# Fairview Ave. North Bridge Slip Sliding Away: Challenges in Foundation Design with Flow Loads and Plastic Hinging

## Abutment and Shaft Design

Western Bridge Engineers Seminar 2017

HNTB

# INTRODUCTIONS

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HNTB PM/Structural Engineer

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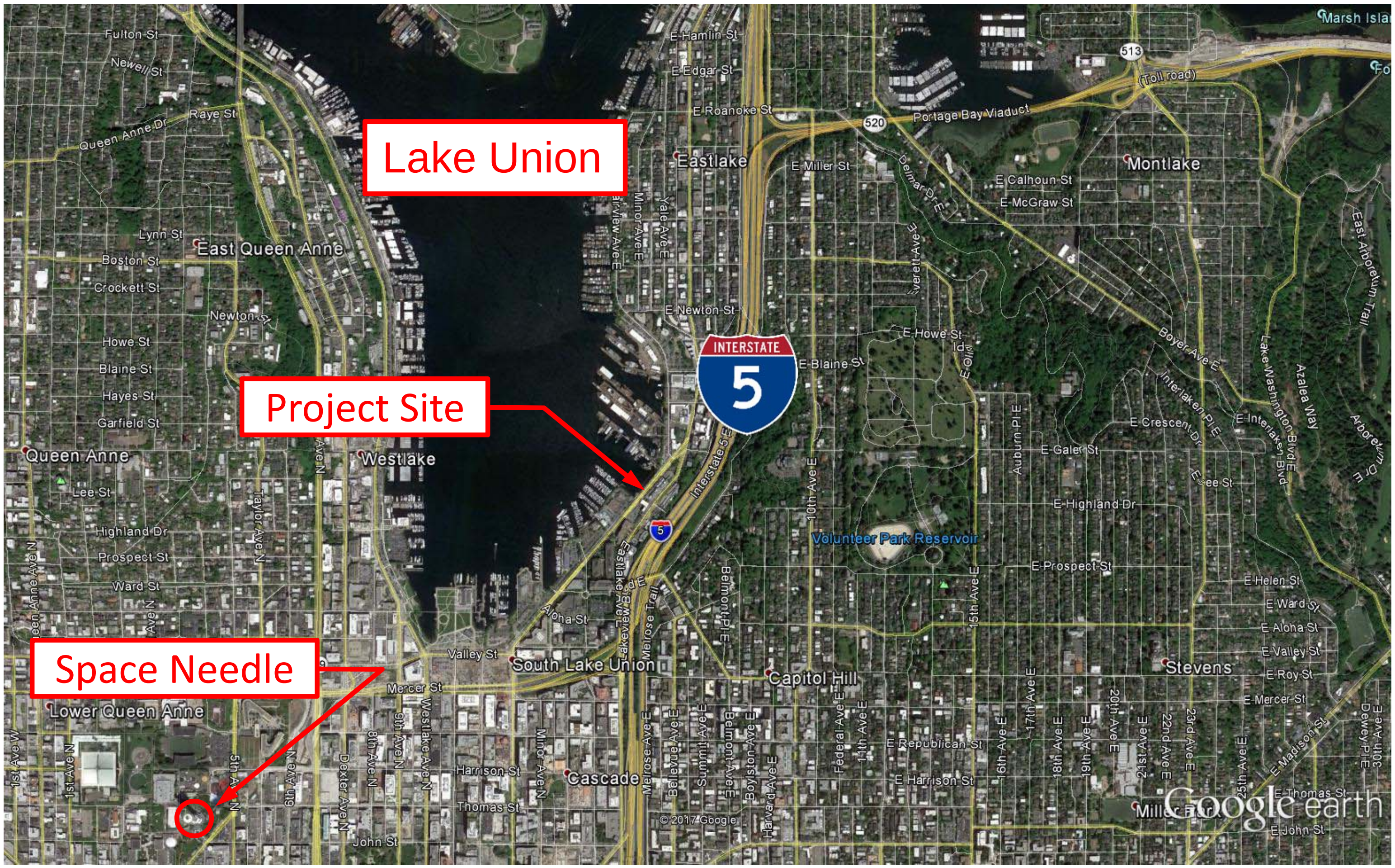
Lead Structural Engineer

# Fairview Ave. Bridge – Seattle, WA

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# Fairview Ave. Bridge – Seattle, WA

# Fairview Ave. Bridge – Seattle, WA

SDOT

Seattle Department of Transportation

# EXISTING BRIDGES

# EXISTING BRIDGES


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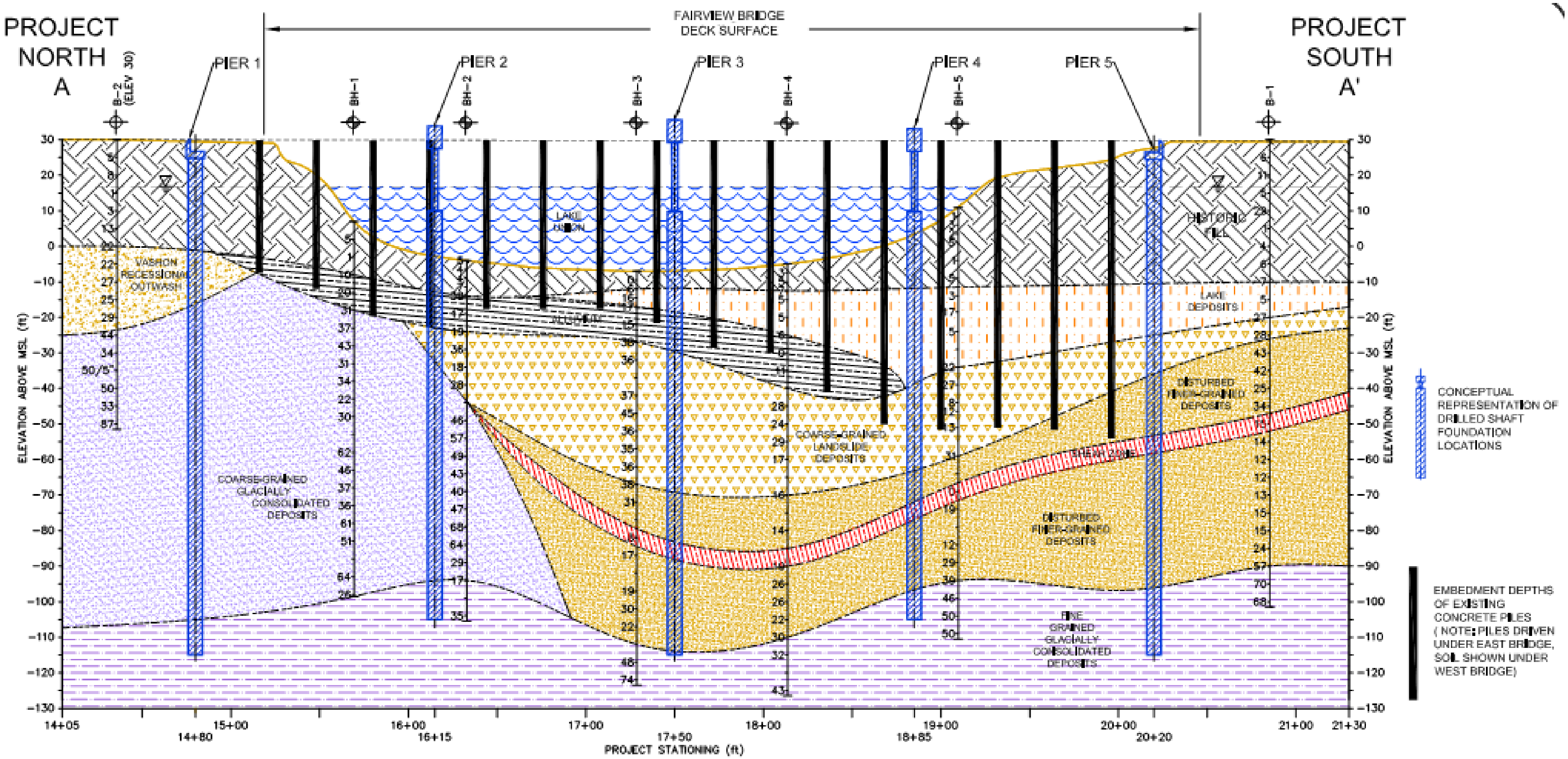
# EXISTING BRIDGES

# Geological Profile - Longitudinal

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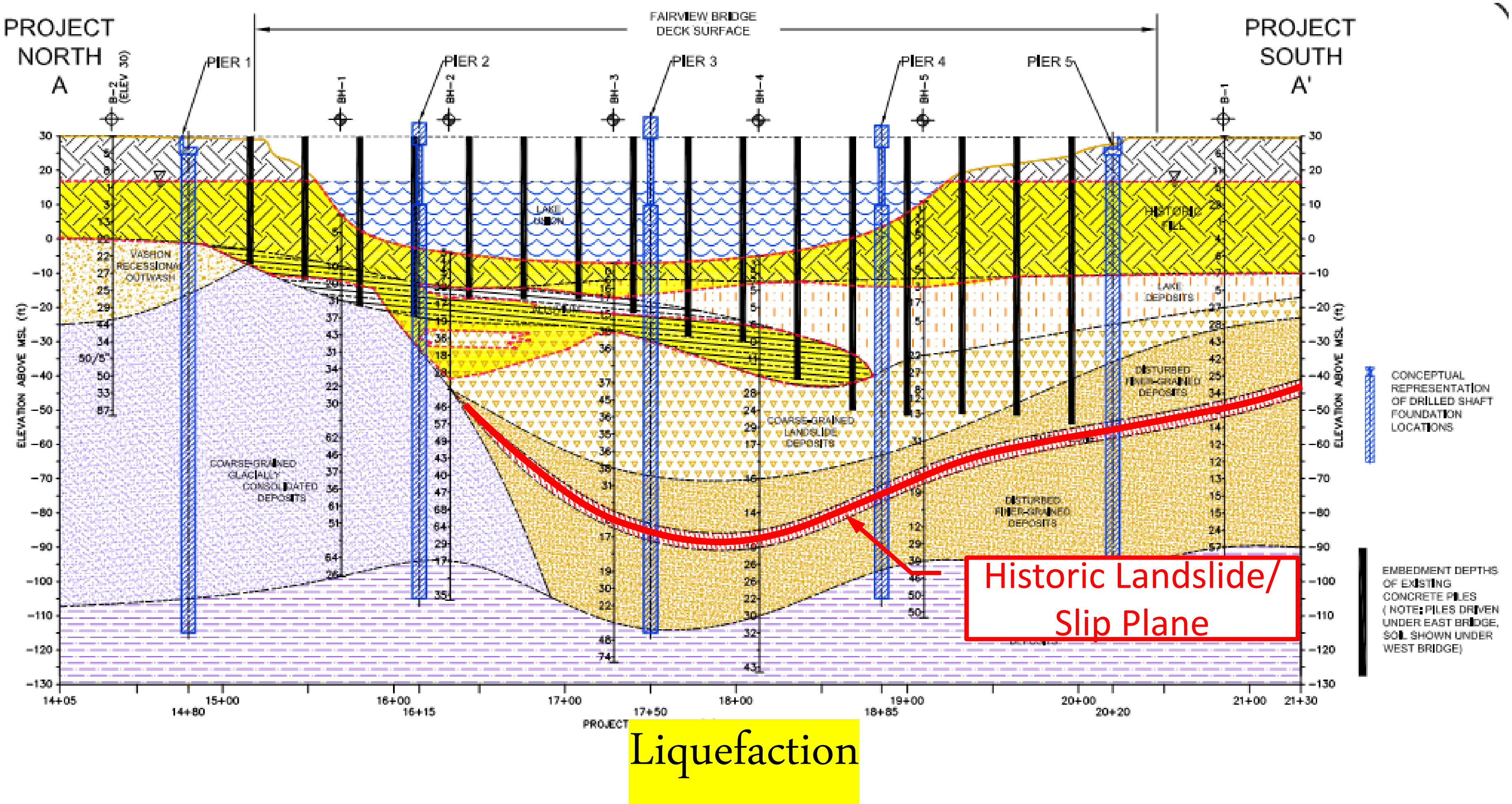
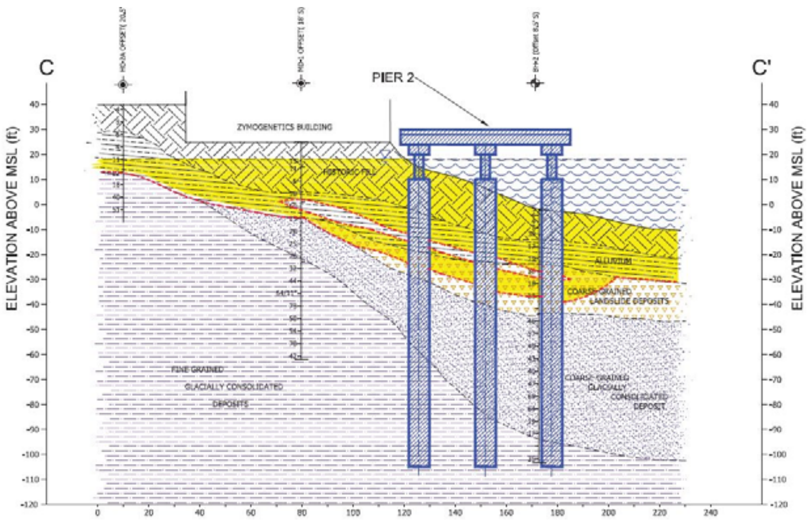
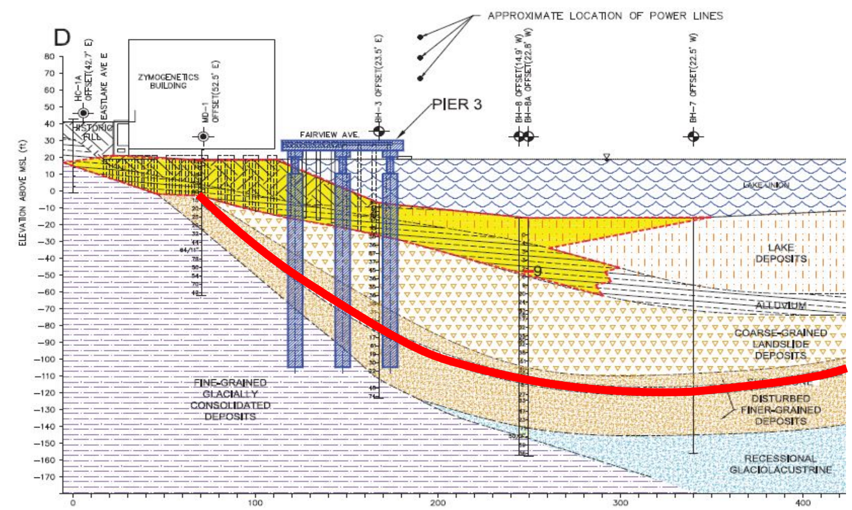
# Geological Profile - Longitudinal



