Innovative Large Shaft Repair for Abraham Lincoln Cable-Stayed Bridge

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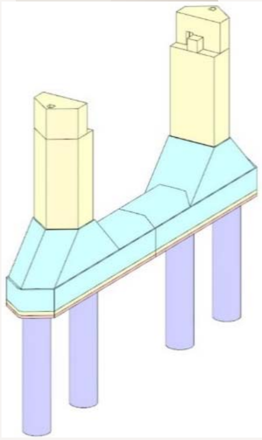
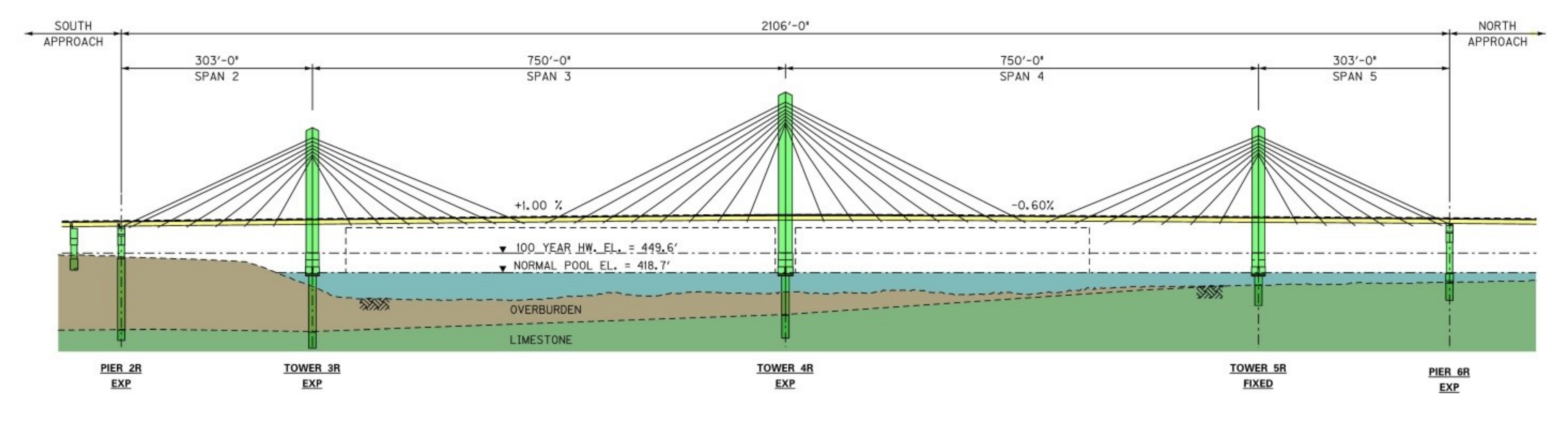
COWI

1. Introduction

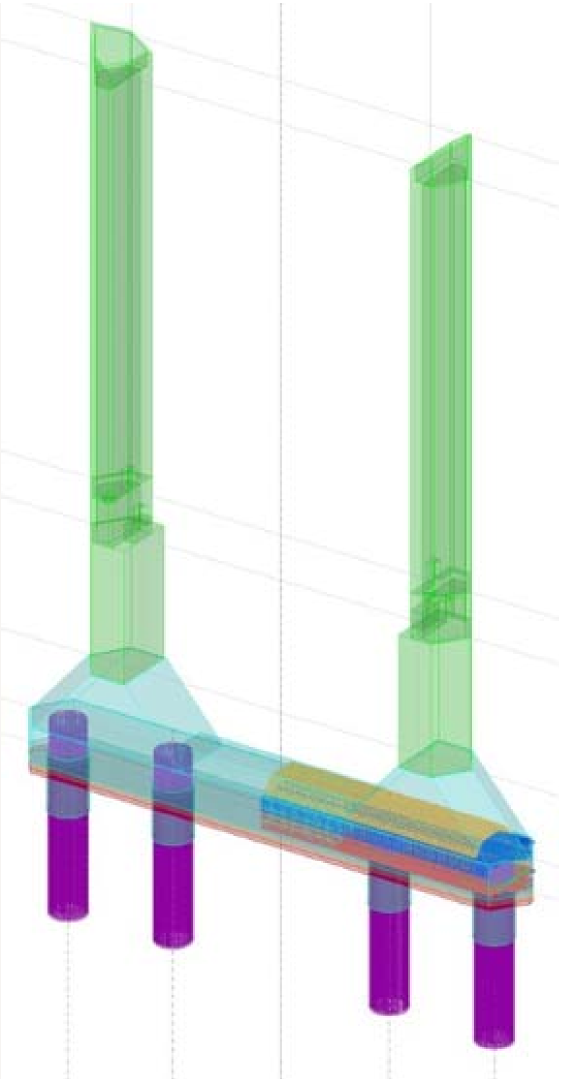
- Span arrangement: two main spans of 750 ft each; two end spans of 303 ft each
- Tower foundations: 12-ft diameter drilled shafts in a single row
- Rock sockets – 18' to 32' in limestone along the sloping bedrock





