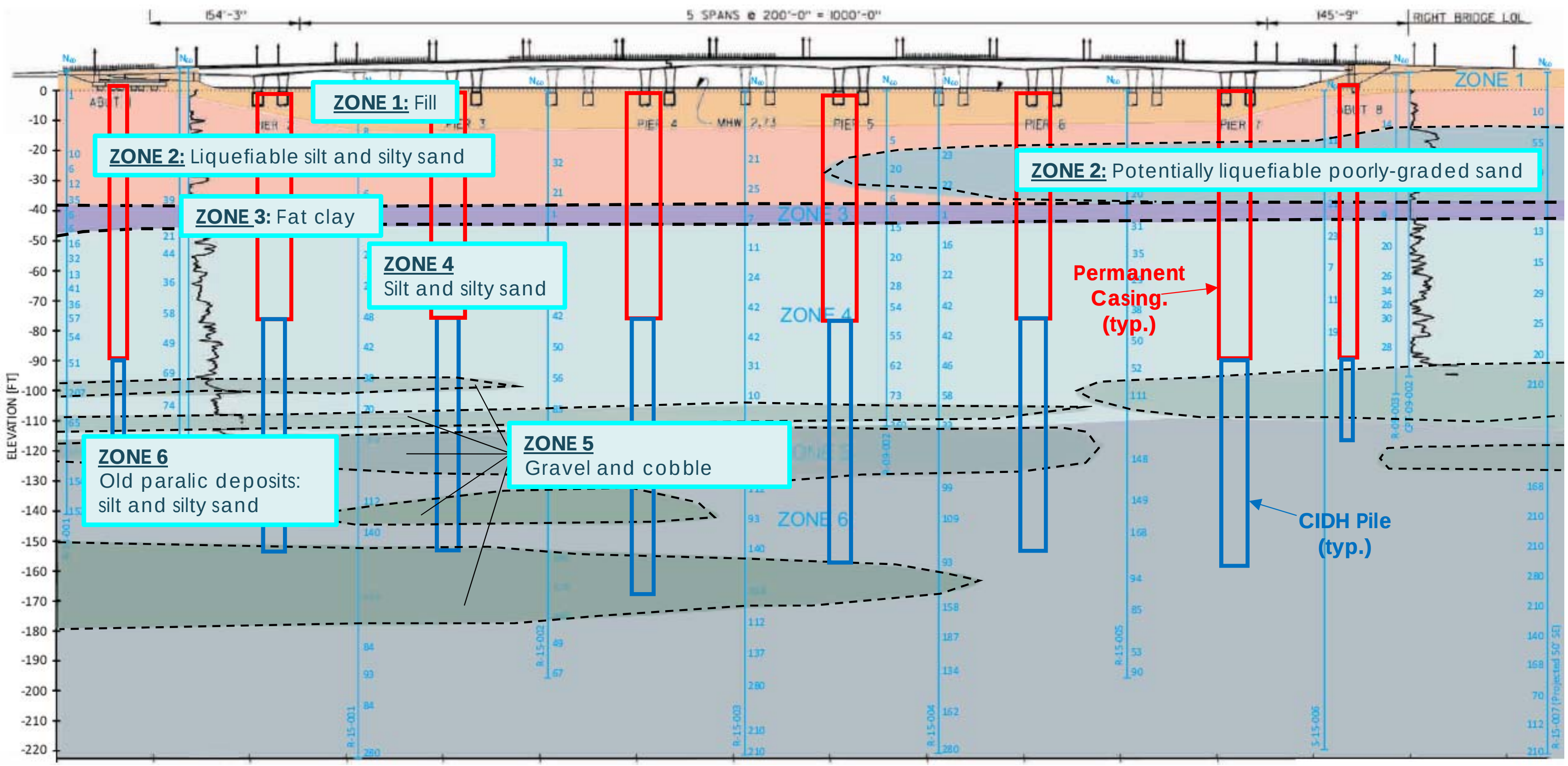
CIDH PILES

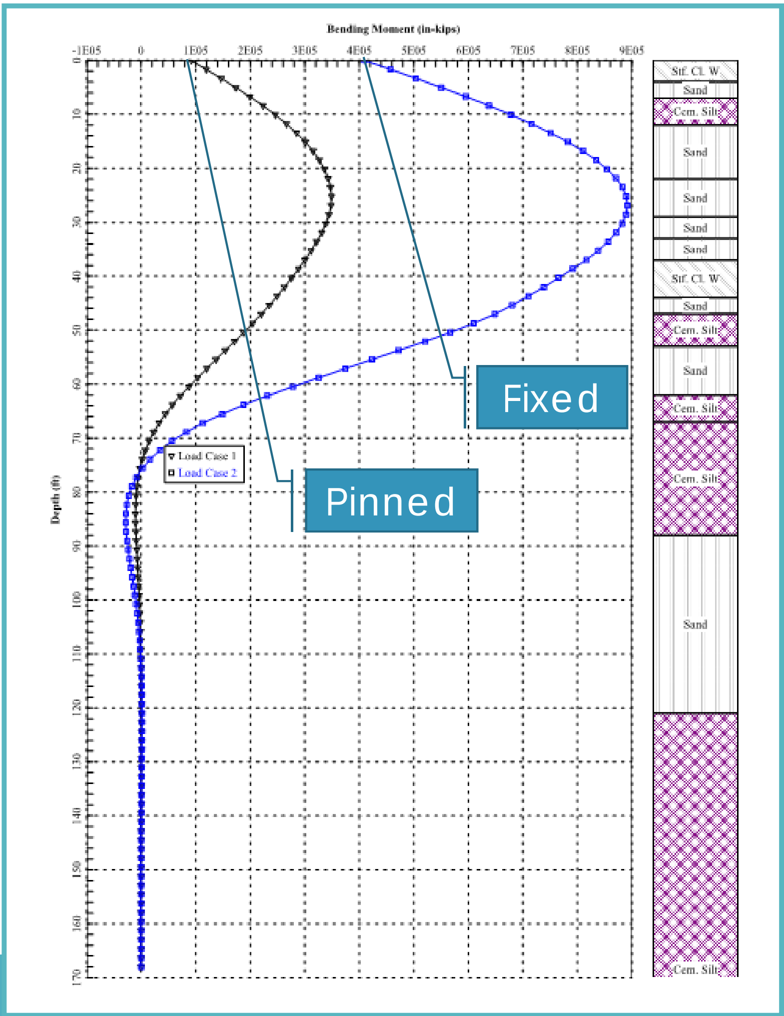
- Friction (f=0.7): 1.25 x AASHTO LRFD BDS (Reese & O'Neill, 1999) b-method
- End Bearing (f=0.7): Capacity to be verified by full scale axial load test on sacrificial pile (Osterberg Cell Method)

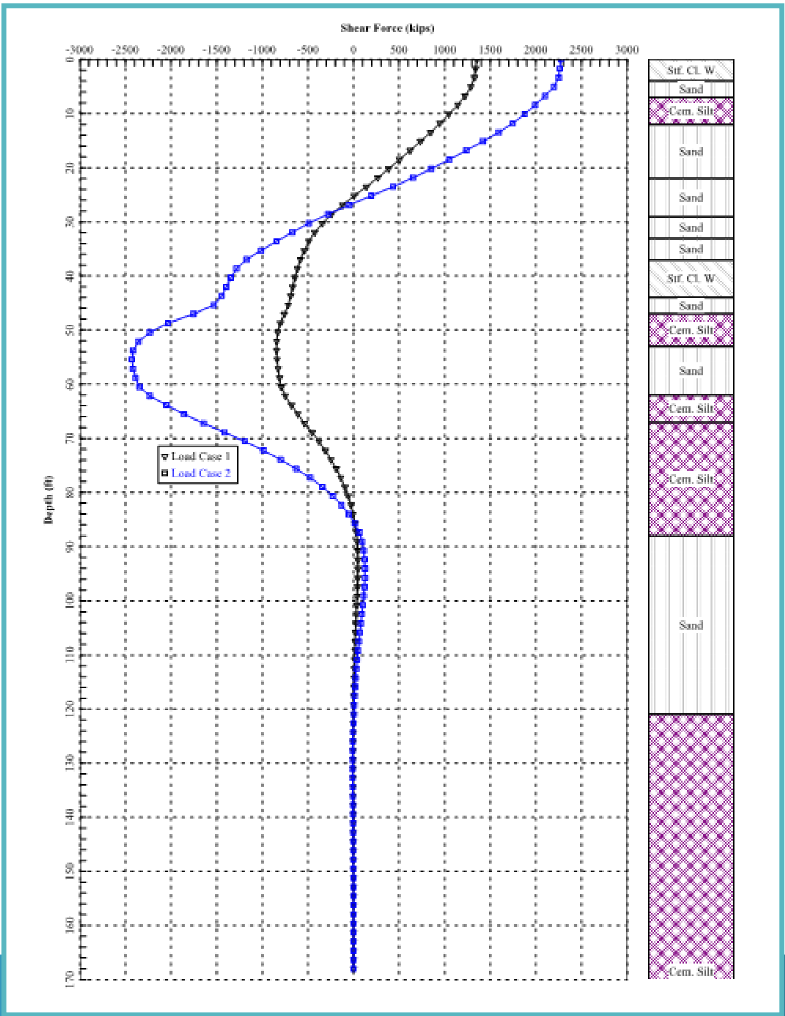
Pile Data Table

Location	Pile Type	Nominal Resistance (kips)		Steel Casing Specified Tip Elevation (ft)	Design Tip Elevation (ft)	Specified Tip Elevation (ft)
		Compression	Tension			
Abut 1L	60" CIDH with 72" permanent steel casing	2470	N/A	-90.0	-117.0 (a-I, c), -56.5 (d)	-117
PIER 2L	108" CIDH with 120" permanent steel casing	9130	N/A	-77.0	-162.0 (a-I, c), -108.0 (a-II), -94.0 (d)	-162
PIER 3L	108" CIDH with 120" permanent steel casing	9220	N/A	-77.0	-163.0 (a-I, c), -109.2 (a-II), -94.0 (d)	-163
PIER 4L	108" CIDH with 120" permanent steel casing	10280	N/A	-77.0	-175.0 (a-I, c), -104.2 (b), -94.0 (d)	-175
PIER 5L	108" CIDH with 120" permanent steel casing	8880	N/A	-77.0	-159.0 (a-I, c), -105.6 (a-II), -94.0 (d)	-159
PIER 6L	108" CIDH with 120" permanent steel casing	8290	N/A	-77.0	-152.0 (a-I, c), -102.0 (a-II), -94.0 (d)	-152
PIER 7L	108" CIDH with 120" permanent steel casing	8430	N/A	-90.0	-160.0 (a-I, c), -105.0 (a-II), -94.0 (d)	-160
Abut 8L	60" CIDH with 72" permanent steel casing	2270	N/A	-90.0	-116.0 (a-I, c), -55.5 (d)	-116