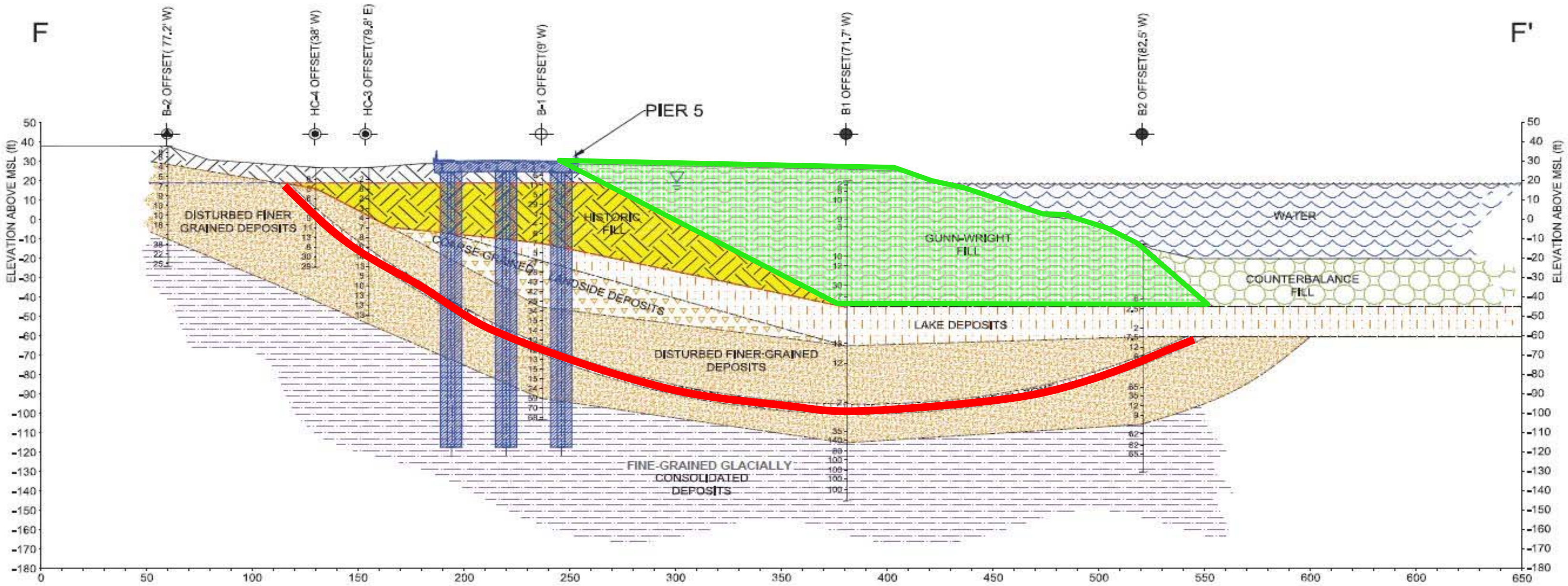
# Geological Profile – Piers 2 and 3




- Layers Vary
- Interspersed Non-Liquefiable Layers
- Slip Plane = Long Shafts

# Geological Profile – Pier 5 (abutment)

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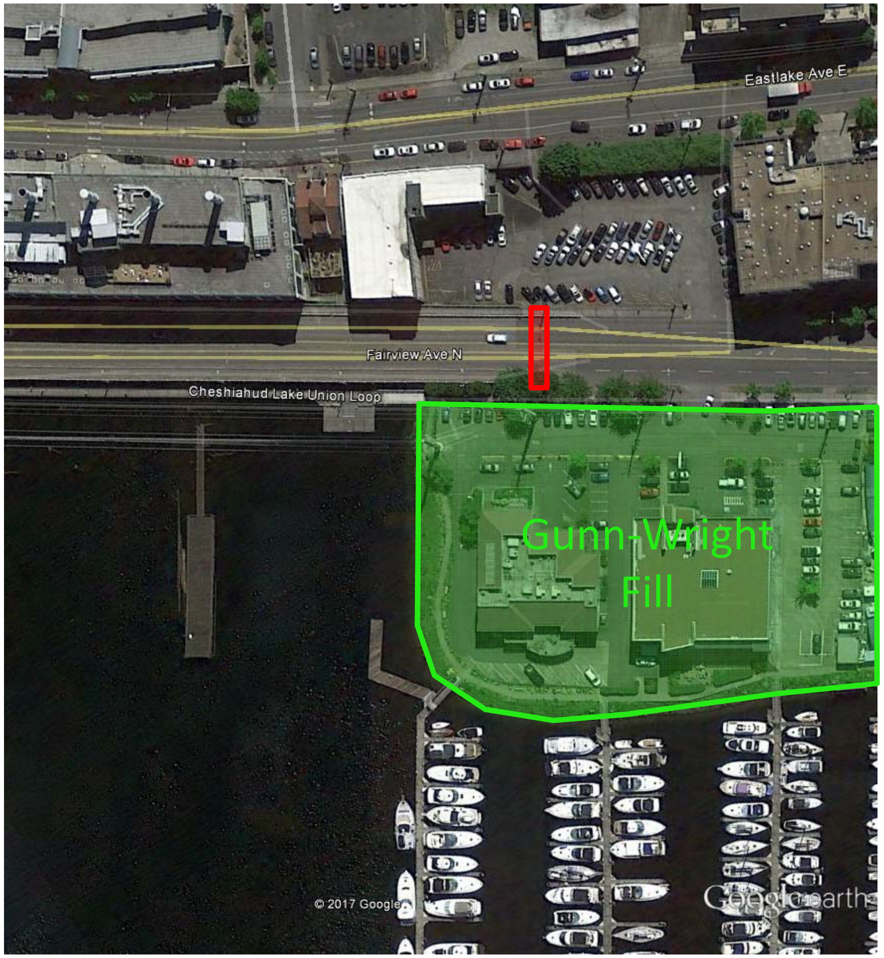
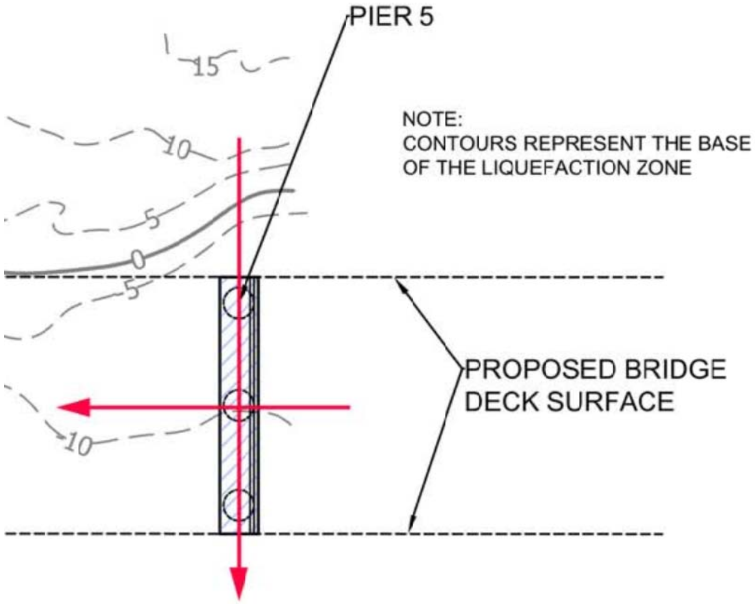
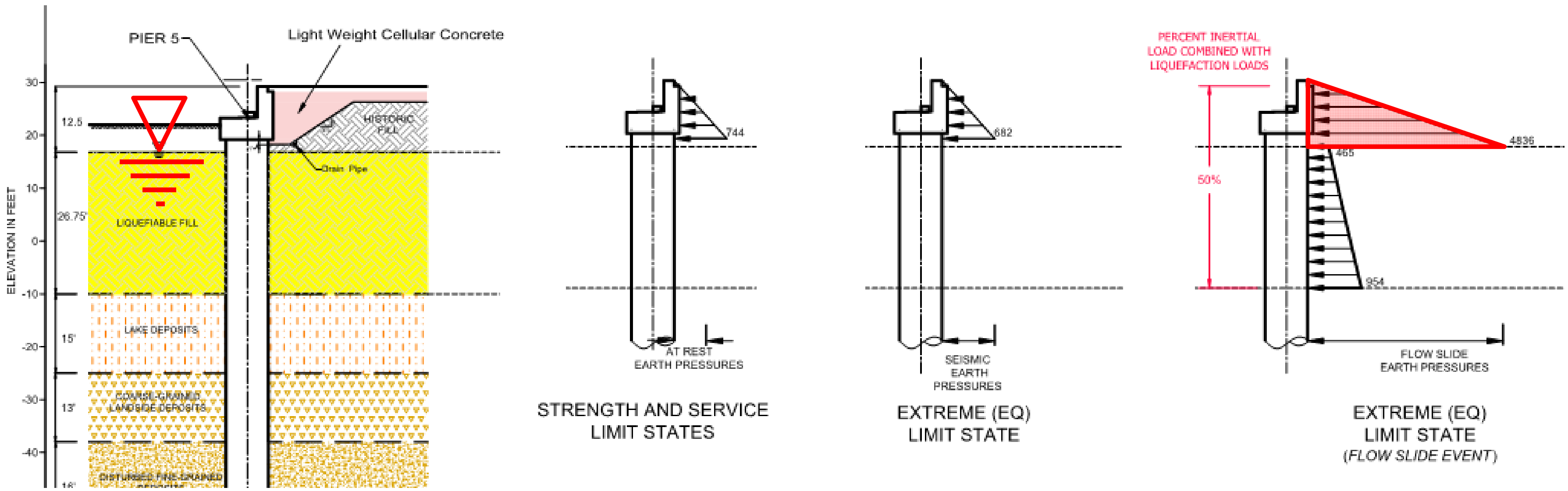
# Gunn-Wright Fill Pad



# Abutment Loading
# & Design Challenges




- High “Flow Loads” during Extreme Event
- Non-Liquified Crust
- Abutment Back Wall “Sail”