2. Tower Foundation

- Foundation – Cantilever in longitudinal direction; framing action in transverse direction
- Flexible in longitudinal direction
- Bridge behavior sensitive to p-y spring stiffness in global Soil-Structure interaction modeling
- Geotechnical axial load carrying capacity solely from rock socket side shear and end bearing

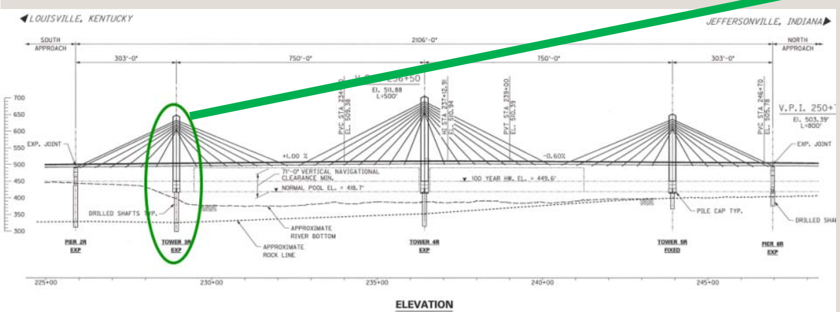


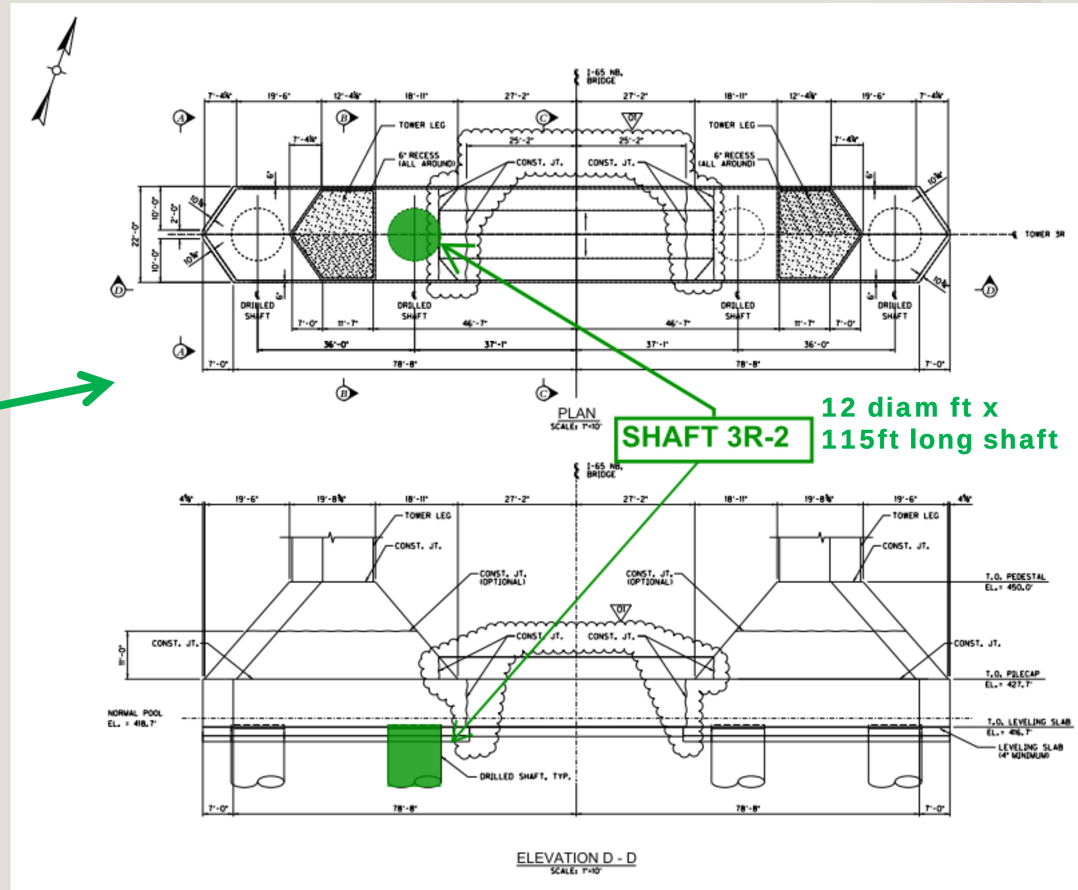
3. Construction Issues

› 80 CY of concrete lost

(equivalent to ~20ft in 12ft diameter shaft)

› Poor quality concrete

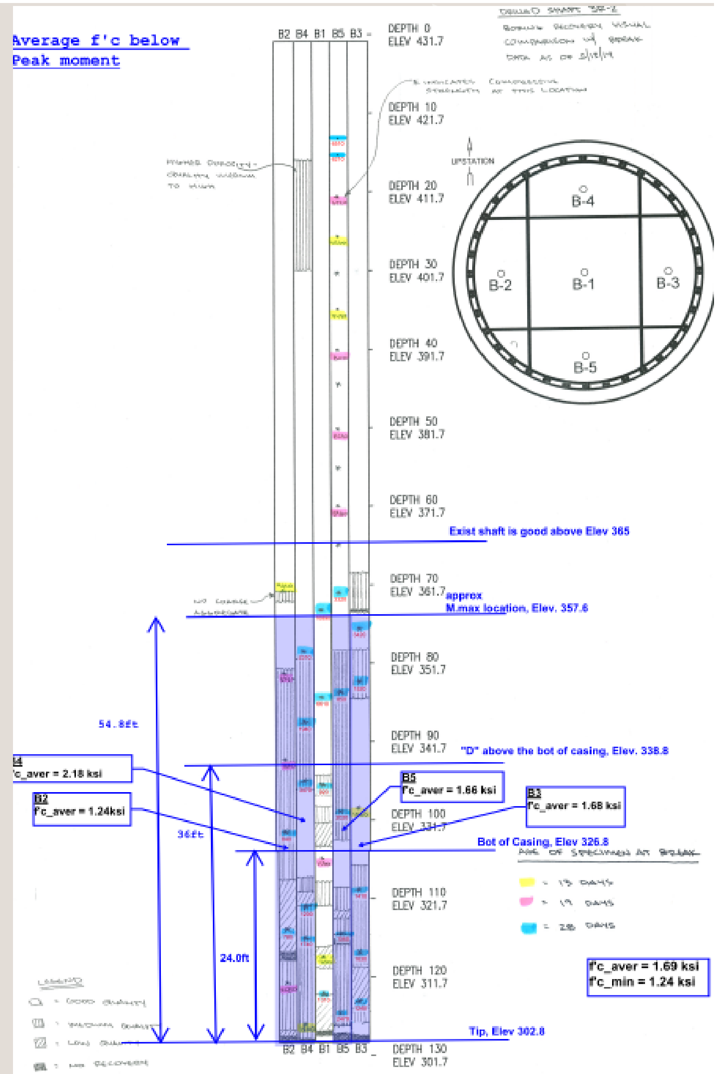




3. Construction Issues (cont.)

- Coring samples
- 1.7ksi average f'c in bottom part of the shaft

Photo 16 3R-2 Center Boring Closeup 123.6' to 124.5'
Box ? of ?