Casing and Pile Lengths







Moment & Shear Demands along Shaft from LPILE

Pier Pile

7' column and 10' casing with column pinned at bottom

ADVANTAGES	▪ Nominal moment transfer to shaft and seismic shear demand is approximately ½ ▪ Reduced rebar congestion in the CIDH pile ▪ Satisfies all Caltrans SDC 1.7 seismic checks
DISADVANTAGES	▪ Difficult inspection of pin ▪ Stainless steel or dual coated pin reinforcement is recommended ▪ Column-shaft interface to be placed 2' below the total permanent scour elevation

Lateral Spreading at Abutments

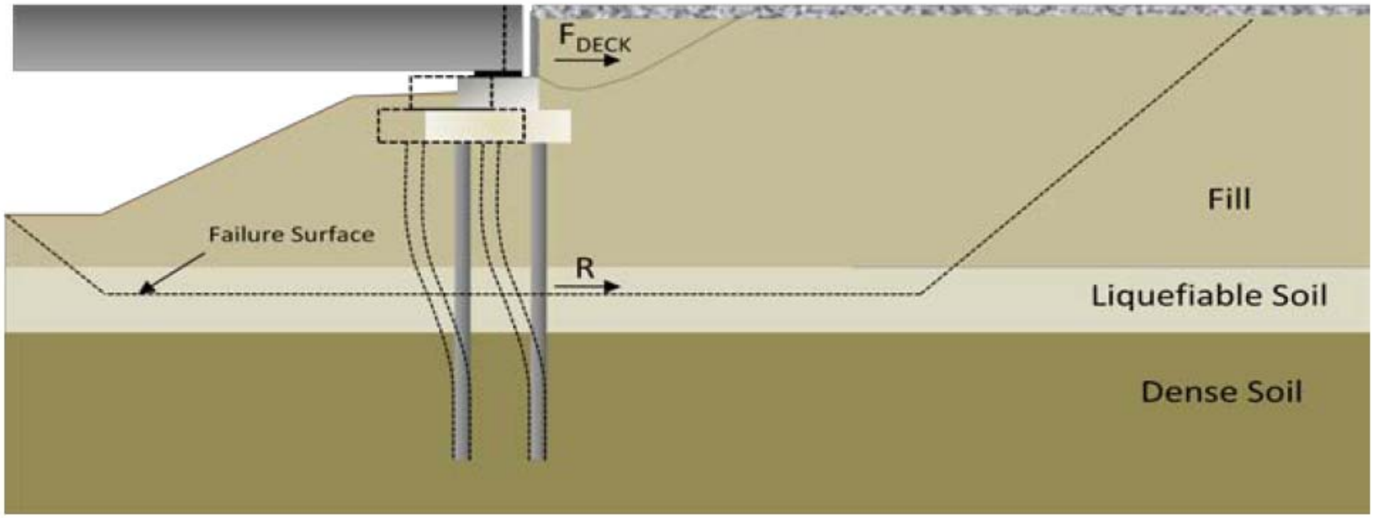
Guidelines on Foundation Loading and Deformation Due to Liquefaction Induced Lateral Spreading