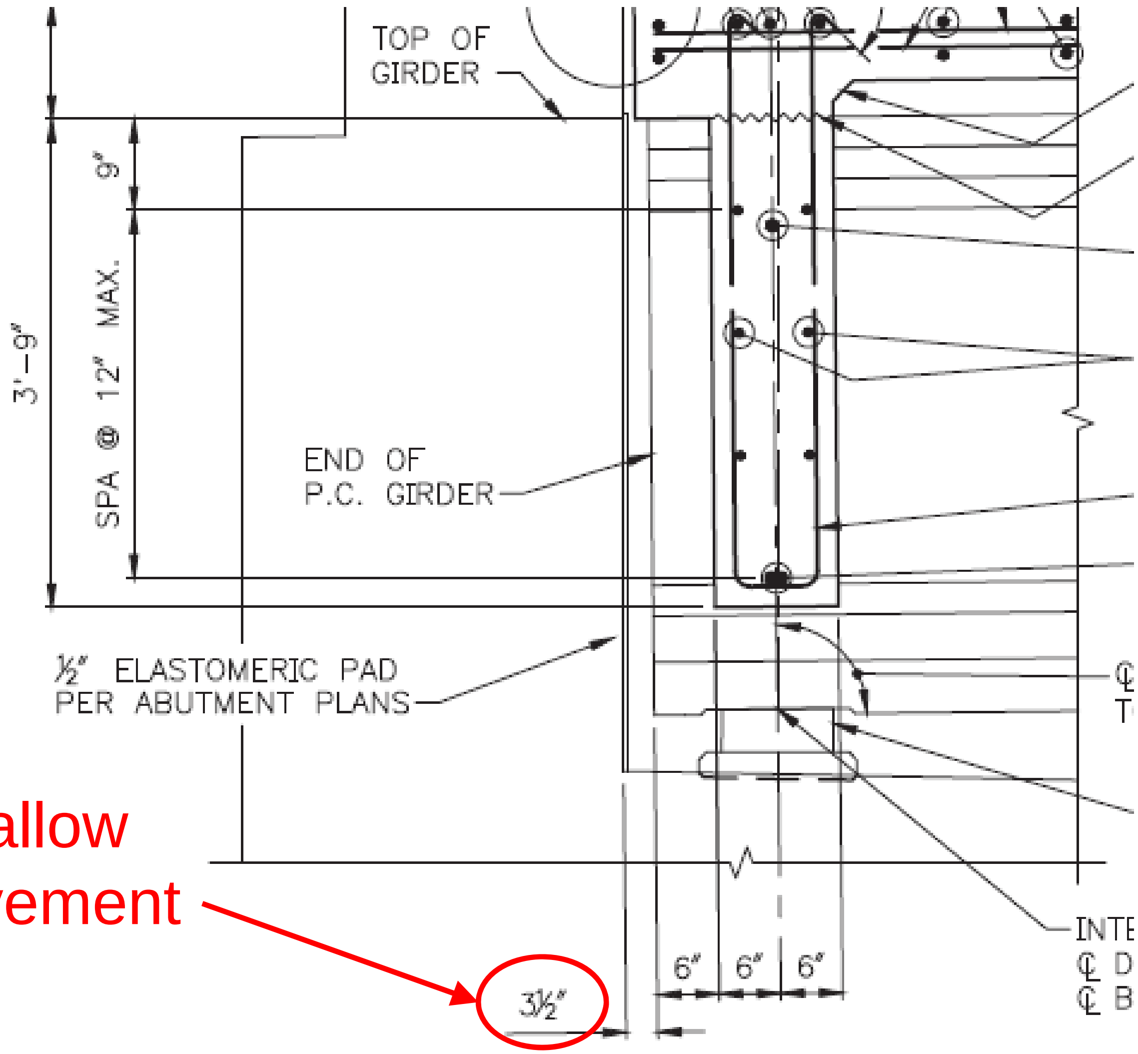
# ABUTMENTS

## Design Options/Decisions

1. Ground Improvement
2. Braced abutment
3. Free Abutment

# 1. GROUND IMPROVEMENT

# 2. BRACED ABUTMENTS

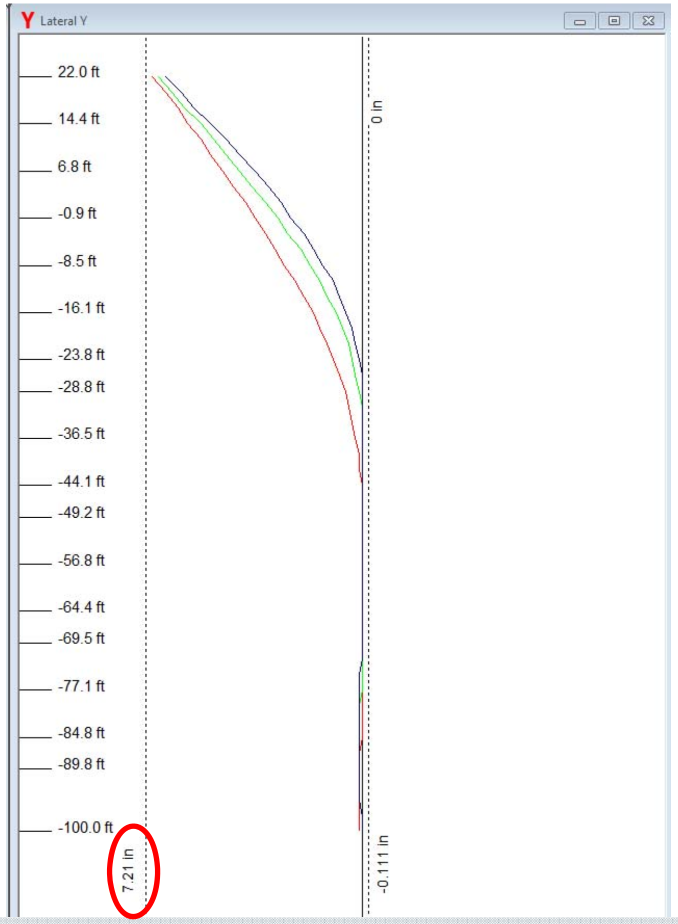



Design gap to allow
for service movement

# 2. BRACED ABUTMENTS

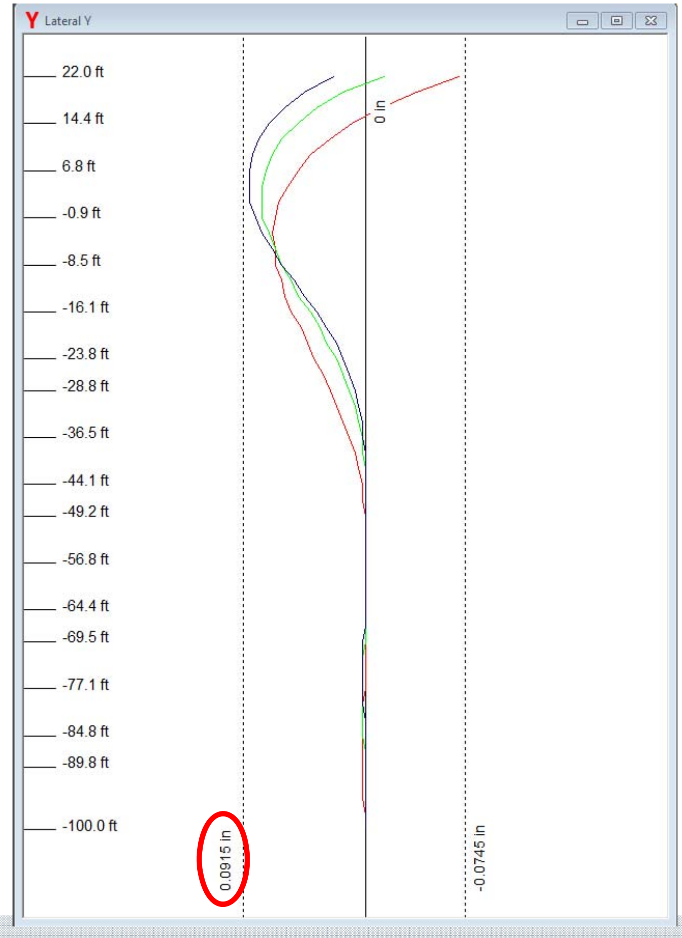
## BRACED PIN FORCE

Deflection =7.21”




## FULL PIN FORCE

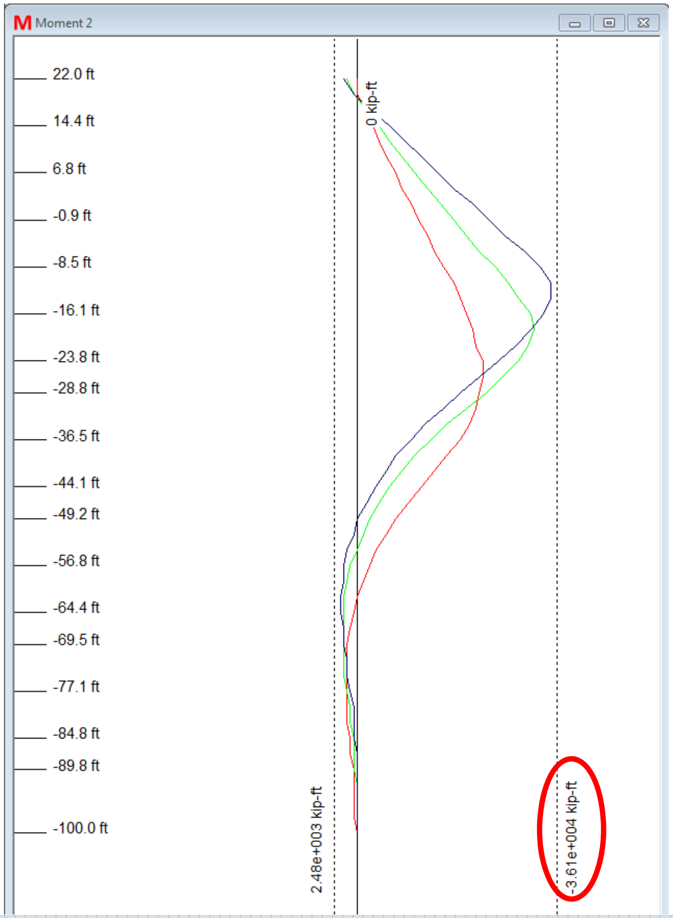
Deflection = 0.09”