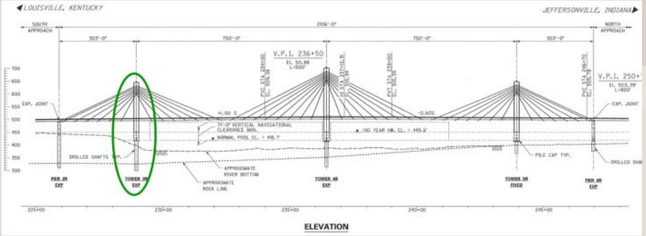


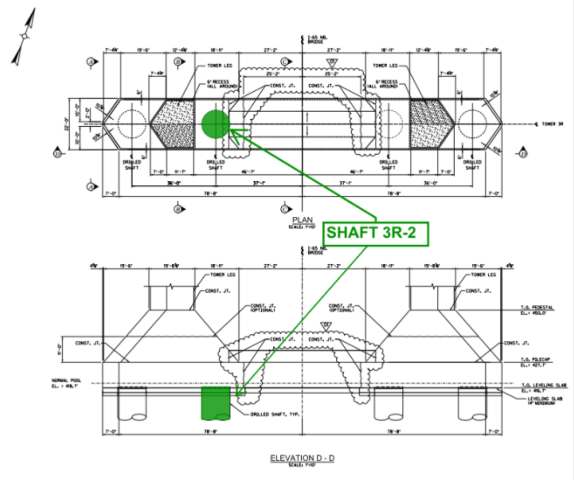
4. Retrofit solution requirements

› Match original stiffness

› Provide required axial geotechnical and structural capacities as in the original design

› Minimize impact to construction schedule





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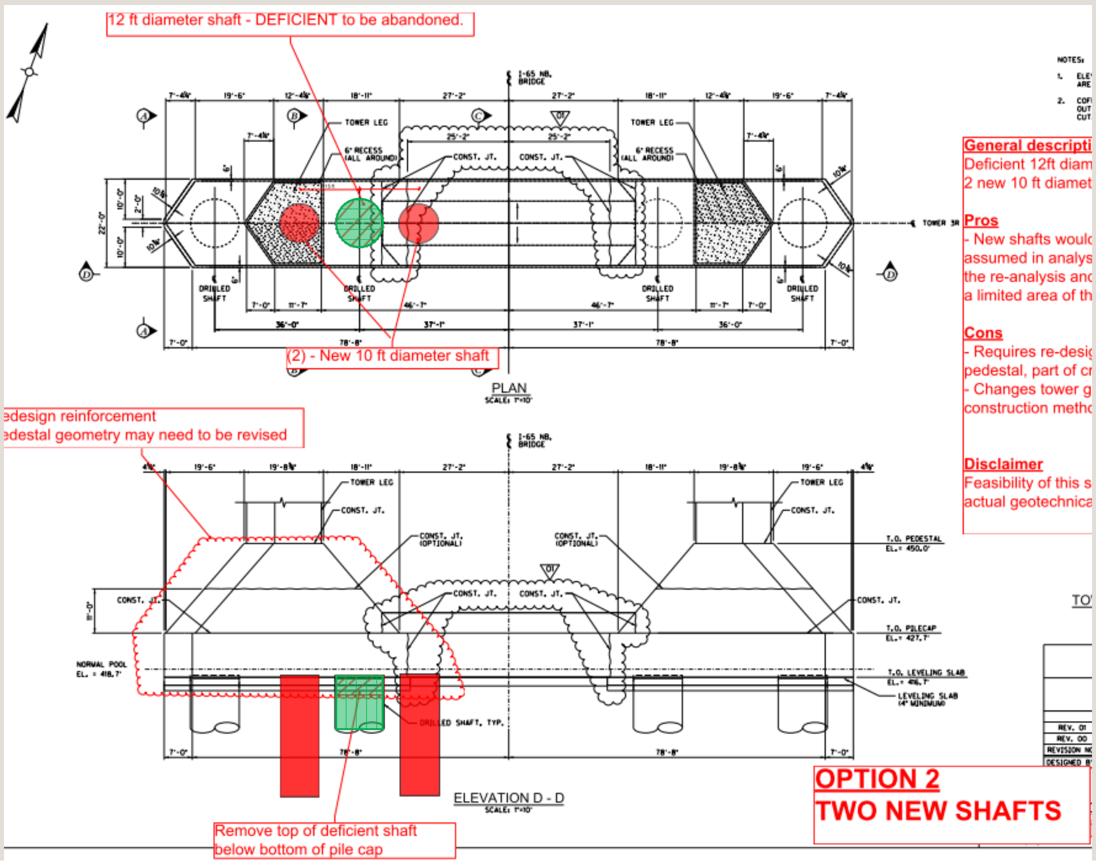
5. Solutions Considered