February, 2011

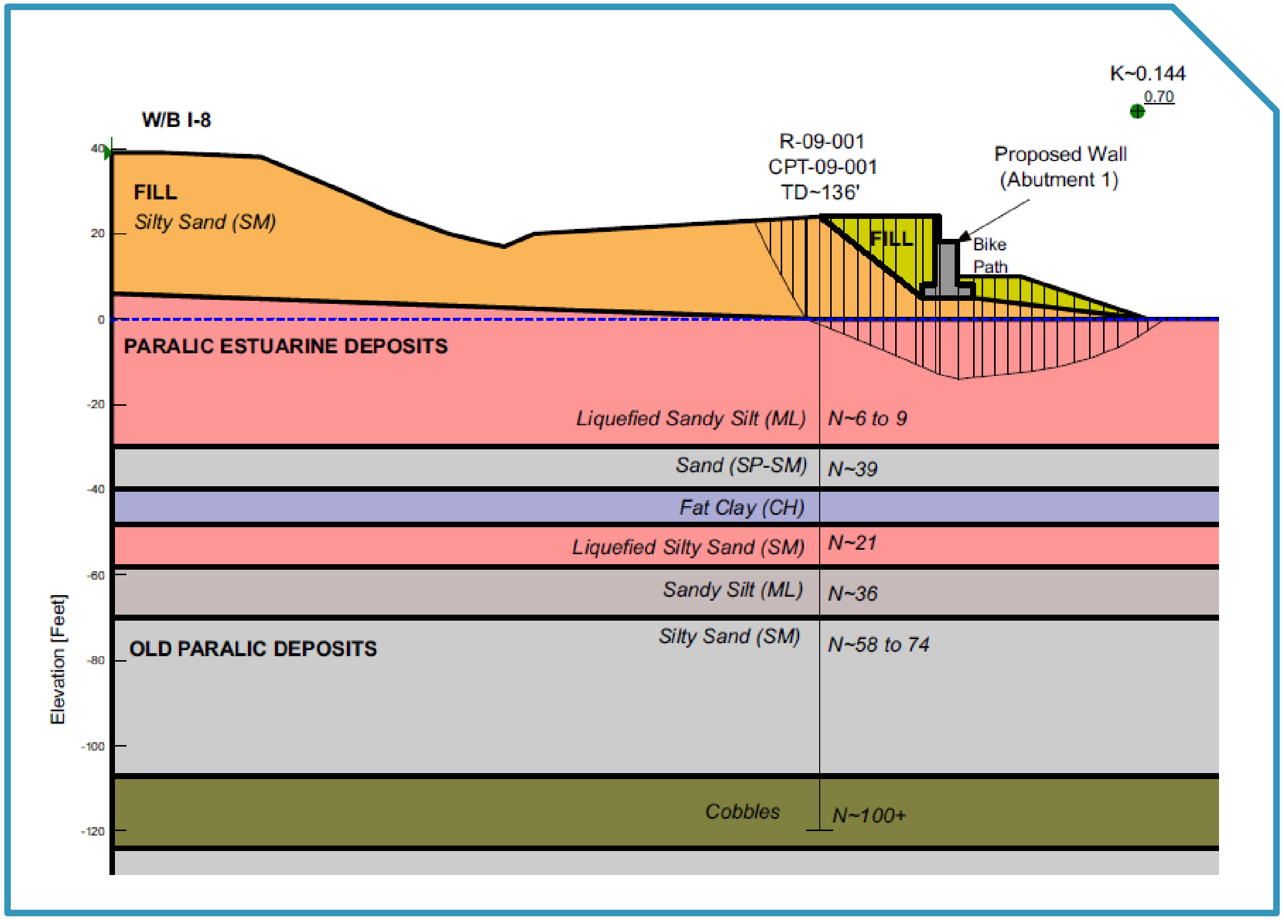
MEMO TO DESIGNERS 20-15 • NOVEMBER 2016

LRFD

20-15 LATERAL SPREADING ANALYSIS FOR NEW AND EXISTING BRIDGES



For PGA/3 ~ 0.144g, F.S. < 1.0 with liquefaction



Slope Stability Analysis

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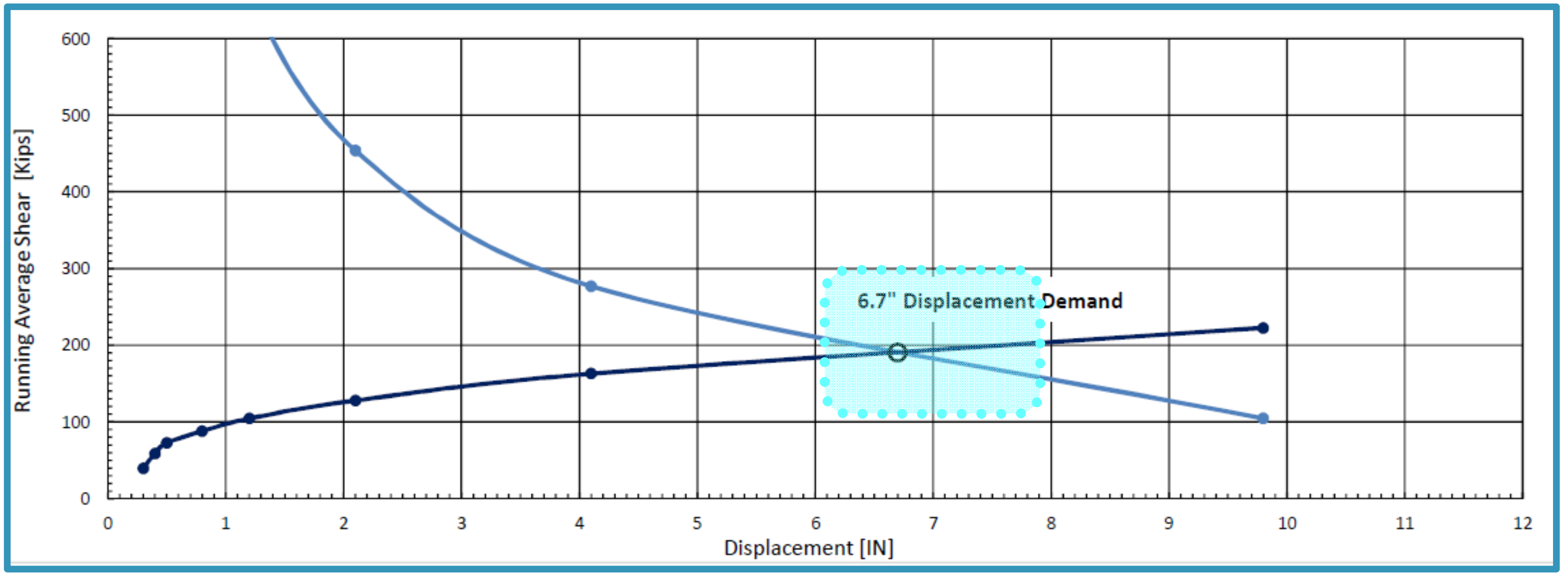
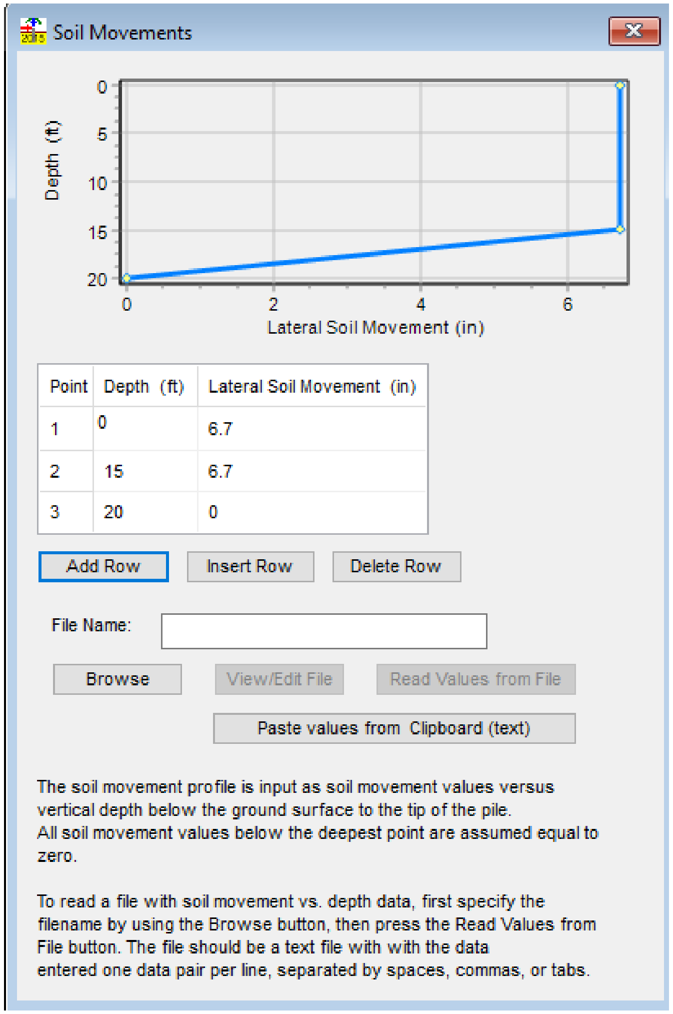
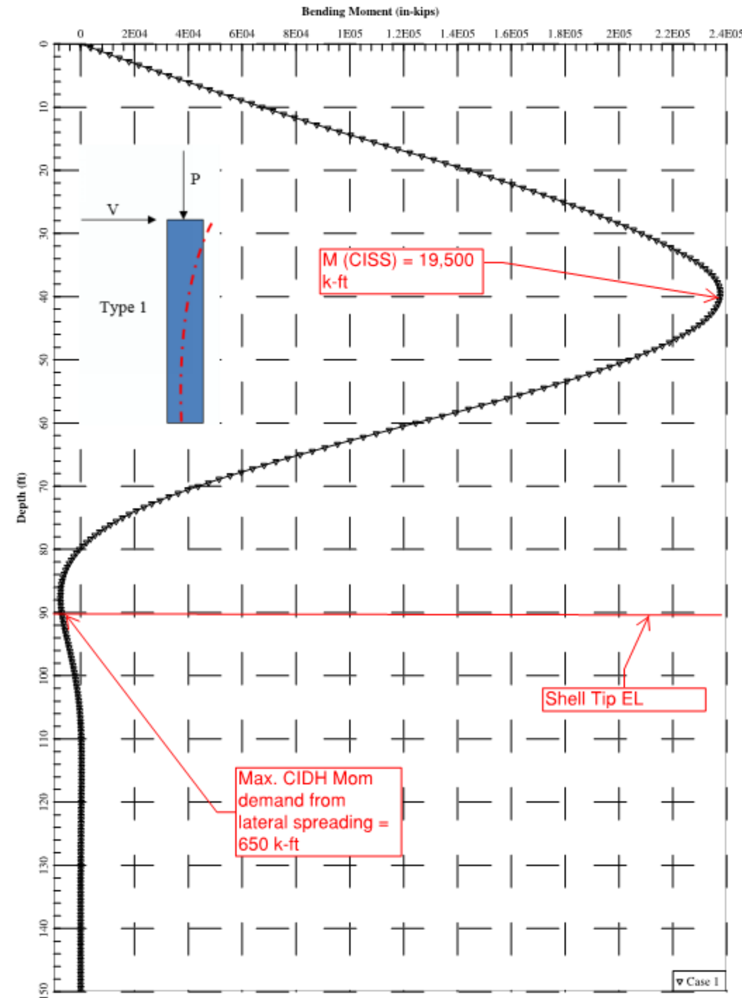
Lateral Spreading Equivalent Displacement



- The potential exists for lateral spread of the river levees given a large earthquake on the Rose Canyon fault zone (Mw~6.8 to 7.2) and soil liquefaction.
- The proposed 6’ diameter pile groups should limit deformation to <12” at the abutment locations.





LPile Analysis

Why a new bridge?

Seismic Impacts on Bridge Foundation Design

Column-Pile Shaft Pin Details

Pile Shaft Optimization – Structure Performance and Cost

Agenda

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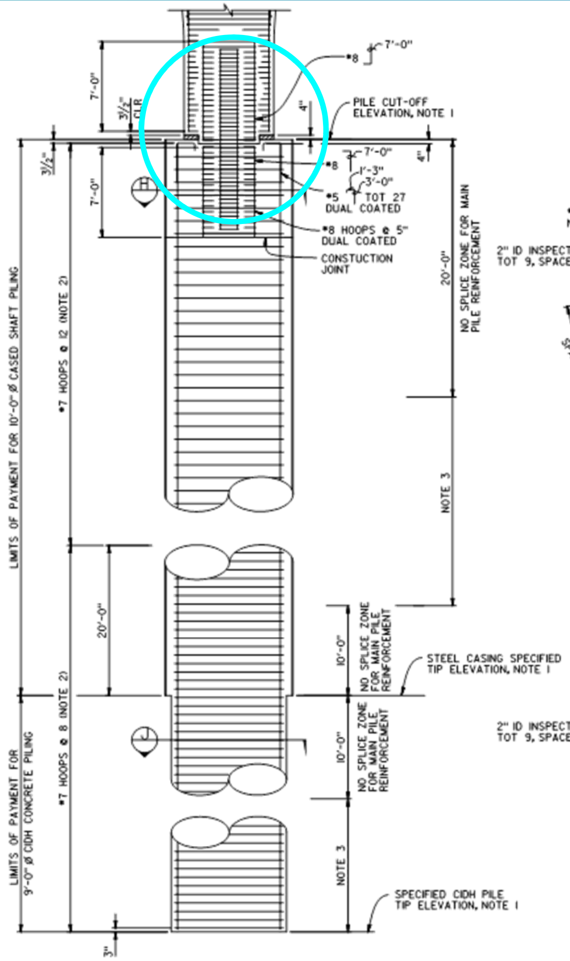
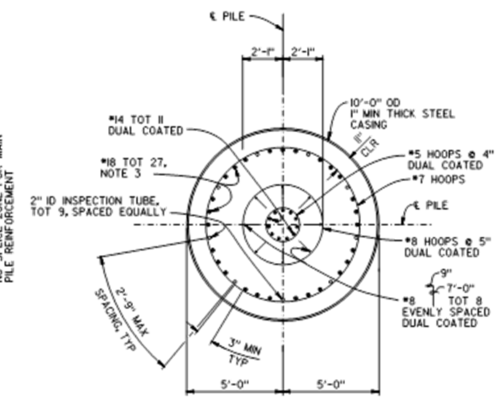
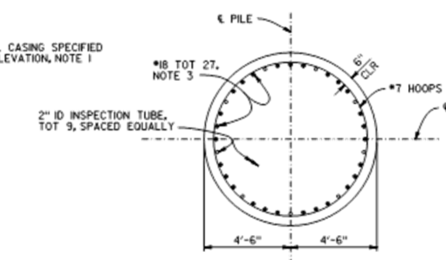
Pier Pile Pin Details





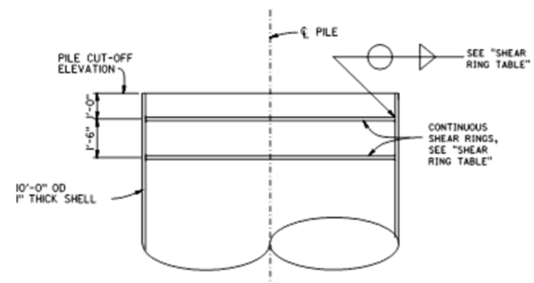
SECTION H
⅜"=1'-0"



SECTION J
⅜"=1'-0"

NOTES:

1. FOR PILE CUT-OFF ELEVATION, STEEL CASING SPECIFIED TIP ELEVATION AND SPECIFIED CIDH PILE TIP ELEVATION, SEE "PILE DATA TABLE" ON "FOUNDATION PLAN NO. 1" SHEET.
2. ALL HOOPS ARE "ULTIMATE" BUTT SPLICE CONTINUOUS.
3. ONLY STAGGERED "ULTIMATE BUTT SPLICE IS ALLOWED FOR MAIN PILE REINFORCEMENT IN ALLOWABLE SPLICE ZONE.