# 2. BRACED ABUTMENTS

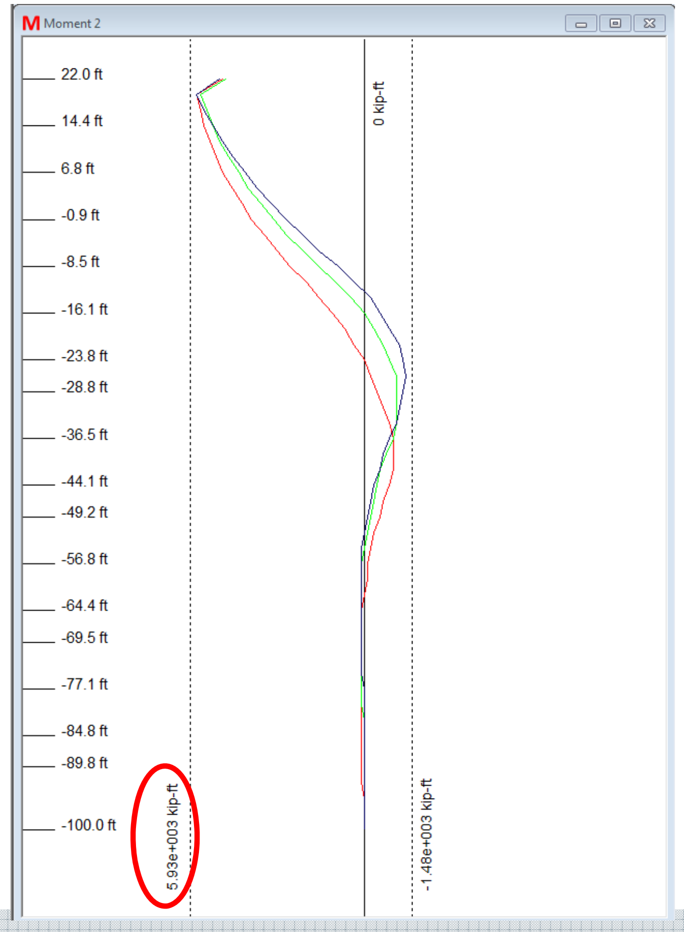
**BRACED PIN FORCE**

$M_{Max}$ = 36,000 kip-ft




**FULL PIN FORCE**

$M_{Max}$ = 5,900 kip-ft

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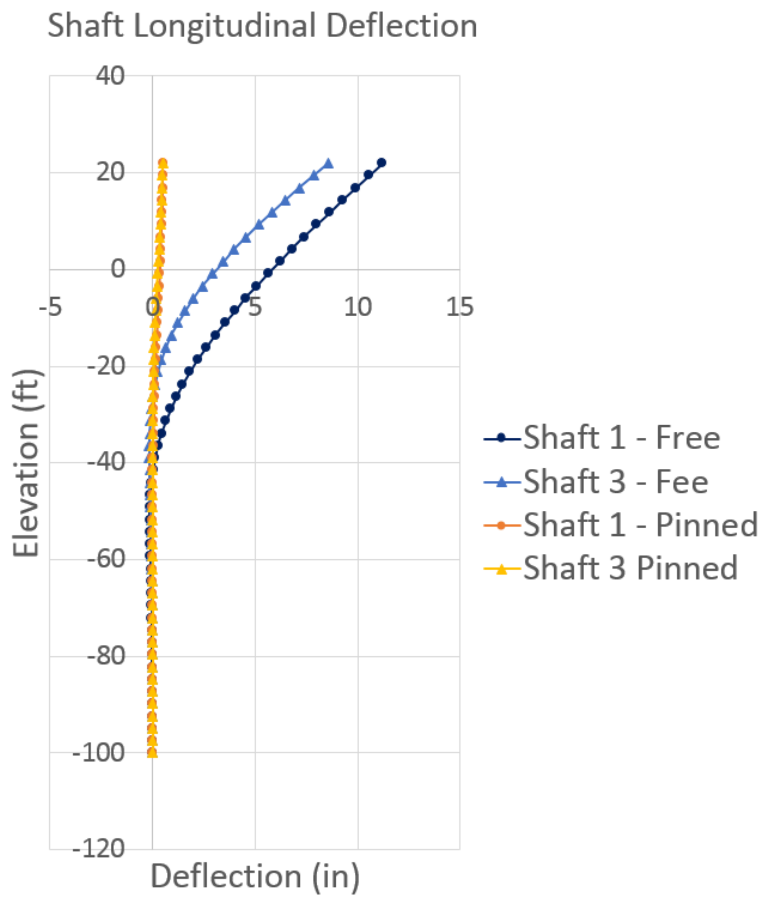
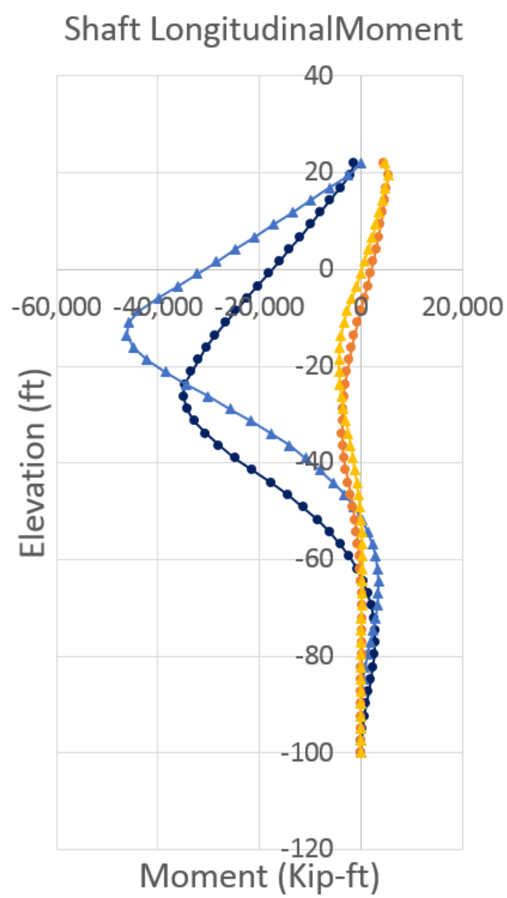
# 3. FREE ABUTMENTS

| | | |
|---|---|---|
| Shaft 1 Free: | Deflection =11.2" | $M_{Max}$ = 35,000 kip-ft |
| Shaft 3 Free: | Deflection = 8.5" | $M_{Max}$ = 46,000 kip-ft |
| Pinned: | Deflection = 0.5" | $M_{Max}$ = 5,400 kip-ft |

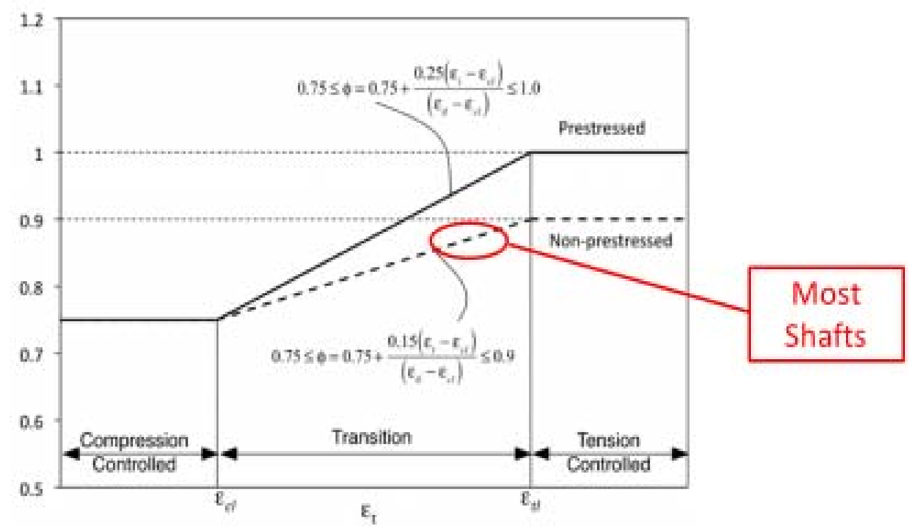


# ABUTMENT REINFORCING

## Shaft Reinforcing:

1. <u>Inner Concentric Ring</u>
   - WSDOT BDM 7.8.2.P “Use of two concentric circular rebar cages shall be avoided”
2. <u>#18 ~ 3 Bar Bundles</u>
   - Similar capacity as inner concentric ring
   - 3 bar #18 bundle not permitted for “flexural members”
   - Shafts in transition zone
3. <u>Materials</u>
   - 80 KSI Steel
   - 5,000 psi concrete

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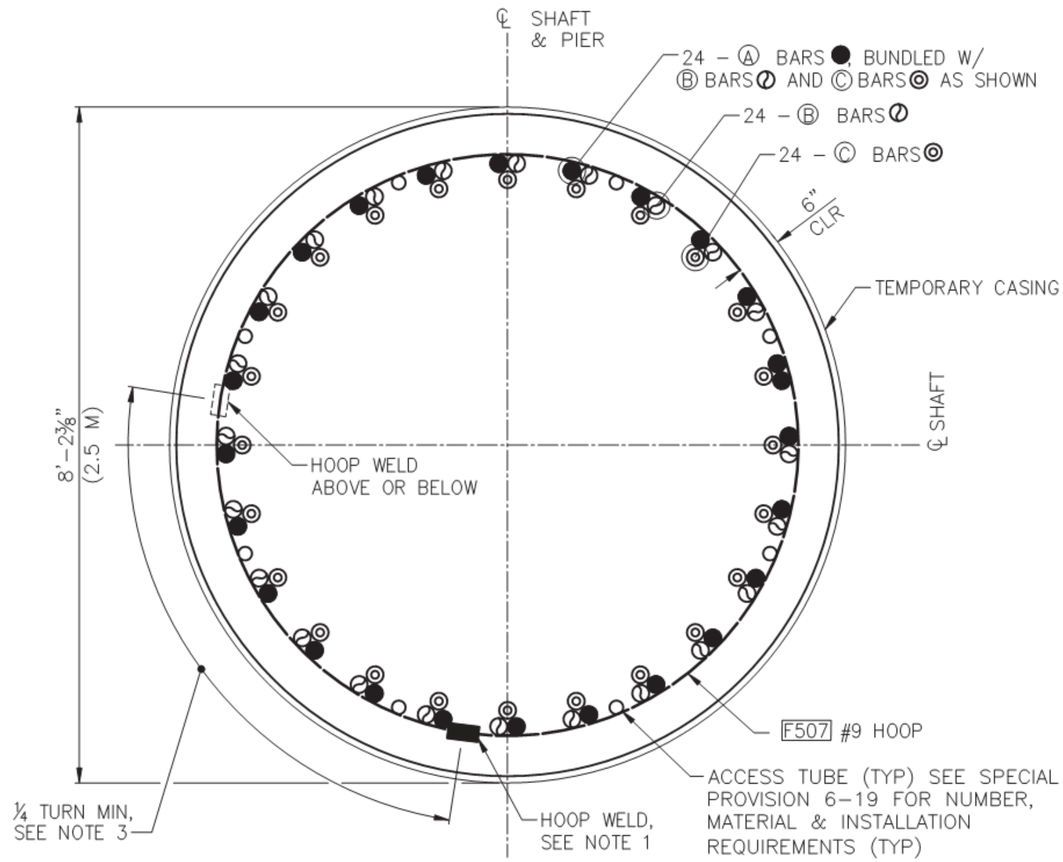
# ABUTMENT SHAFTS – FINAL

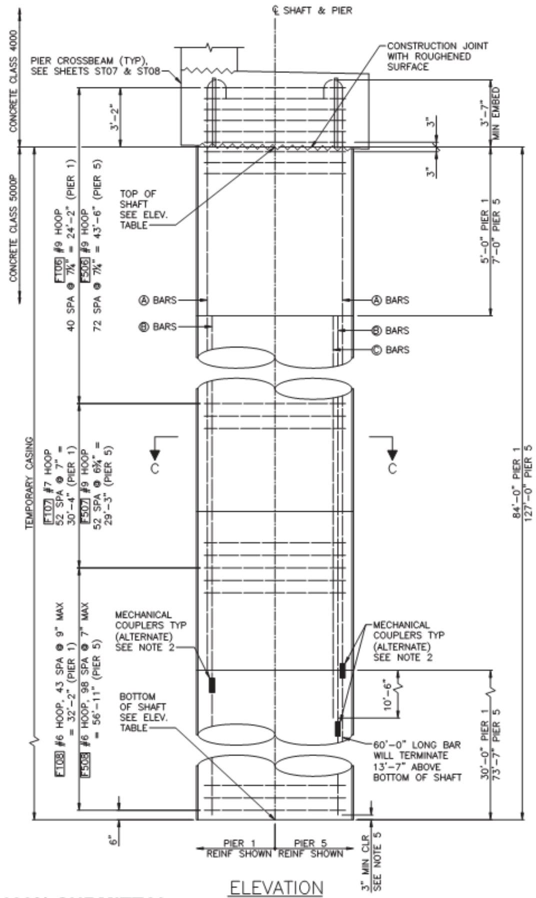


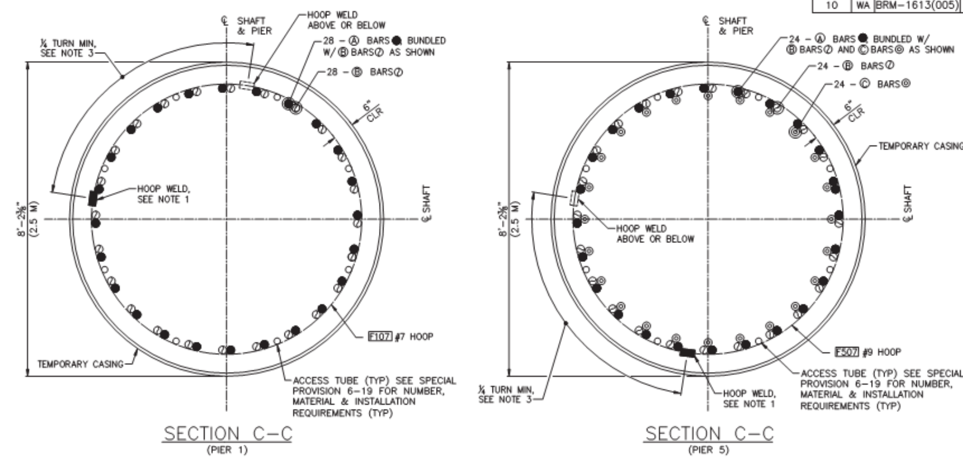

SECTION C–C

(PIER 5)

# ABUTMENT SHAFTS – FINAL

| REGION NO. | STATE | FEDERAL AID PROJECT NO. | SHEET NO. |
|---|---|---|---|
| 10 | WA | BRM-1613(005) | 73 |




## DRILLED SHAFT REINFORCING TABLE

| | | Ⓐ BARS | | Ⓑ BARS | | Ⓒ BARS | |
|---|---|---|---|---|---|---|---|
| | NO. OF SHAFTS | MARK | TOTAL BARS | MARK | TOTAL BARS | MARK | TOTAL BARS |
| PIER 1 | 3 | F101 #14 | 28 | F102 #14 COUPLED W/ F103 #14 * | 14<br>14 | – | – |
| | | | | F104 #14 COUPLED W/ F105 #14 * | 14<br>14 | | |
| PIER 5 | 3 | F501 #18 COUPLED W/ F502 #18 @ EVERY OTHER BAR ** | 24<br>12 | F503 #18 COUPLED W/ F504 #18 @ EVERY OTHER BAR ** | 24<br>12 | F505 #18 | 24 |

SEE SECTION C–C FOR BAR ARRANGEMENT
SEE NOTE 4

* THE F102 / F103 AND F104 / F105 BARS SHALL BE ON ALTERNATING BUNDLES
** THE F502 AND F504 SHALL BE ON ALTERNATING BUNDLES

## SHAFT ELEVATION TABLE

| PIER NO. | TOP OF SHAFT ELEVATION | | | BOTTOM OF SHAFT ELEVATION | | |
|---|---|---|---|---|---|---|
| | SHAFT | | | SHAFT | | |
| | A | B | C | A | B | C |
| 1 | 20.64 | 21.10 | 20.58 | −63.4 | −62.9 | −63.4 |
| 5 | 19.60 | 20.06 | 19.54 | −107.4 | −106.9 | −107.4 |

## NOTES:

1. ALL HOOPS SHALL HAVE WELDED LAP SPLICES OR BUTT WELDS. SEE BUTT WELD DETAIL ON SHEET ST06A.
2. NO MORE THAN 50% OF BARS SHALL BE SPLICED OR COUPLED CLOSER THAN 4 FEET APART, MEASURED BETWEEN CENTERLINE OF COUPLERS.
3. ALL HOOP WELDS SHALL BE STAGGERED ¼ TURN MIN. NO SPIRAL OR HOOP WELD SHALL BE WITHIN ¼ TURN OF ANY WELDS OF THE ADJACENT (UP OR DOWN) SPIRAL OR TWO (2) HOOPS.
4. ALL LONGITUDINAL SHAFT REINFORCEMENT BARS Ⓐ, Ⓑ AND Ⓒ SHALL MEET THE REQUIREMENTS OF ASTM A706 GRADE 80.
5. 3" MIN. CLR. MAY BE WAIVED IF STEEL REINFORCING BAR CAGE SUPPORT IS PROVIDED PER THE SPECIAL PROVISIONS.
6. NO PAYMENT SHALL BE MADE FOR CASING SHORING FOR PIER 1 OR PIER 5 SHAFTS.

**100% SUBMITTAL**
**NOT FOR CONSTRUCTION**

ST05
PIERS 1 & 5 SHAFTS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BRIDGE REPLACEMENT

PC TS4986A
CO TS4986C
VAULT PLAN NO. 782-289
SHEET 73 OF 155

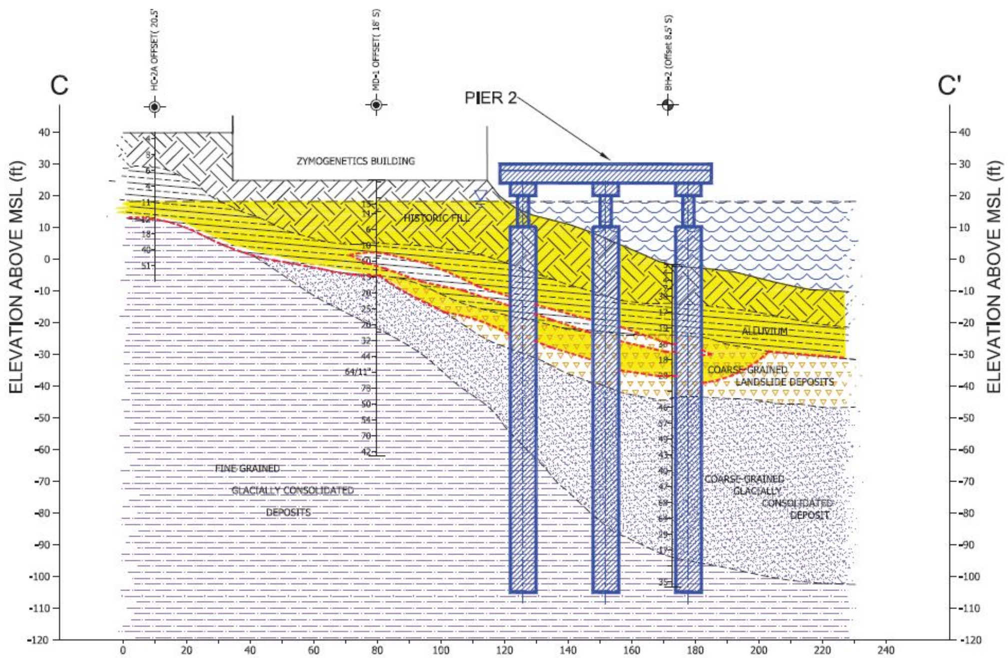
# ABUTMENT CONCLUSIONS

1. Evaluate traditional design
2. Increase material strengths ($f_y$ = 80 ksi)
3. Increase reinforcing (triple bundled #18)
4. Reduce flow loads
   - Ground improvement
   - Evaluate pinned abutments
   - Materials to reduce passive pressure crust

# INTERMEDIATE PIERS

## Design Challenges

- Poor Soil Conditions – low soil strength, liquefaction
- High flow loads during Seismic Event
- Shafts designed for Capacity Protection
- Appropriate combination of overstrength requirements and flow loads

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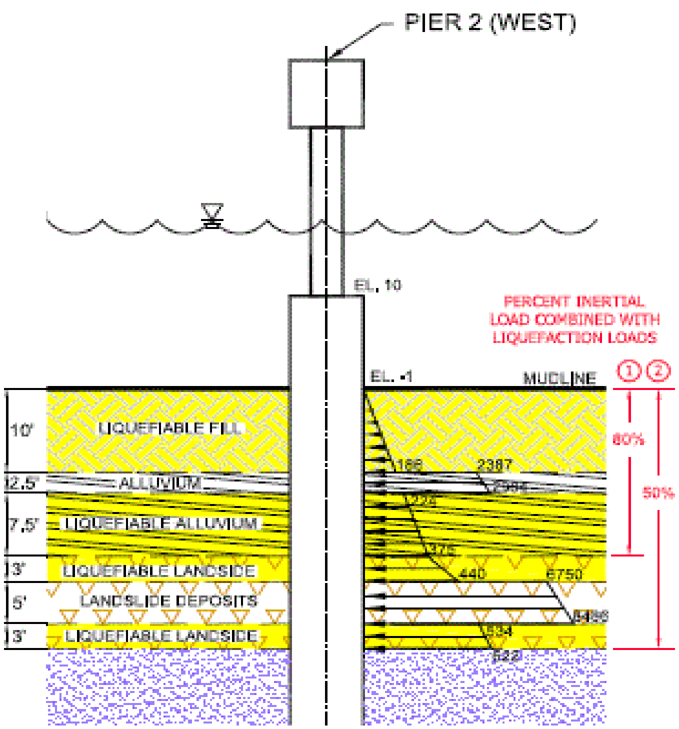
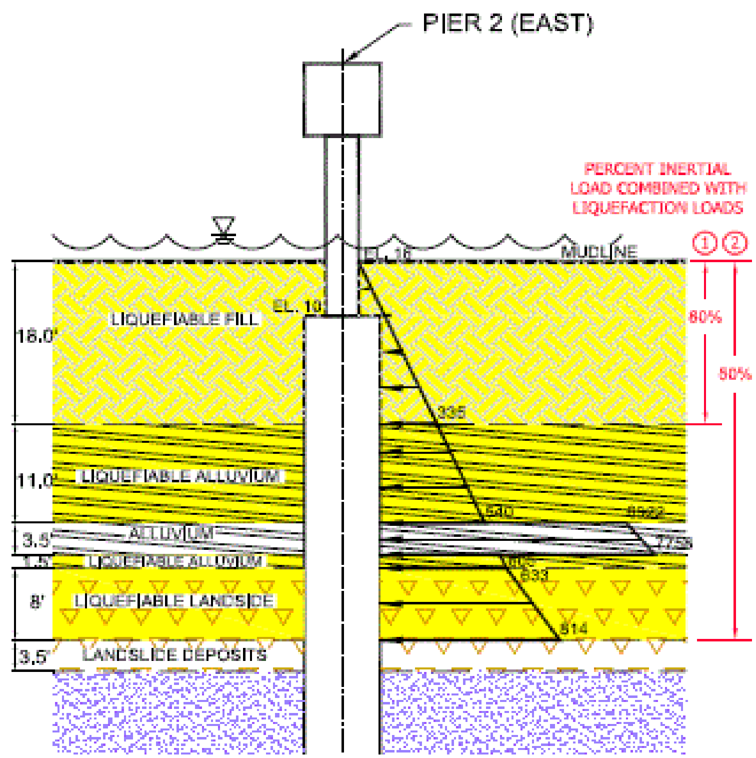
# Pier 2 - Flow Slide Event Loads

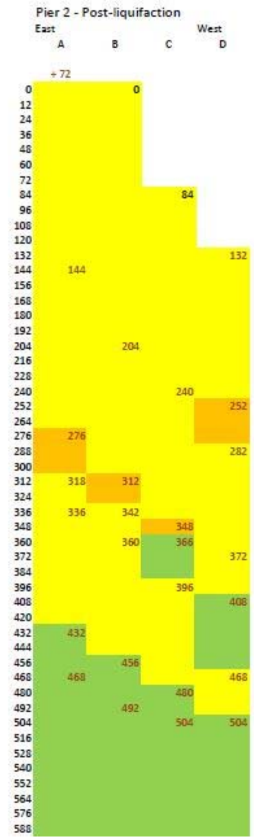



- High "Flow Loads" during Extreme Event
- Flow Load Timing
  - Upper layer with 80% inertial loads
  - Full flow with 50% inertial loads

# Soil Profile – Data for L-Pile

- Graphical Representation of Soil Profiles




Depth to top of soil profile = -72 in.

| Column A | | | | | | | |
|---|---|---|---|---|---|---|---|
| Layer depth | section height | Unit Weight | Friction Angle | Shear Strength | Shear Strength | k (p-y modulus) | Strain factor |
| in. | in. | pci / pcf | deg. | psi | psf | pci | |
| 0 / 216 | 216 | 0.0356 / 61.517 | 9 | | | 20 | |
| 216 / 348 | 132 | 0.0356 / 61.517 | 10 | | | 20 | |
| 348 / 390 | 42 | 0.0356 / 61.517 | 36 | | | 50 | |
| 390 / 408 | 18 | 0.0356 / 61.517 | 10 | | | 20 | |
| 408 / 504 | 96 | 0.0438 / 75.686 | 13 | | | 20 | |
| 504 / 540 | 36 | 0.0438 / 75.686 | 40 | | | 125 | |
| 540 / 540 | 0 | 0.0438 / 75.686 | 13 | | | 20 | |
| 540 / 888 | 348 | 0.0435 / 75.168 | 39 | | | 125 | |
| 888 / 2200 | 1312 | 0.0322 / 55.642 | | 42.1 / 42.1 | 6062.4 / 6062.4 | 2000 | 0.004 |

Effective width = 96 in.