SHEAR RING DETAIL FOR STEEL CASING
½"=1'-0"

SHEAR RING TABLE

SHEAR RING OPTIONS		FILLET WELD
REINF BAR SIZE	BAR STOCK SIZE	
#6	⅝" x ⅝"	½"

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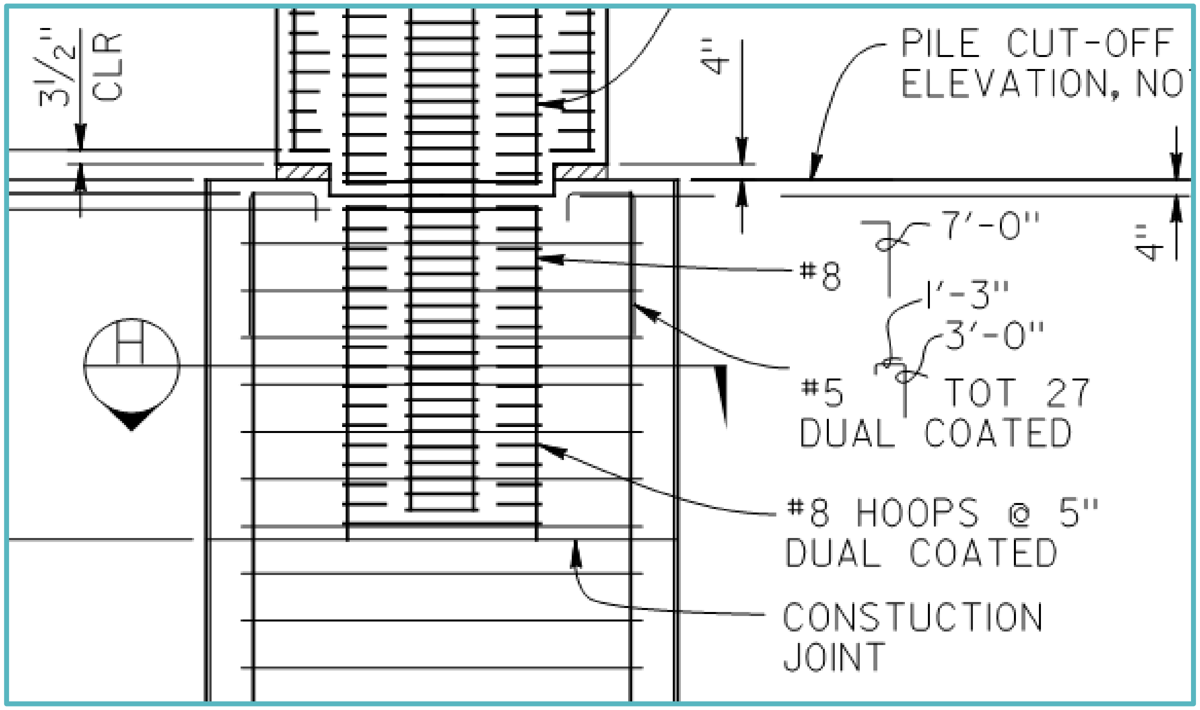
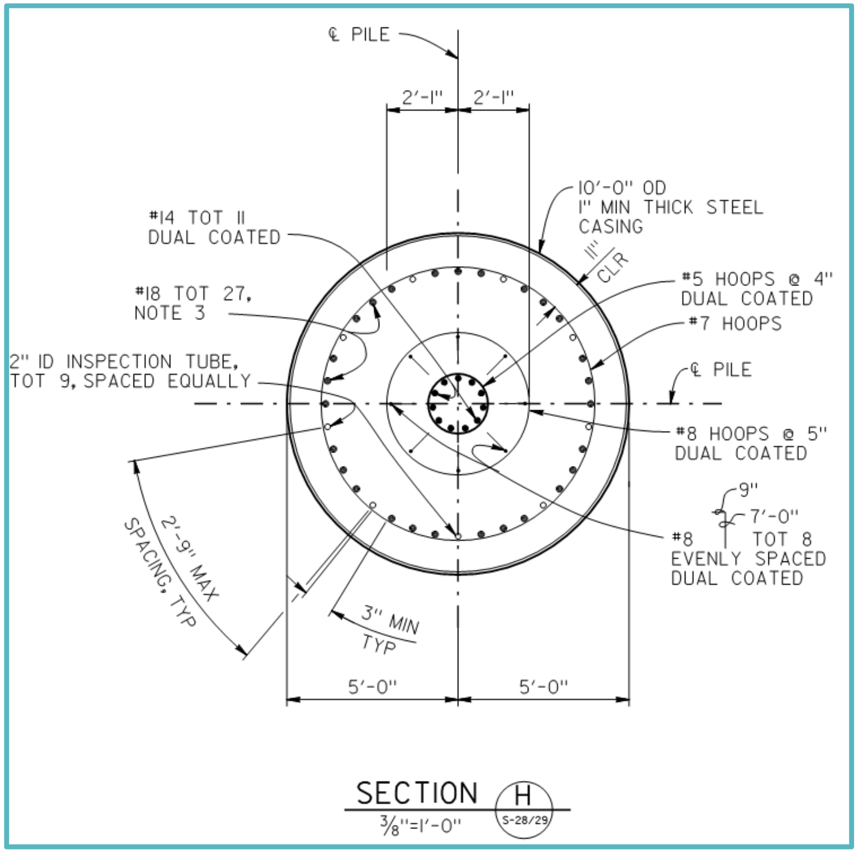
Pin Details





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Moment at Pin

Section Details:

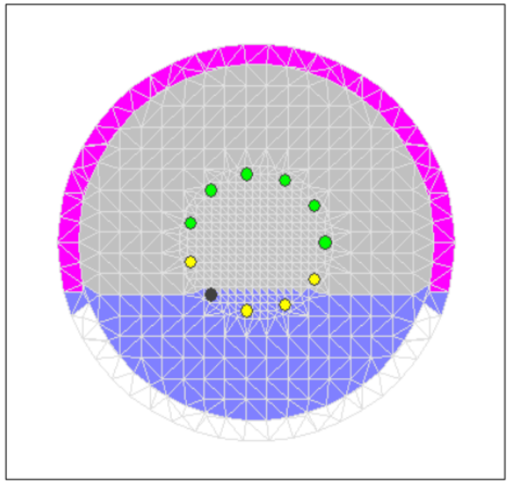
X Centroid:	.4671E-6 ft
Y Centroid:	67.69E-9 ft
Section Area:	17.67 ft^2

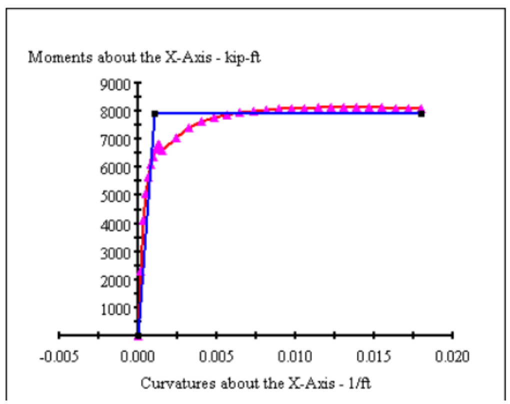
Loading Details:

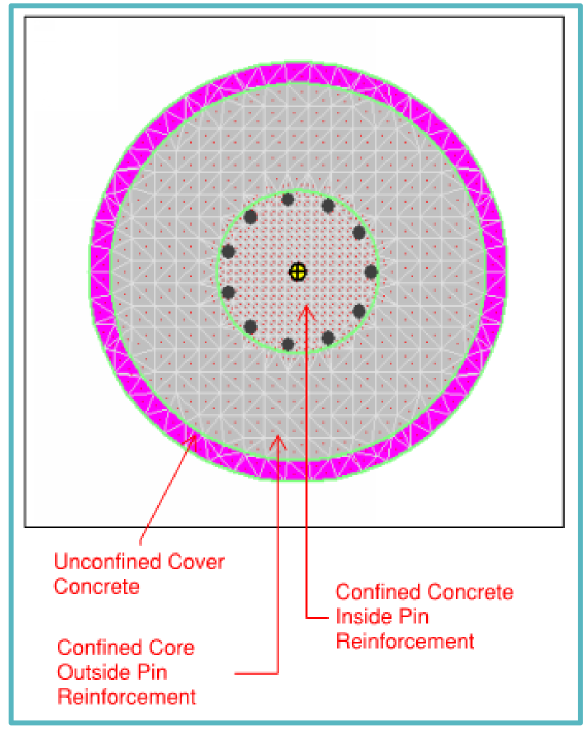
Constant Load - P:	4893 kips
Incrementing Loads:	Mxx Only
Number of Points:	31
Analysis Strategy:	Displacement Control

Analysis Results:

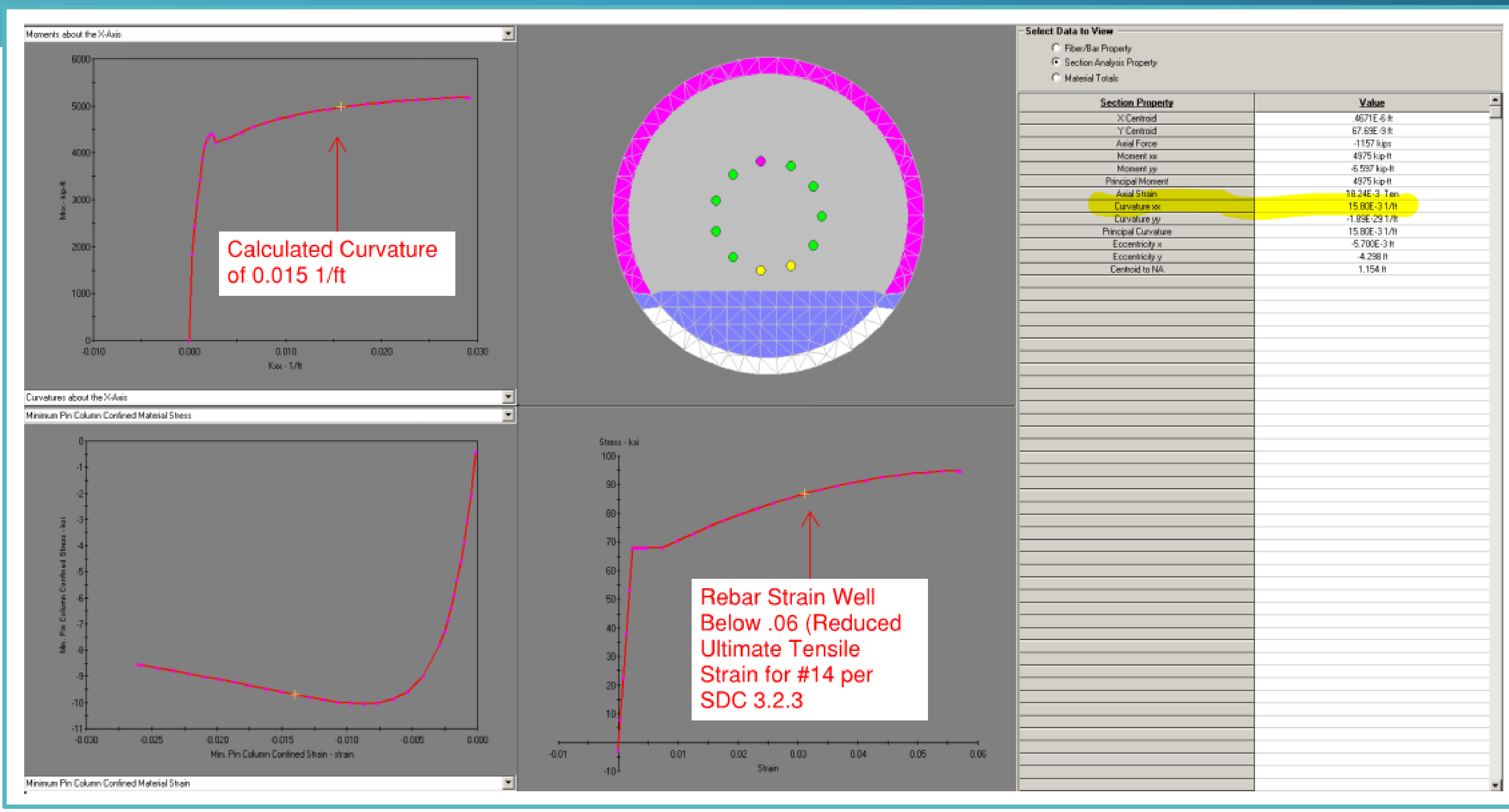
Failing Material:	Pin Column Confined
Failure Strain:	26.11E-3 Compression
Curvature at Initial Load:	-2.51E-13 1/ft
Curvature at First Yield:	.7835E-3 1/ft
Ultimate Curvature:	17.99E-3 1/ft
Moment at First Yield:	6071 kip-ft
Ultimate Moment:	8095 kip-ft
Centroid Strain at Yield:	.2078E-3 Comp
Centroid Strain at Ultimate:	10.55E-3 Ten
N.A. at First Yield:	-.2652 ft
N.A. at Ultimate:	.5867 ft
Energy per Length:	138.4 kips
Effective Yield Curvature:	1.022E-3 1/ft
Effective Yield Moment:	7922 kip-ft
Over Strength Factor:	1.0000
EI Effective:	7.748E+6 kip-ft^2
Yield EI Effective:	0 kip-ft^2
Bilinear Harding Slope:	0 %
Curvature Ductility:	17.59







Pin Rebar Strain



Why a new bridge?