- L-Pile properties entered for each pier
- Interpolation used for middle pier

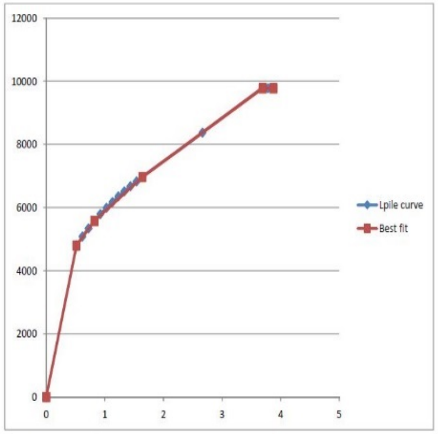
# Soil Springs - P-Y Curves from L-Pile

Pier 2, Column C

P-Y Curve LINK2C3 depth = 28 feet

| y, in | p, lbs/in | slope |
|---|---|---|
| 0 | 0 | |
| 0.5144 | 4793.98764 | 9320 |
| 0.61673 | 5083.28947 | 2827 |
| 0.71905 | 5341.6714 | 2525 |
| 0.82138 | 5576.21762 | 2292 |
| 0.92371 | 5791.72921 | 2106 |
| 1.02604 | 5991.62736 | 1953 |
| 1.12836 | 6178.44577 | 1826 |
| 1.23069 | 6354.11921 | 1717 |
| 1.33302 | 6520.16233 | 1623 |
| 1.43535 | 6677.78563 | 1540 |
| 1.53767 | 6827.97353 | 1468 |
| 1.64 | 6971.53863 | 1403 |
| 2.665 | 8378.80585 | 1373 |
| 3.69 | 9786.07308 | 1373 |
| 3.78225 | 9786.07308 | 0 |
| 3.8745 | 9786.07308 | 0 |

| | |
|---|---|
| 0 | 0 |
| 0.514 | 4794.0 |
| 0.821 | 5576.2 |
| 1.640 | 6971.5 |
| 3.690 | 9786.1 |
| 3.875 | 9786.1 |




| | |
|---|---|
| location | 28 |
| length | 96 |
| -939.463 | -0.32288 |
| -939.463 | -0.3075 |
| -669.268 | -0.13667 |
| -535.317 | -0.06845 |
| -460.223 | -0.04287 |
| 0 | 0 |
| 460.2228 | 0.042867 |
| 535.3169 | 0.068448 |
| 669.2677 | 0.136667 |
| 939.463 | 0.3075 |
| 939.463 | 0.322875 |

- Typical P-Y Curve

Spring values modified for group effects

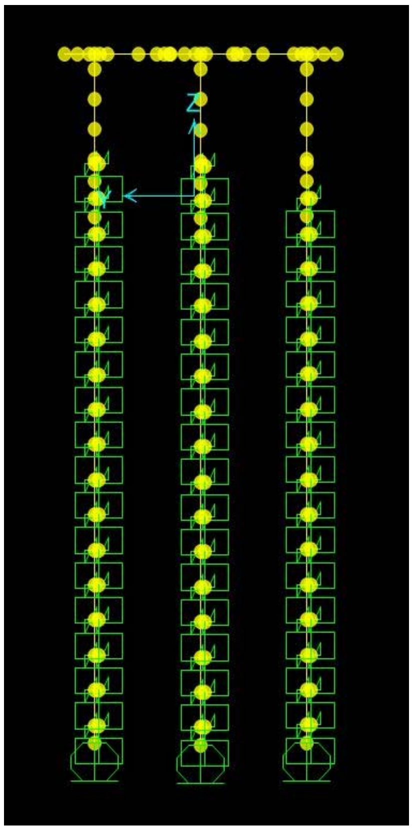
**Table 11.**
**P Multipliers for Center-to-Center Spacing of 3.2 Shaft Diameters**

| Row | P Multiplier |
|---|---|
| 1 | 0.82 |
| 2 | 0.44 |
| 3 or more | 0.33 |

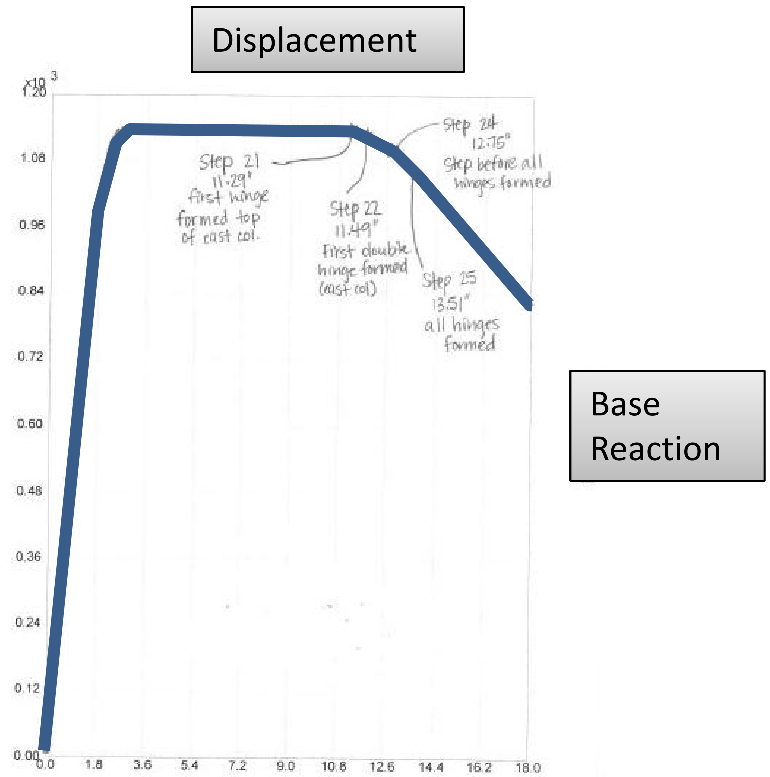
Parallel Direction


Perpendicular Direction

# CSi Bridge -
# Pushover Analysis with Soil Springs



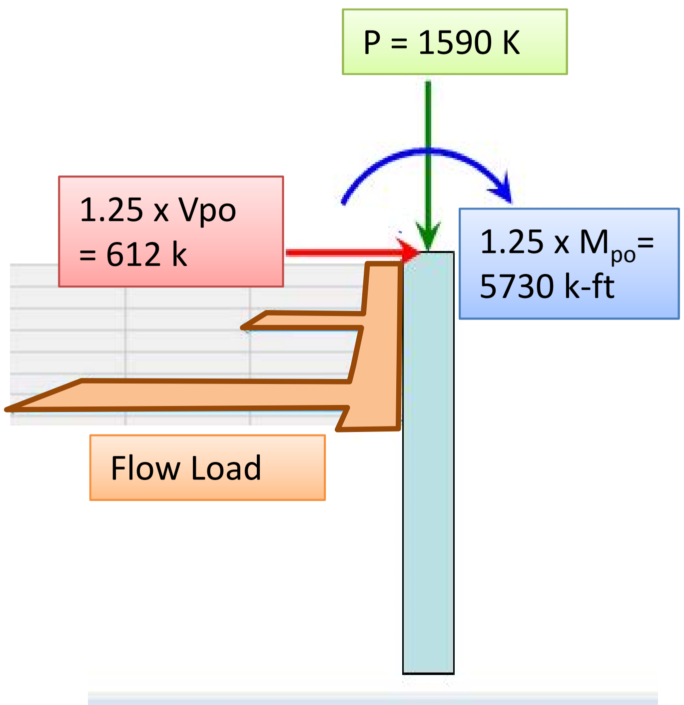
- Pier 2 Pushover Model



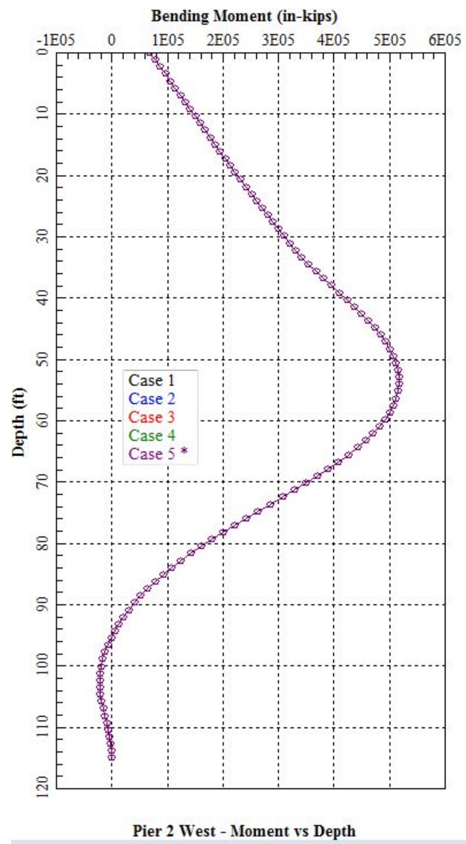

- Pier 2 Pushover Curve

# L-Pile -

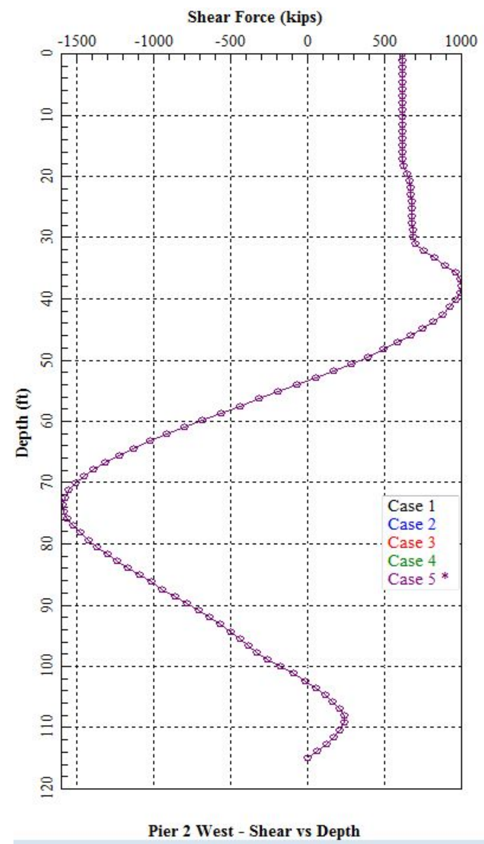
# Shaft Strength Demands




Shaft Loading




Moment Demand




Shear Demand

# INTERMEDIATE PIERS

## Design Results and Options/Decisions

### Meeting high flexural demands in shafts

A. Increase Strength of Shafts

- Increase number of shafts
- Use 3-bar bundles of reinforcement
- Use concentric rings of reinforcement
- Increase material strength

B. Decrease demands in shafts

- Reduce inertial forces with flow loads
    - NO Reduction in column plastic hinge.
- Reduce of the multiplier on $M_{po}$ in combination with flow loads.

# INTERMEDIATE PIERS

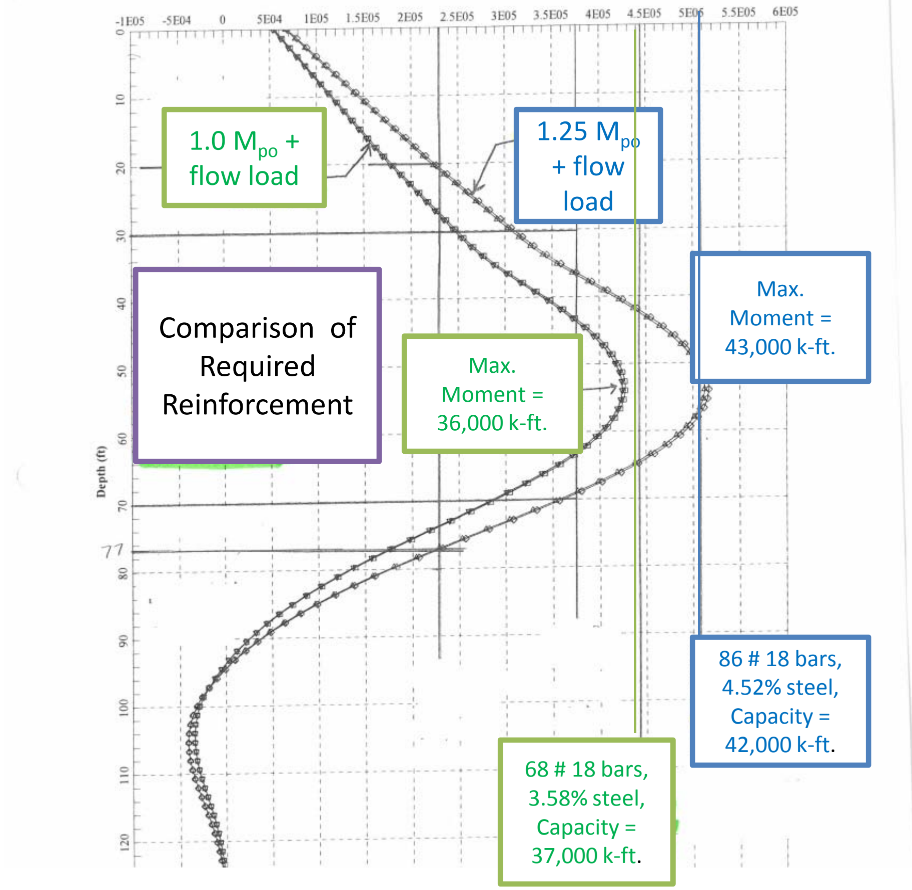
## 1.25 $M_{po}$ vs 1.0 $M_{po}$ when combined with flow loads

- AASHTO Code requires $M_{ne} > 1.25 \times M_{po}$
- Reduction of the multiplier: AASHTO Guide Spec 8.9 States:
  - "With the Owner's approval, the factor of 1.25 may be reduced to 1.0 for the liquefied configuration."
- The Code does not address combination with flow loads.
- Flow load occurs after the maximum inertial load

# INTERMEDIATE PIER OPTIONS

## $1.25M_{po}$ vs $1.0\ M_{po}$ - Forces generated in Shafts

### Moment in Shafts – Pier 2, west side




- Flow load analysis assumes no soil resistance in the flow zone.
- $1.25 \times M_{po}$ + NO flow load results are similar to $1.0 \times M_{po}$ + flow loads

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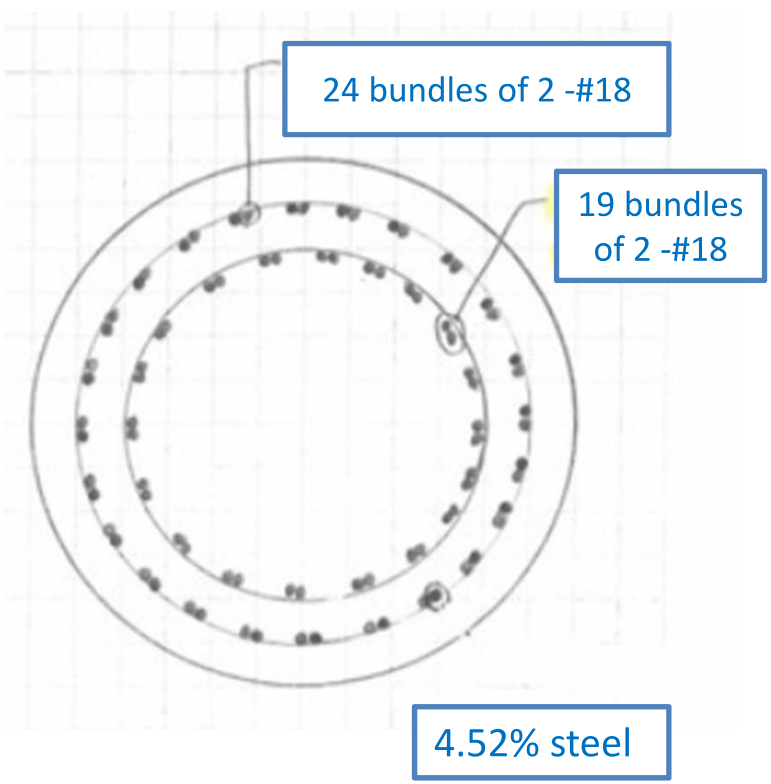
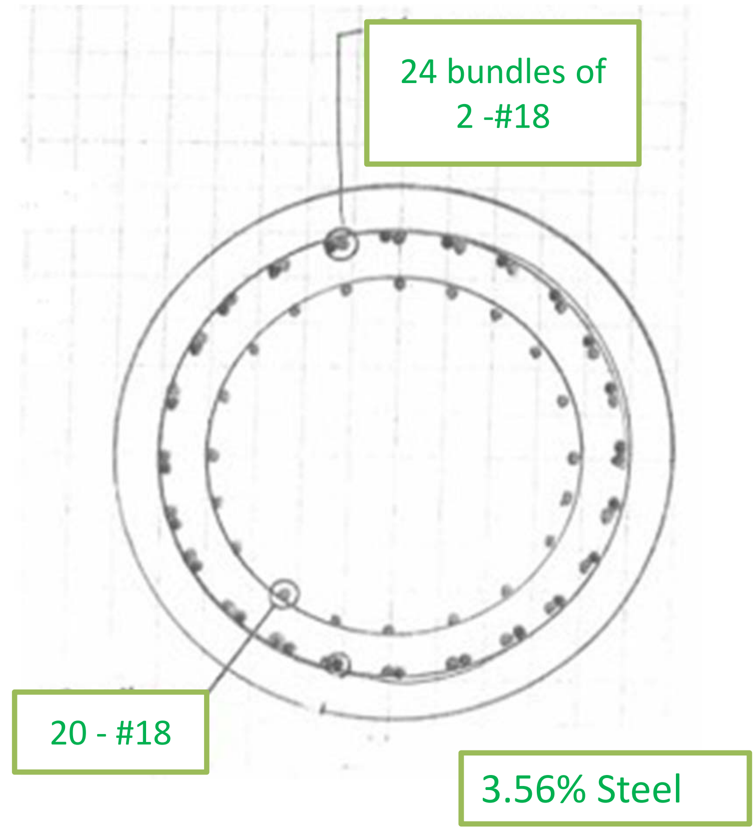
# INTERMEDIATE PIER OPTIONS

## $1.25M_{po}$ vs $1.0\ M_{po}$ - Reinforcement in Shafts

Pier 2 - Design for 1.25 $M_{po}$ with flow loads




Pier 2 - Design for 1.0 $M_{po}$ with flow loads
OR for 1.25 $M_{po}$ without flow loads



# INTERMEDIATE PIERS

## Use of Higher Strength Materials

- Use of 80 ksi Reinforcement
  - Reduces reinforcement
  - Meets design strength without 3 bar bundles or a concentric inner ring.
  - Availability increasing, already being used.
- Use of Concrete with $f_c$' = 5000 psi
  - Best practice to match 80 ksi reinforcement.
  - Stiffer shaft reduces maximum moment
  - Increases shear capacity

Shortly after our discussions with SDOT and WSDOT on the use of 5000 ksi concrete in shafts, this memorandum was issued by WSDOT.

Washington State Department of Transportation
Bridge and Structures Office

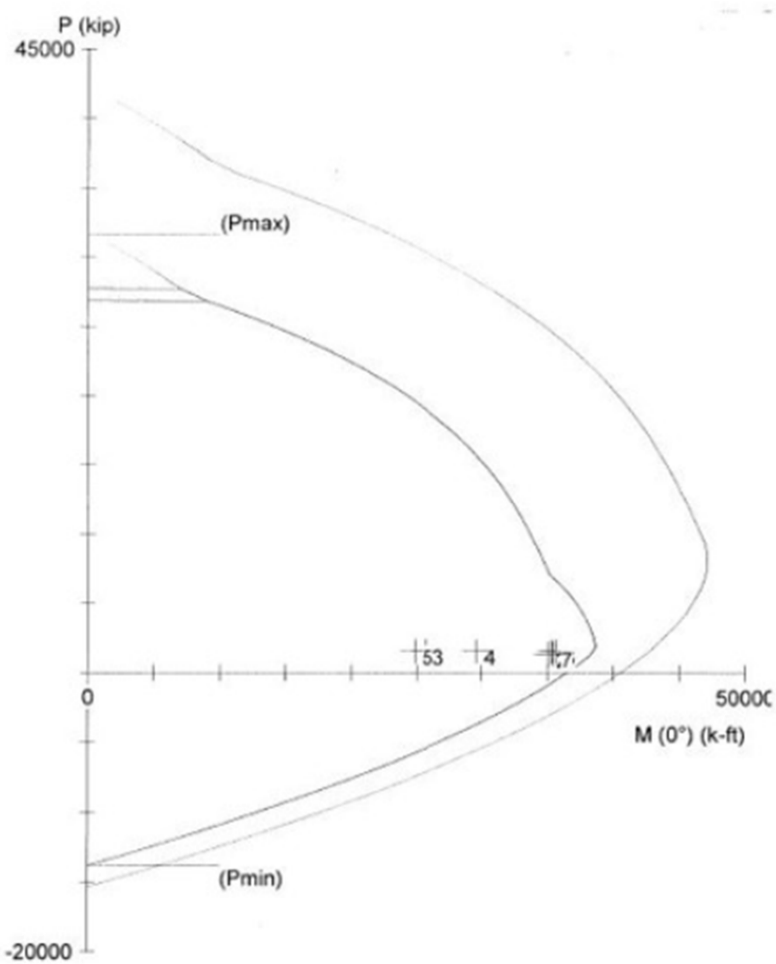
**Design Memorandum**

TO: All Design Section Staff
FROM: Bijan Khaleghi
DATE: September 23, 2016
SUBJECT: Concrete Class 5000P in Bridge Foundations

This design memorandum allows the use of Concrete Class 5000P for piles, shafts, and deep foundations for bridges and other structures. Concrete Class 5000P should be called out in the Plans by designers for use in deep foundations for bridges and may be specified in other locations where Concrete Class 4000P would otherwise be specified.

# INTERMEDIATE PIERS

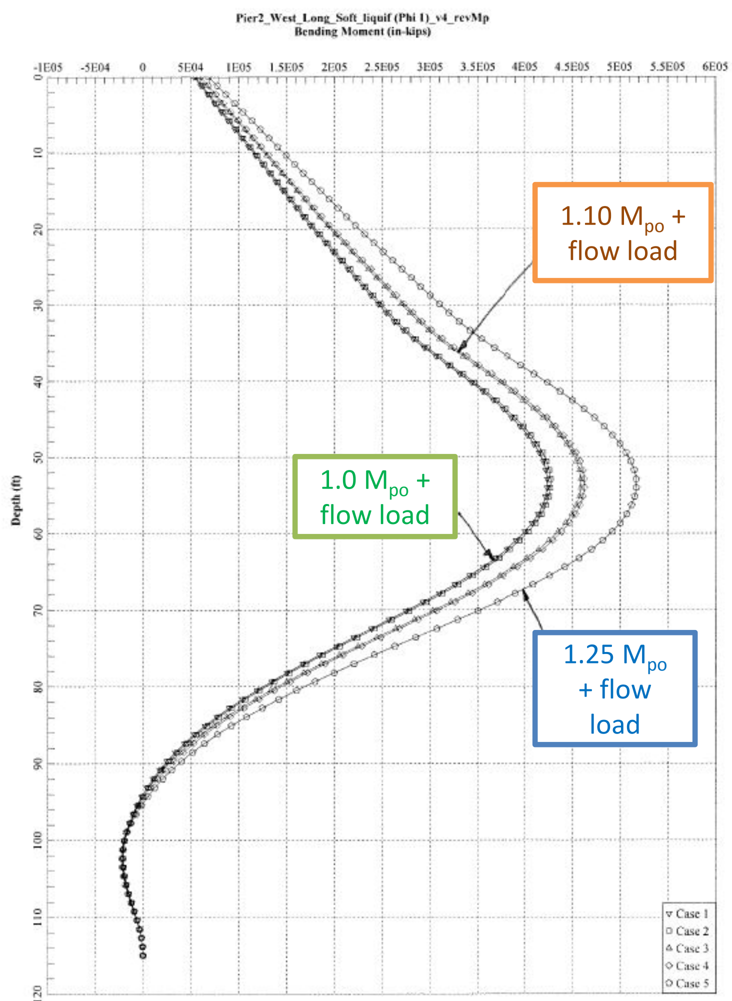
## Revised Analysis with Higher Strength Materials

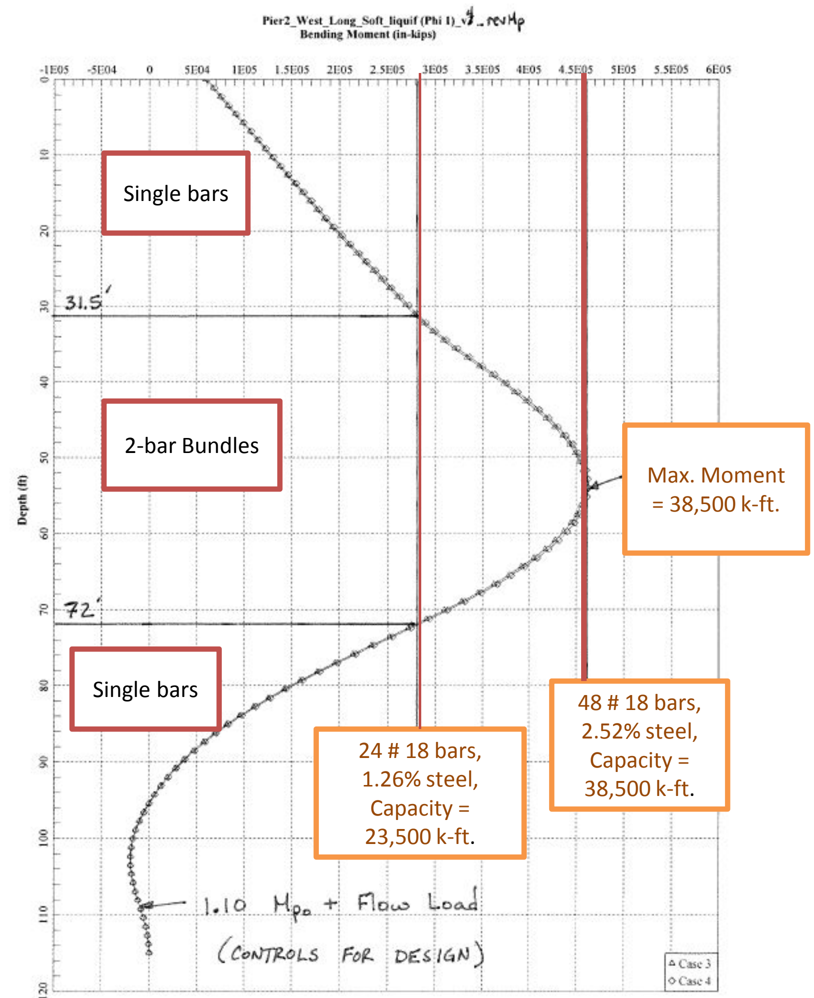



- Column Strength analysis using spColumn software
- Results for max. reinforcement in one layer with 2-bar bundles
  - 24 bundles of 2 -#18 bars
  - Based on 6" of cover and minimum allowed bar spacing