Seismic Impacts on Bridge Foundation Design

Column-Pile Shaft Pin Details

Pile Shaft Optimization – Structure Performance and Cost

Agenda

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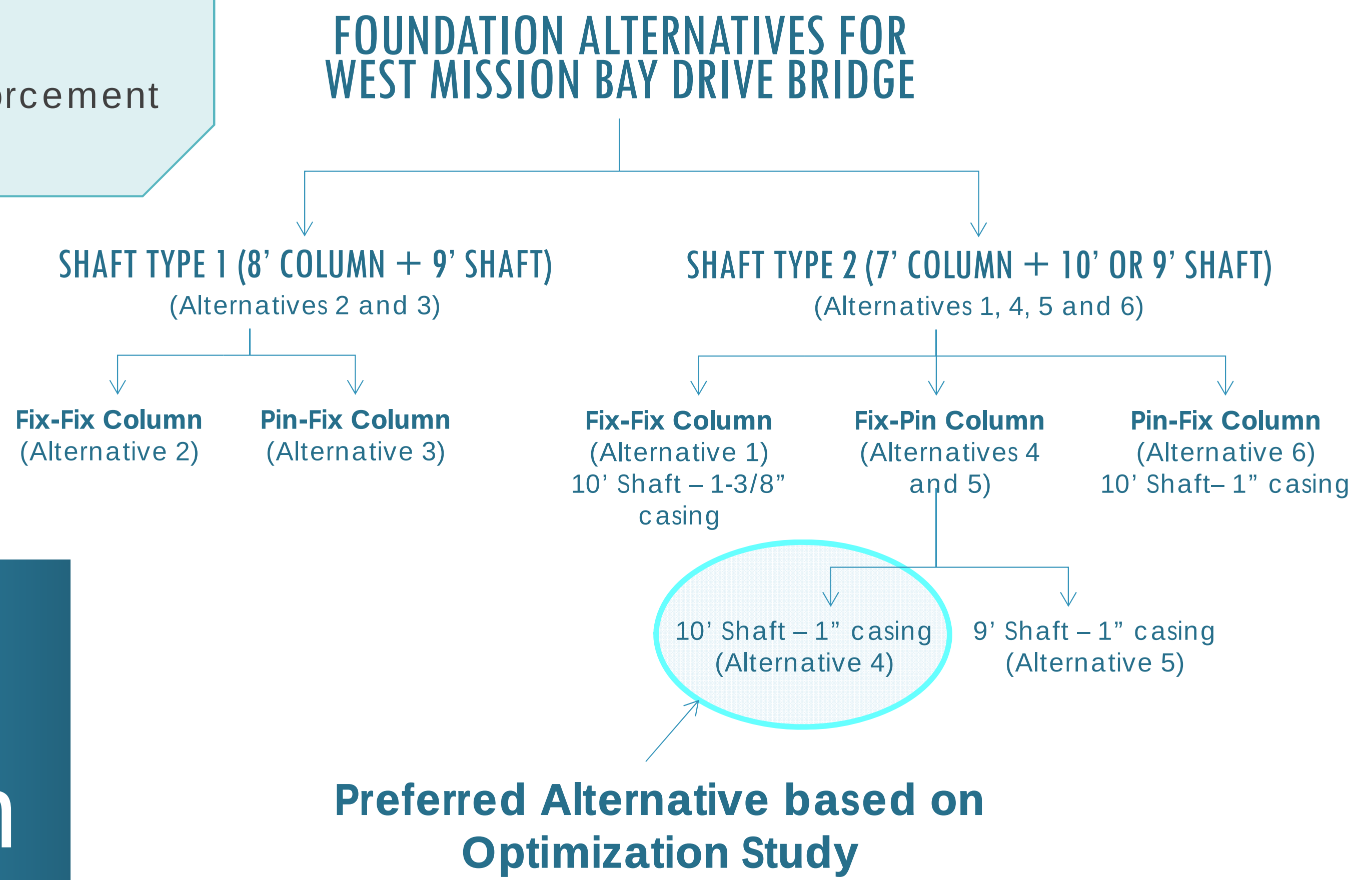
STUDY ALTERNATIVE SUMMARY

- Column and shaft size
- Column fixity: fix or pin
- Shaft type: Type 1 or Type 2
- Column and shaft details: reinforcement details and casing thickness



Pier Pile Optimization

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Pier Pile Optimization

Alternative Comparison

	TYPE 1 SHAFT			TYPE 2 SHAFT		
	Alt # 1	Alt # 2	Alt # 3	Alt # 4	Alt # 5	Alt # 6
Shaft Type	Type 2	Type 1	Type 1	Type 2	Type 2	Type 2
Column Top Fixity	Fix	Fix	Pin	Fix	Fix	Pin
Column Bottom Fixity	Fix	Fix	Fix	Pin	Pin	Fix
Column Geometry						
Diameter (ft) =	7	8	8	7	7	7
Long. Reinf	37-#14	26-#18	26-#18	37-#14	37-#14	37-#14
Long. Reinf %	1.50%	1.50%	1.50%	1.50%	1.50%	1.50%
Transv. Reinf.	Bund.#8@5	Bund.#8@5	Bund.#8@5	Bund.#8@5	Bund.#8@5	Bund.#8@5
Pile Shaft Geometry						
Diameter Cased Shaft (ft) =	10	9	9	10	9	10
Casing thickness (in) from constructability =	1.375	1.00	1.00	1.00	1.00	1.00
Long. Reinf % (Cased Shaft) =	1.81% *	1.13% (26-#18)*	1.13% (26-#18)*	1.21% *	2.01% *	1.81% *
Transv. Reinf. (Cased Shaft) =	#8@12	#8@12	#8@12	#8@12	#8@12	#8@12
Cut off Elevation (ft) =	-4	-4	-4	-4	-4	-4
Diameter CIDH Socket (ft) =	9	8	8	9	8	9
Long. Reinf % (CIDH Socket) =	2.23%	1.43%	1.43%	1.49%	2.55%	2.23%
Transv. Reinf. (CIDH Socket) =	#8 bundled @ 7	#8 bundled @ 7	#8 bundled @ 7	#8@12	#8@6	#8@5

PREFERRED ALTERNATIVE BASED ON OPTIMIZATION STUDY

Pier Pile Optimization

Seismic Analysis Summary

	Alt # 1	Alt # 2	Alt # 3	Alt # 4	Alt # 5	Alt # 6
Shaft Type	Type 2	Type 1	Type 1	Type 2	Type 2	Type 2
Column Top Fixity	Fix	Fix	Pin	Fix	Fix	Pin
Column Bottom Fixity	Fix	Fix	Fix	Pin	Pin	Fix

Preliminary Seismic Analysis Summary (For Liquefied Soil Condition)

	Alt # 1	Alt # 2	Alt # 3	Alt # 4	Alt # 5	Alt # 6
Δd (in)	18.20	24.83	56.29	28.99	38.22	41.21
Total Δy = Δycol + Δftg (in)	9.80	10.98	21.96	19.27	29.82	32.61
Δc (in)	20.40	19.56	93.52	29.75	40.29	43.09
T (sec)	1.60	2.09	5.30	2.41	3.03	3.86
μd	1.86	2.26	2.56	1.50	1.28	1.26
Δ_D/Δ_c	0.89	1.27	0.60	0.97	0.95	0.96
(PXΔr)/(0.2Mp:column)	0.64	0.72	1.99	0.72	0.81	0.77

Preliminary Seismic Analysis Summary (For Non-Liquefied Soil Condition)

	Alt # 1	Alt # 2	Alt # 3	Alt # 4	Alt # 5	Alt # 6
Δd (in)	4.40	9.62	24.57	7.67	8.58	14.17
Total Δy = Δycol + Δftg (in)	3.10	3.22	5.53	3.25	3.59	3.60
Δc (in)	8.70	8.74	26.45	13.73	14.07	14.08
T (sec)	0.80	1.01	2.08	0.87	1.00	1.33
μd	1.42	2.99	4.44	2.36	2.39	3.93
Δ_D/Δ_c	0.51	1.10	0.93	0.56	0.61	1.01
(PXΔr)/(0.2Mp:column)	0.29	0.37	0.90	0.39	0.45	0.56

PREFERRED ALTERNATIVE BASED ON OPTIMIZATION STUDY

Pier Pile Optimization

Pile Shaft Design Summary

***NOTE**:

1. Moment and shear demands were based on 1.2 overstrength factor. For Type 2 shafts the overstrength moment demands were multiplied by 1.25.
2. D/C ratio of CIDH Socket is limited to 0.5 as per Caltrans recommendation.
3. Alternative 1 required 1.375" casing thickness to satisfy the higher moment demands due to fix-fix condition.
4. 1" thick min. casing used for constructability.
5. Sacrificial loss of casing thickness was included in calculating the casing capacity.