# INTERMEDIATE PIERS

## Revised Analysis with Higher Strength Materials

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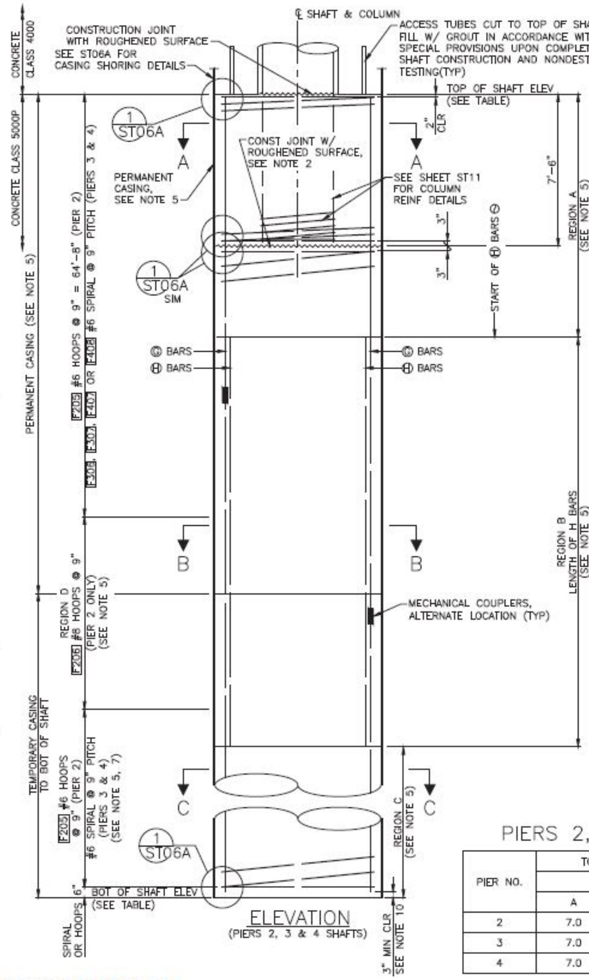
# INTERMEDIATE PIER

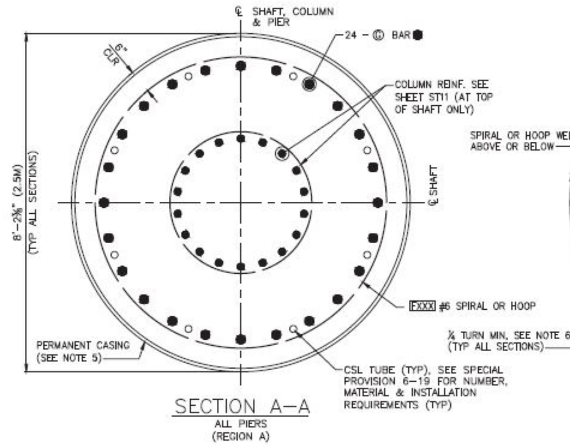
## CONCLUSIONS

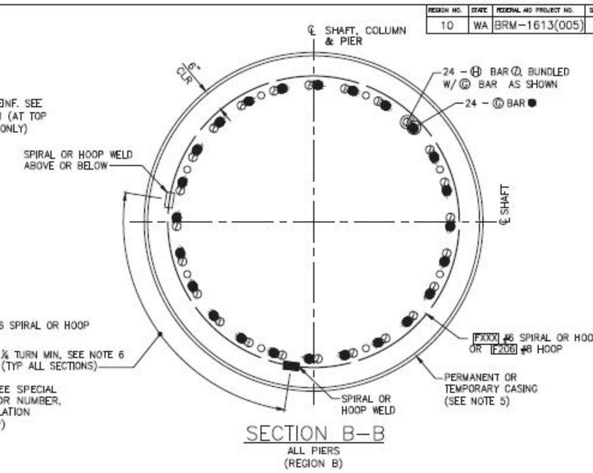
- Higher Strength Materials
- Design for greater of:
  - 1.10 $M_{po}$ with the flow loads or
  - 1.25 $M_{po}$ without flow loads
- Reduces shaft reinforcement so one ring of 2-bar bundles is adequate

# INTERMEDIATE SHAFTS – FINAL SHEET

| REGION NO. | STATE | FEDERAL AID PROJECT NO. | SHEET NO. |
|---|---|---|---|
| 10 | WA | BRM-1613(005) | 74 |

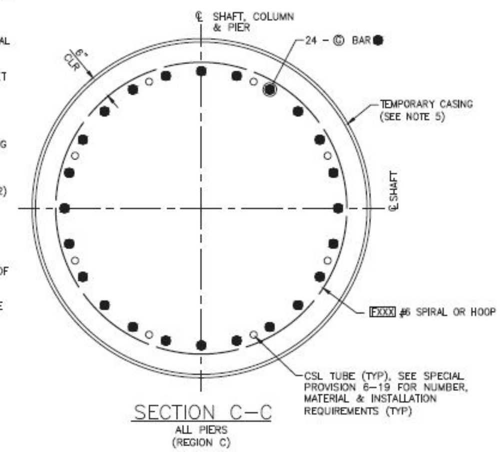



## NOTES:

1. SEE SPIRAL TERMINATION DETAIL ON SHEET ST06A. SPIRAL TERMINATION DETAIL TO BE USED FOR SPIRAL REINFORCEMENT ONLY.
2. REMOVE SEDIMENT LAITENCE AND WEAK CONCRETE TO SOUND CONCRETE PRIOR TO SETTING COLUMN REINFORCEMENT. (IF CONTRACTOR ELECTS TO NOT HAVE A CONSTRUCTION JOINT, SPIRAL REINFORCEMENT TO BE CONTINUOUS THROUGH THIS SECTION.)
3. ALL #6 SPIRALS SHALL HAVE WELDED LAP SPLICES. SEE WELDED LAP SPLICE DETAIL ON SHEET ST06A.
4. ALL #6 OR #8 HOOPS SHALL HAVE WELDED LAP SPLICES OR BUTT WELDS. SEE WELDED LAP SPLICE DETAIL OR BUTT WELD DETAIL ON SHEET ST06A.
5. FOR ALL TABLES TO DEFINE REINFORCING REGIONS, REINFORCING BARS, AND PERMANENT CASING LENGTH, SEE SHEET ST06A.
6. ALL SPIRAL OR HOOP WELDS SHALL BE STAGGERED ¼ TURN MIN. NO SPIRAL OR HOOP WELD SHALL BE WITHIN ¼ TURN OF ANY WELDS OF THE ADJACENT (UP OR DOWN) SPIRAL OR TWO (2) HOOPS.
7. #6 SPIRAL @ 9" PITCH SHALL BE USED FOR FULL LENGTH OF SHAFTS AT PIERS 3 & 4.
8. FOR CASING SHORING DETAILS, SEE SHEET ST06A.
9. ALL LONGITUDINAL SHAFT REINFORCING, BARS Ⓖ AND Ⓗ, SHALL MEET THE REQUIREMENTS OF ASTM A706 GRADE 80.
10. 3" MIN. CLR. MAY BE WAIVED IF STEEL REINFORCING BAR CAGE SUPPORT IS PROVIDED PER THE SPECIAL PROVISIONS.



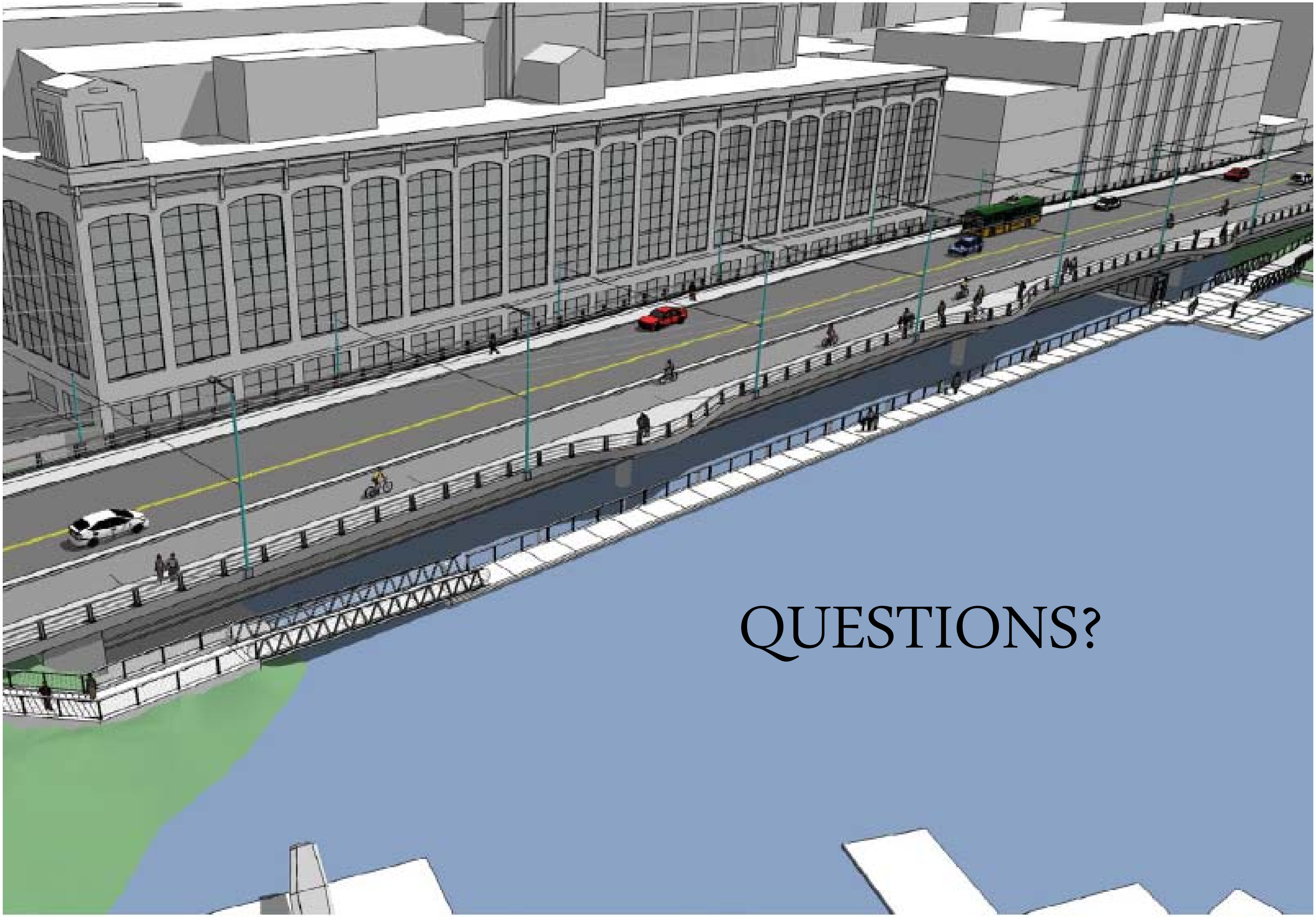

### PIERS 2, 3, & 4 SHAFT ELEVATION TABLE

| PIER NO. | TOP OF SHAFT ELEVATION | | | BOTTOM OF SHAFT ELEVATION | | |
|---|---|---|---|---|---|---|
| | SHAFT | | | SHAFT | | |
| | A | B | C | A | B | C |
| 2 | 7.0 | 7.0 | 7.0 | −108.0 | −108.0 | −108.0 |
| 3 | 7.0 | 7.0 | 7.0 | −108.0 | −123.0 | −123.0 |
| 4 | 7.0 | 7.0 | 7.0 | −108.0 | −128.0 | −128.0 |

**100% SUBMITTAL**
**NOT FOR CONSTRUCTION**

ST06
PIERS 2, 3 & 4 SHAFTS

HNTB



# QUESTIONS?