	Alt # 1	Alt # 2	Alt # 3	Alt # 4	Alt # 5	Alt # 6
Shaft Type	Type 2	Type 1	Type 1	Type 2	Type 2	Type 2
Column Top Fixity	Fix	Fix	Pin	Fix	Fix	Pin
Column Bottom Fixity	Fix	Fix	Fix	Pin	Pin	Fix
Preliminary Pile Shaft Design Summary (For Liquefied Soil Condition)						
Mu - Maximum Moment in Cased Shaft (k-ft)	135,375	92,750	92,750	75,000	85,300	107,500
Mu @ Cased Shaft/CIDH Socket Interface (k-ft)	72,875	29,600	28,300	19,750	19,750	41,750
ϕMne Cased Shaft Concrete Section (k-ft)	51,680			40,100	39,980	51,680
Mp Cased Shaft Concrete Section (k-ft)	54,520			42,330	42,320	54,520
Casing Thickness needed for Capacity (in) =	1.375			0.750	1.000	1.000
ϕMne Casing (k-ft) with fye = 51 ksi	81,296	Plastic Hinge in Type 1 Shaft	Plastic Hinge in Type 1 Shaft	41,776	46,644	57,487
ϕMne(Total) Cased Shaft Concrete + Casing (k-ft)	132,976			81,876	86,624	109,167
D/C Ratio (Mu-max/ϕMne) of Cased Shaft at Max. Moment =	1.02			0.92	0.98	0.98
D/C Ratio (Mu/ϕMne) of Cased Shaft at Socket Interface =	0.55			0.24	0.23	0.38
ϕMne CIDH Socket (k-ft)	49,460	29,900	29,900	38,135	36,815	49,460
Mp CIDH Socket (k-ft)	53,305	31,470	31,470	40,950	39,820	53,305
D/C Ratio (Mu/ϕMne) of CIDH Socket at Max. Moment =	1.47	0.99	0.95	0.52	0.54	0.84
Vu CIDH Socket (kips)	3,620	3,200	2,900	1,700	1,900	2,700
ϕVn CIDH Socket (k-ft)	3,275	2,790	2,790	1,850	2,125	2,725

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Project Status

- **Construction Cost**
  - $95 million (bridge) + $10 million (roadway)
- **Schedule**
  - Start of construction scheduled for early 2018

SUMMARY:
Caltrans DES/OEE Deep Foundation Design Preferences and Upcoming Design Memos

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Pile Shaft Design in Liquefiable Zone

1
- Design substructure for both liquefied and non-liquefied soil layers
  - Satisfy height/diameter ratio of > than 4.0 for fixed-fixed condition (Seismic Design and Retrofit of Reinforced Concrete Short Columns and Pier Walls MTD 20-18 Draft)

2
- Satisfy new Caltrans MTD and BDP requirements
  - Type Selection for Abutments – MTD 5-1 (Mar 2017)
  - Tip Post-Grouting of Drilled Shafts – MTD 3-8 (Oct 2016)
  - Lateral spreading analysis for new and existing bridges – MTD 20-15 (May 2017)
  - Caltrans BDP Chapter 16 – Deep Foundations (Feb 2015)

3
- Satisfy upcoming Caltrans SDC requirements
  - For columns $P_{DL}/fc'Ag < 0.1$ (maybe 0.15 max)
  - At permanent casing – CIDH interface, flexure demand/capacity ratio < 0.5
  - Pin details between column and shaft

4
- Construction considerations for CIDH piles
  - Foundation Report for Bridges (Feb 2017): http://www.dot.ca.gov/hq/esc/geotech/geo_manual/page/FR_for_Bridges_Feb2017.pdf

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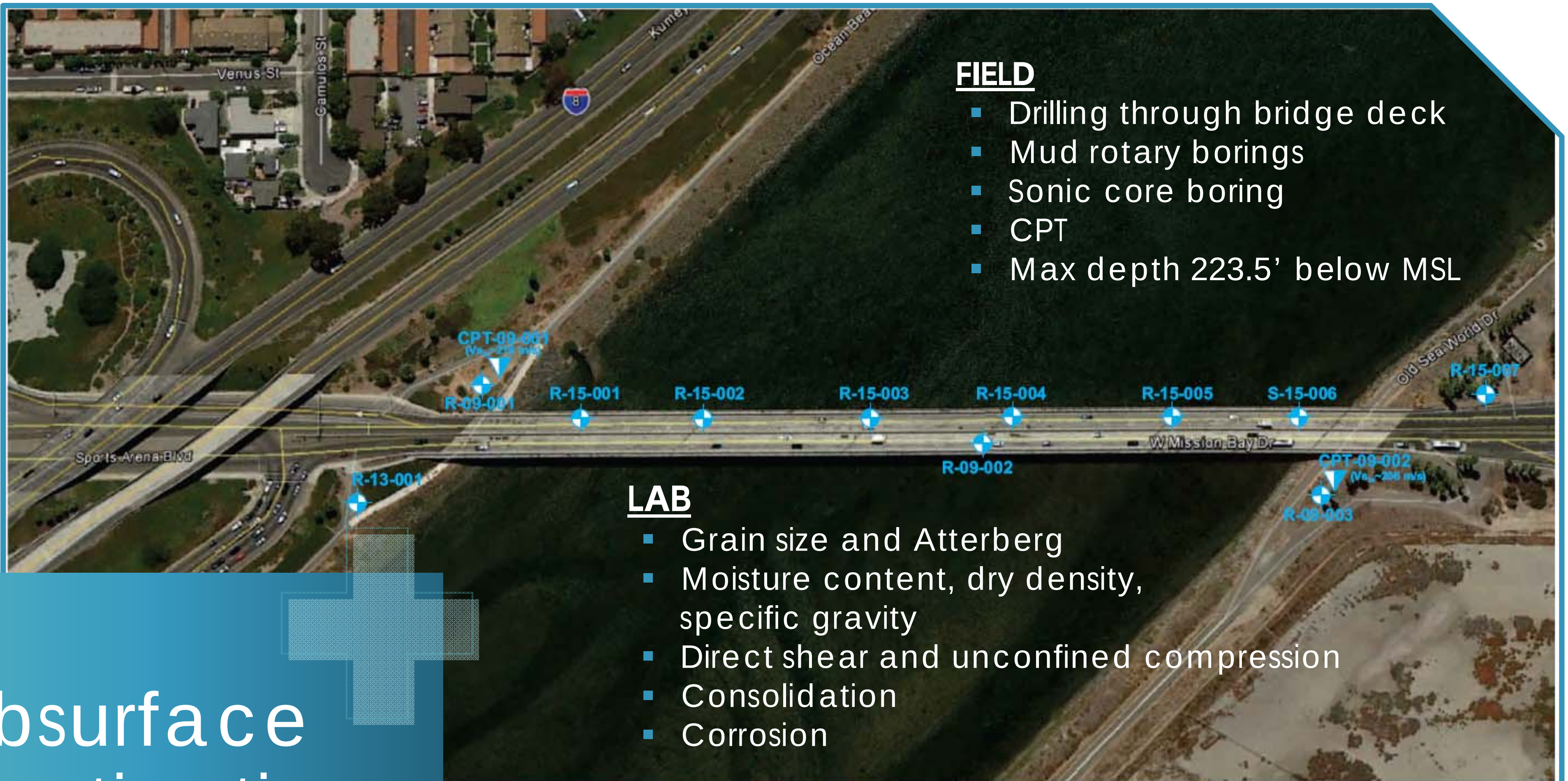

FIELD

- Drilling through bridge deck
- Mud rotary borings
- Sonic core boring
- CPT
- Max depth 223.5’ below MSL

LAB

- Grain size and Atterberg
- Moisture content, dry density, specific gravity
- Direct shear and unconfined compression
- Consolidation
- Corrosion

Subsurface Investigation

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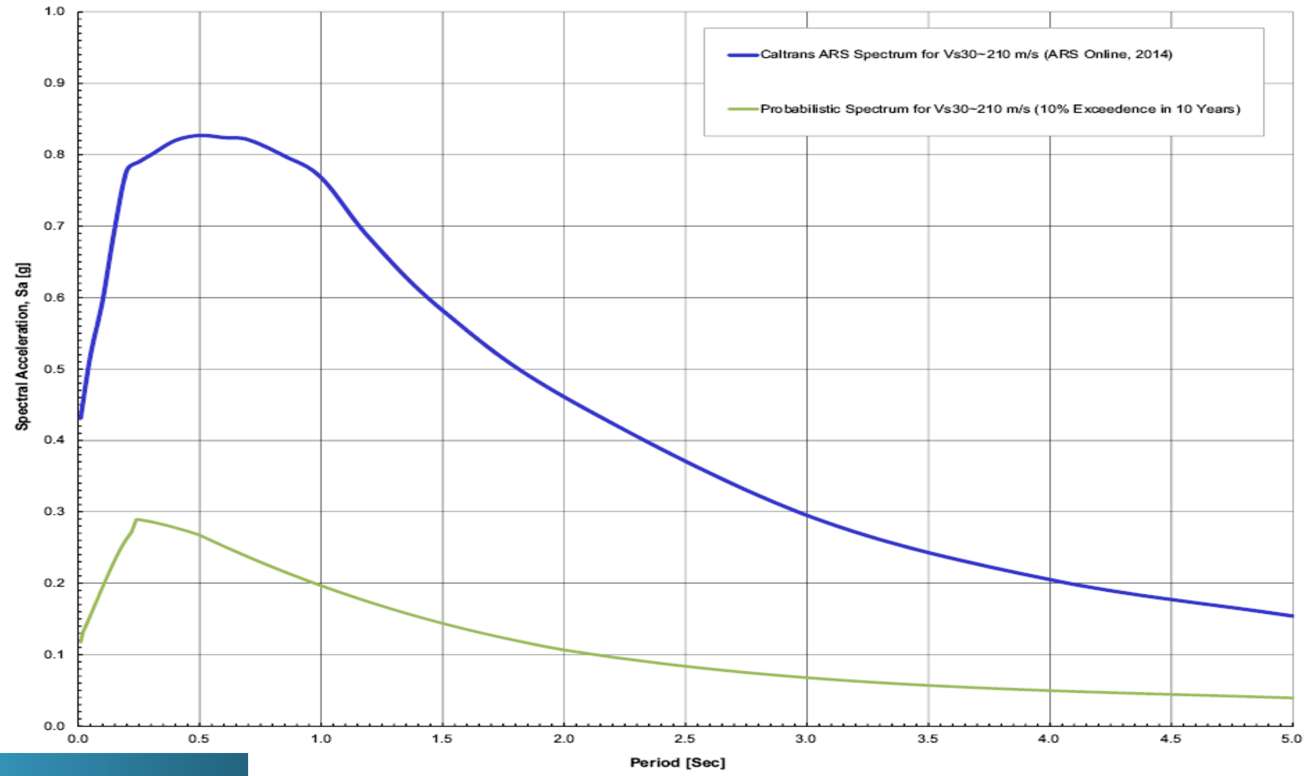

Spectral Period [S]	Sa [g] Vs ~ 210 m/s	Sa [g] 10% in 10 Yrs
0.010	0.431	0.117
0.050	0.518	0.155
0.100	0.595	0.194
0.150	0.696	0.232
0.200	0.778	0.263
0.250	0.790	0.289
0.300	0.800	0.286
0.400	0.820	0.278
0.500	0.827	0.267
0.600	0.824	0.252
0.700	0.821	0.237
0.850	0.798	0.216
1.000	0.768	0.197
1.200	0.683	0.173
1.500	0.582	0.144
2.000	0.461	0.106
3.000	0.295	0.068
4.000	0.205	0.050
5.000	0.154	0.039

Seismic Design

Seismic CPT Vs30 = 675 – 715 ft/s (average 695 ft/s)

ARS Design PGA = 0.431g

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Lateral Spreading Analysis

- Both SLOPE/W and LPILE were used
- Caltrans ARS Online was used for design spectrum based on Vs30 ~ 210 m/s
- Caltrans ARS Design PGA ~ 0.431g
- Residual strengths were based on Seed and Harder using the corrected SPT data

LPILE Analysis

- LPILE was also used to evaluate the response of a single 6' diameter pile with a permanent steel shell (a 0.8 p-multiplier was used for group efficiency).
- Soil displacements were applied in the LPILE model down to the critical failure plane from SLOPE/W.
- Soil displacements ranging from 0.3 to 9.8 inches were applied based on the Bray and Travasarou methodology, corresponding to seismic yield coefficients ranging from 0.05 to 0.40g.
- The results of the SLOPE/W and LPILE analyses were compared to determine the displacement demand on the abutment piles (~6 to 7" < 12" OK).

Pier Pile Optimization

Pier Length Summary

	Alt # 1	Alt # 2	Alt # 3	Alt # 4	Alt # 5	Alt # 6
Shaft Type	Type 2	Type 1	Type 1	Type 2	Type 2	Type 2
Column Top Fixity	Fix	Fix	Pin	Fix	Fix	Pin
Column Bottom Fixity	Fix	Fix	Fix	Pin	Pin	Fix
Pile Tip Elevations (Strength)						
Pile Tip Elev Right Bridge (ft) =	-167	-185	-185	-167	-185	-167
Pile Tip Elev Left Bridge (ft) =	-174	-190	-190	-174	-190	-174
Pile length Right Bridge (ft) =	163	181	181	163	181	163
Pile length Left Bridge (ft) =	170	186	186	170	186	170
Length/Diameter ≤ 30, MTD 3-1 (L/D) =	17	21	21	17	21	17
Casing length (ft) =	103	103	103	103	103	103
Pile Tip Elevations (Seismic)						
Pile Tip Elev - Axial (ft) =	-120	-120	-120	-120	-120	-120
Pile Tip Elev - Lateral for Liquefied Case (ft) =	-162	-167	-167	-149	-158	-159

***NOTE**:

1. Pile tip elevation shown are from preliminary analysis and were adjusted for the final design
2. Longer pile lengths for the 9' diameter cased shafts
3. The pile tip elevations are governed by Strength Limit State Loads
4. Factor of safety = 1.5 for determination of pile lengths for lateral stability

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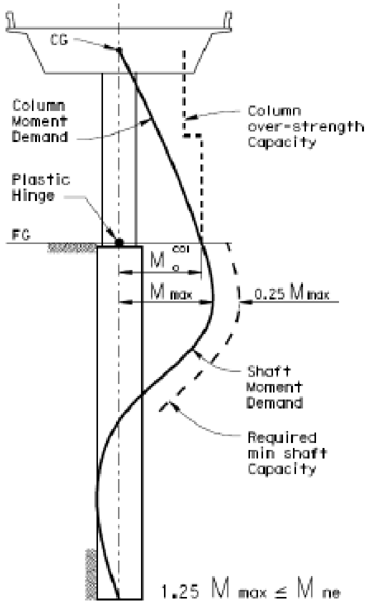
Type 2 Shaft Moment Demand (SDC 7.7.3.2)

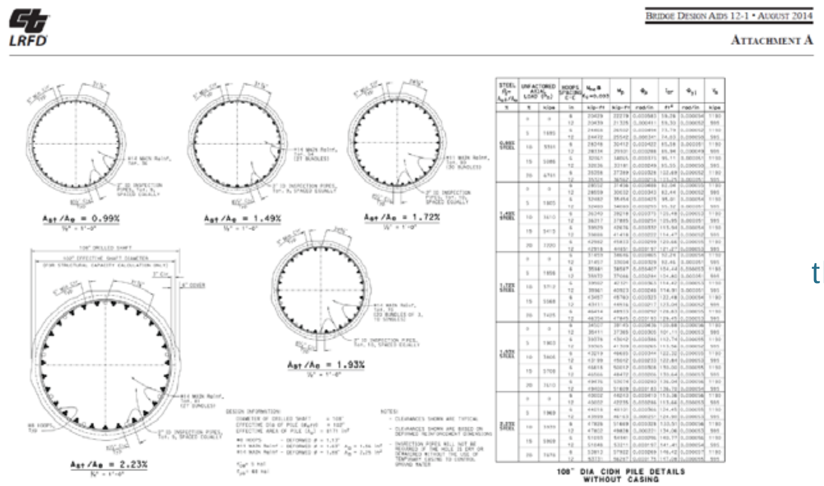


Type 2 Cased Shaft Moment Capacity

Φ Mne of Concrete Section [Estimated as per BDA 12-1 Charts]

+

Φ Mne of Casing



$$M_{ne} = F_{ye} \times Z$$

$$where, \ Z = \frac{d_1^3 - d_2^3}{6}$$

d1 = Diameter of Shaft + Casing thickness (including sacrificial loss)

d2 = Diameter of Shaft

fye = 51 ksi (for *fy* = 45 ksi)

The cased shaft capacity is obtained through superposition of the CIDH and casing individual capacity

Pile Shaft Design

- For Fixed Column: Both Mo and Vo are applied at base of column
- For Pinned Column: Only Vo (1/2 of that for fixed column) is applied at base of column
- The demands in the shaft are obtained from LPILE analysis.

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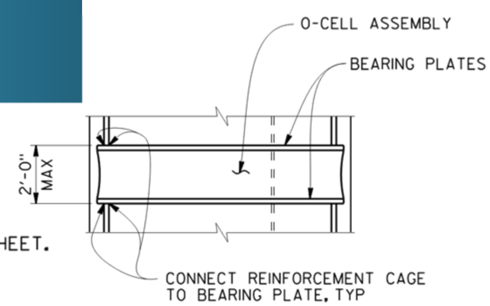
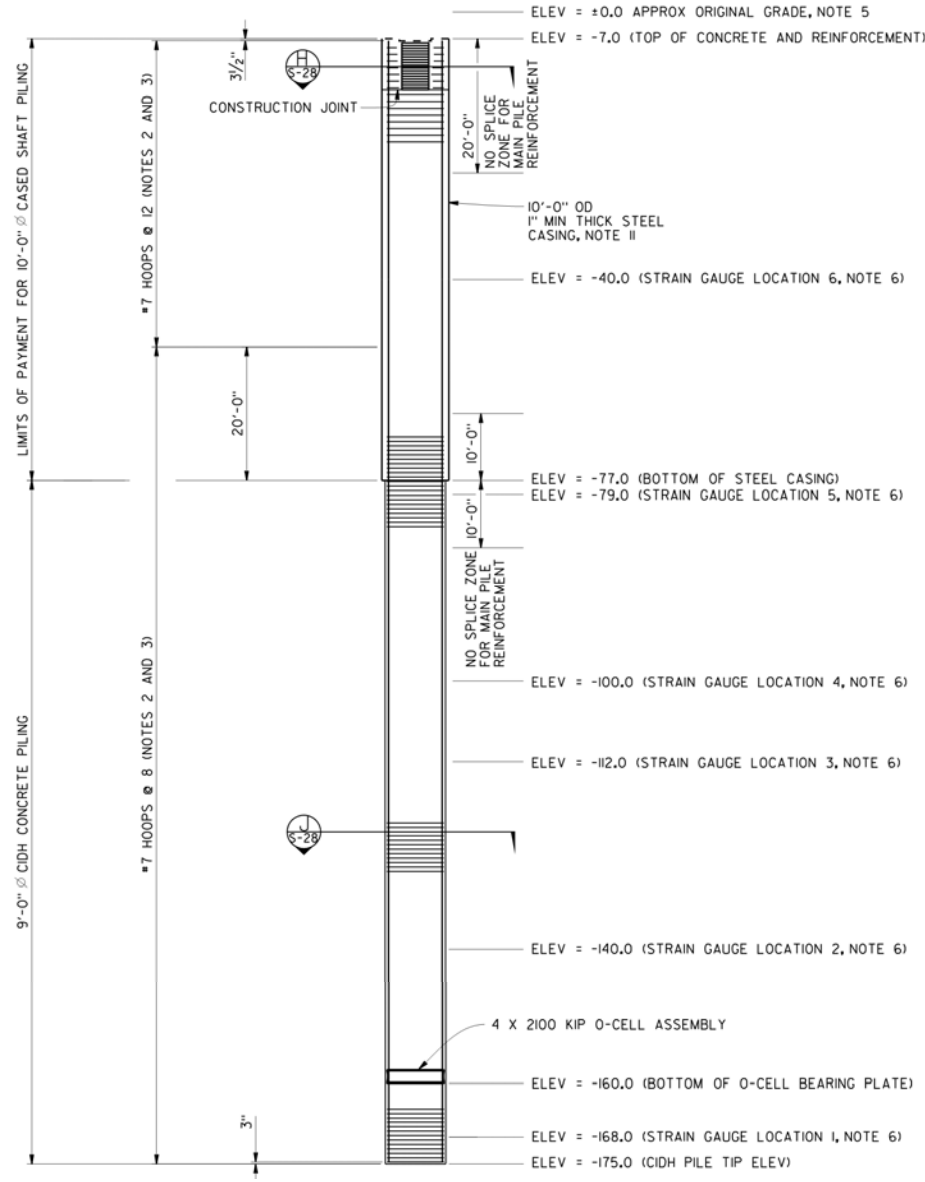
Pile Load Test





NOTES:

1. FOR LOCATION OF TEST PILE, SEE FOUNDATION PLAN NO. 1" SHEET. FOR "SECTION H" AND "SECTION J" SEE "PIER DETAILS NO. 3" SHEET.
2. TEST PILE BAR REINFORCEMENT DETAILS NOT SHOWN SHALL REPLICATE THAT OF THE PRODUCTION PILES.
3. ALL HOOPS ARE "ULTIMATE" BUTT SPLICE CONTINUOUS.
4. ONLY STAGGERED "ULTIMATE BUTT SPLICE IS ALLOWED FOR MAIN PILE REINFORCEMENT IN ALLOWABLE SPLICE ZONE.
5. CONTRACTOR SHALL VERIFY ORIGINAL GRADE AT PROPOSED TEST PILE LOCATION. CONSTRUCTION AND REMOVAL OF SHORING ABOVE PILE CUT-OFF SHALL REPLICATE PRODUCTION PILES.
6. PLACE 4 STRAIN GAUGES UNIFORMLY SPACED AT EACH LOCATION NOTED.
7. THE LOAD TEST PILE CONSTRUCTION SHALL BE IDENTICAL IN ALL RESPECT TO THE PROJECT PRODUCTION PILES INCLUDING METHODS OF INSTALLATION, TESTING, AND ALL MATERIALS.
8. INSTALLATION OF LOAD CELL ASSEMBLY, INSTRUMENTATION TUBES, INSPECTION PIPES, COMPRESSIBLE END BEARING MATERIAL, AND CONNECTION OF ROCK SOCKET REINFORCEMENT TO THE BEARING AND END PLATES SHALL CONFORM THE REQUIREMENTS OF THE LOAD CELL ASSEMBLY MANUFACTURER, AS APPROVED BY THE ENGINEER.
9. LOAD CELL ASSEMBLY SHOWN IS SCHEMATIC ONLY. LOAD CELL ASSEMBLY MANUFACTURER SHALL DESIGN DETAILS OF THE ASSEMBLY, SUBJECT TO APPROVAL OF THE ENGINEER.
10. 2" ID INSPECTION TUBES TOTAL 9 TO BE CARRIED TO BOTTOM OF CIDH PILE AT ELEV = -172.0
11. FOR SHEAR RING DETAIL AT THE TOP OF STEEL CASING, SEE "PIER DETAILS NO. 3" SHEET.

Foundation Cost Comparison

Preliminary Seismic Analysis Summary

***NOTE**:

1. Alternative 1 was used as the baseline for cost comparisons.
2. Cost of Alternatives 2, 3 and 5 were lower than Alternative 1 due to smaller shaft size and thinner shell (cost of furnish shell item is lower).
3. Cost of Alternatives 4 and 6 were lower than Alternative 1 due to thinner shell (cost of furnish shell item is lower)
4. Rebar quantity included both longitudinal and transverse reinforcement.

	Alt # 1	Alt # 2	Alt # 3	Alt # 4	Alt # 5	Alt # 6
Shaft Type	Type 2	Type 1	Type 1	Type 2	Type 2	Type 2
Column Top Fixity	Fix	Fix	Pin	Fix	Fix	Pin
Column Bottom Fixity	Fix	Fix	Fix	Pin	Pin	Fix
<u>Cost Comparison</u>						
CIDH (Cased Shaft) unit price ($/ft) =	2,500	2,175	2,175	2,500	2,175	2,500
CIDH (Cased Shaft) Length total (ΣLc) =	2,472	2,472	2,472	2,472	2,472	2,472
Casing unit price ($/ft) =	2,791	2,000	2,000	2,350	2,000	2,350
Casing Length total (ΣLc) =	2,472	2,472	2,472	2,472	2,472	2,472
CIDH rock socket unit price ($/ft) =	2,175	1,950	1,950	2,175	1,950	2,175
CIDH rock socket Length total (ΣLc) =	1,482	1,902	1,902	1,482	1,902	1,482
CIDH (Cased Shaft) rebar (lbs) =	1,885,413	1,016,895	1,016,895	1,315,181	1,698,718	1,885,413
CIDH rock socket rebar (lbs) =	1,873,693	1,055,705	1,055,705	888,597	1,419,463	1,270,317
Rebar unit price ($/lb) =	1.20	1.20	1.20	1.20	1.20	1.20
Rebar price in cased shaft($/lf) =	915.25	493.64	493.64	638.44	824.62	915.25
Rebar price in CIDH socket ($/lf) =	1,112.30	666.06	666.06	719.51	895.56	1,028.60
Cased shaft unit cost (including rebar and casing) $/ft =	**6,206**	**4,669**	**4,669**	**5,488**	**5,000**	**5,765**
CIDH socket unit cost (including rebar) $/ft =	**3,287**	**2,616**	**2,616**	**2,895**	**2,846**	**3,204**
Total Pier Foundation Cost ($/1000) =	**20,213**	**16,517**	**16,517**	**17,857**	**17,771**	**18,999**
Estimated Savings ($/1000) =	**0**	**3,696**	**3,696**	**2,356**	**2,441**	**1,213**

PREFERRED ALTERNATIVE BASED ON OPTIMIZATION STUDY

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SDC 1.7
Section 7.6.7

Pin Design

$$A_{sk} = \frac{1.2\times(F_{sk} - 0.25P)}{f_y} \quad \text{if } P \text{ is compressive} \qquad (7.6.7\text{-}1)$$

$$A_{sk} = \frac{1.2\times(F_{sk} + P)}{f_y} \quad \text{if } P \text{ is tensile} \qquad (7.6.7\text{-}2)$$

where:

F_{sk} = Shear force associated with the column overstrength moment, including overturning effects (kip)

P = Absolute value of the net axial force normal to the shear plane (kip).

The value of P to be used in the above equations is that corresponding to the column with the lowest axial load (if P is compressive) or greatest axial load (if P is tensile), considering the effects of overturning. However, the same amount of interface shear steel A_{sk}, shall be provided in all column hinges of the bent. The area of dowel reinforcement provided in the hinge to satisfy the column key design shall not be less than 4 in.^{2}

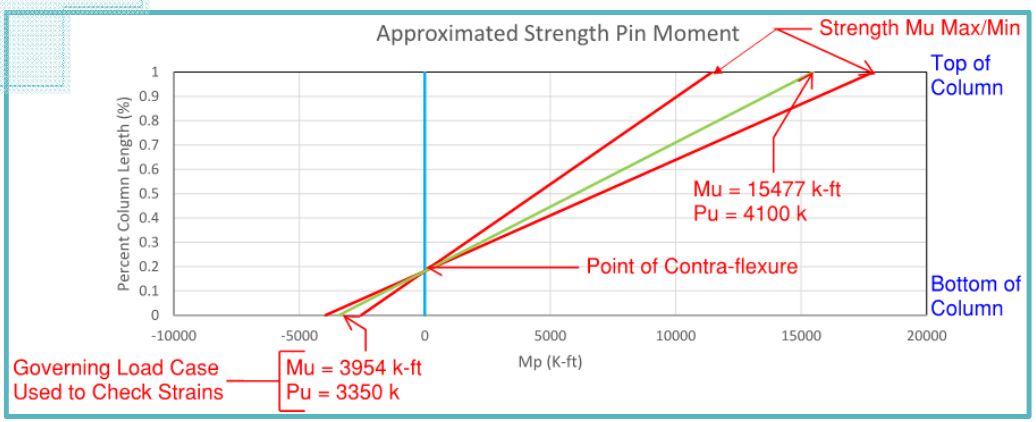
The hinge shall be proportioned such that the area of concrete engaged in interface shear transfer, A_{cv} satisfies the following equations:

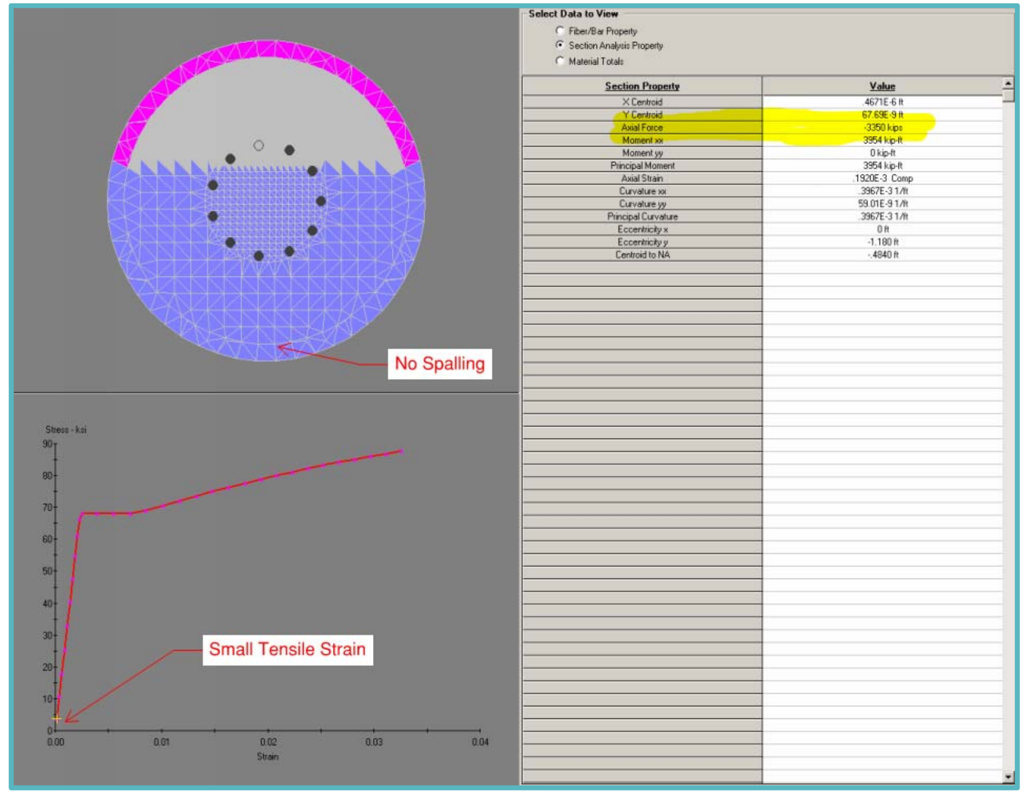
$$A_{cv} \geq \frac{4.0\times F_{sk}}{f_c'} \qquad (7.6.7\text{-}3)$$

$$A_{cv} \geq 0.67\times F_{sk} \qquad (7.6.7\text{-}4)$$

In addition, the area of concrete section used in the hinge must be enough to meet the axial resistance requirements as provided in LRFD-BDS Article 5.7.4.4., based on the column with the greatest axial load.

Pin under Strength Demands





***NOTE**:

1. The axial load and moment at the pin were input in XTRACT to evaluate strains in rebar and concrete
2. The pin rebars are primarily in compression or minimal tension
3. No spalling of pin concrete under strength loads