Two new shafts along CL of Tower



› Pros

  › Can match original stiffness and strength

  › Preserves pilecap outline

  › Conventional construction (less risk)

› Cons

  › Pilecap redesign would delay schedule

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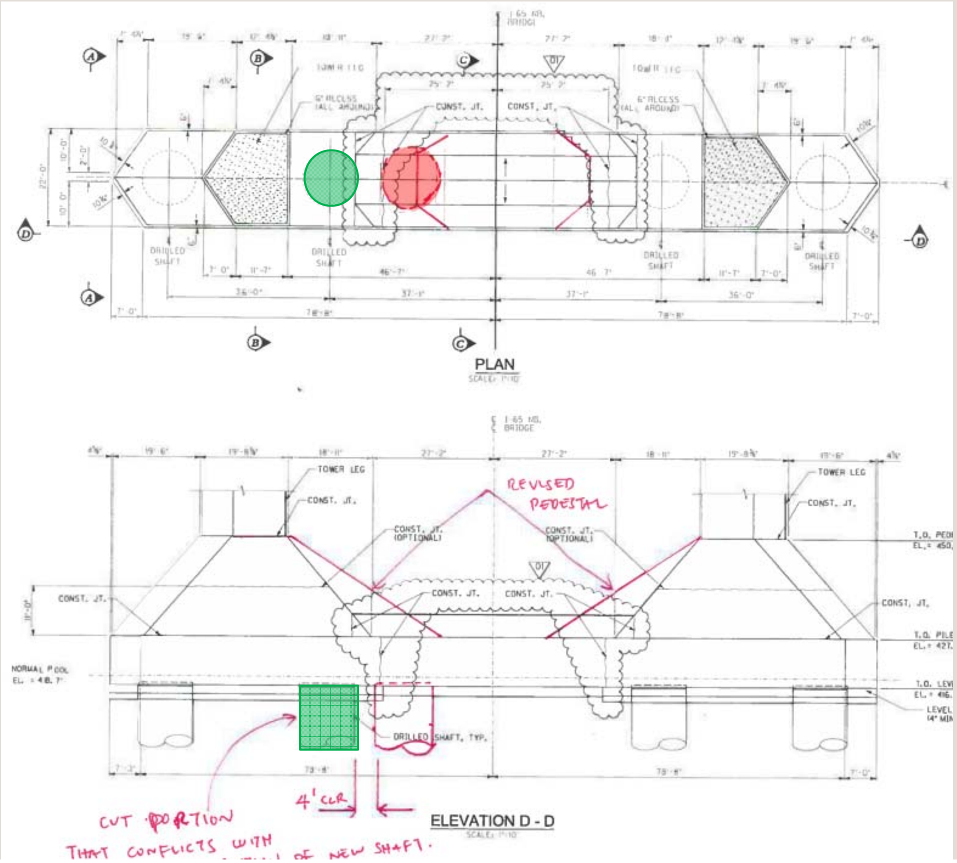
5. Solutions Considered (cont.)

New shaft next to deficient shaft



- Pros
  - Can match original stiffness and strength
  - Conventional construction

    (less risk)

- Cons
  - Pilecap redesign would delay schedule
  - Requires modifications to pilecap concrete outline

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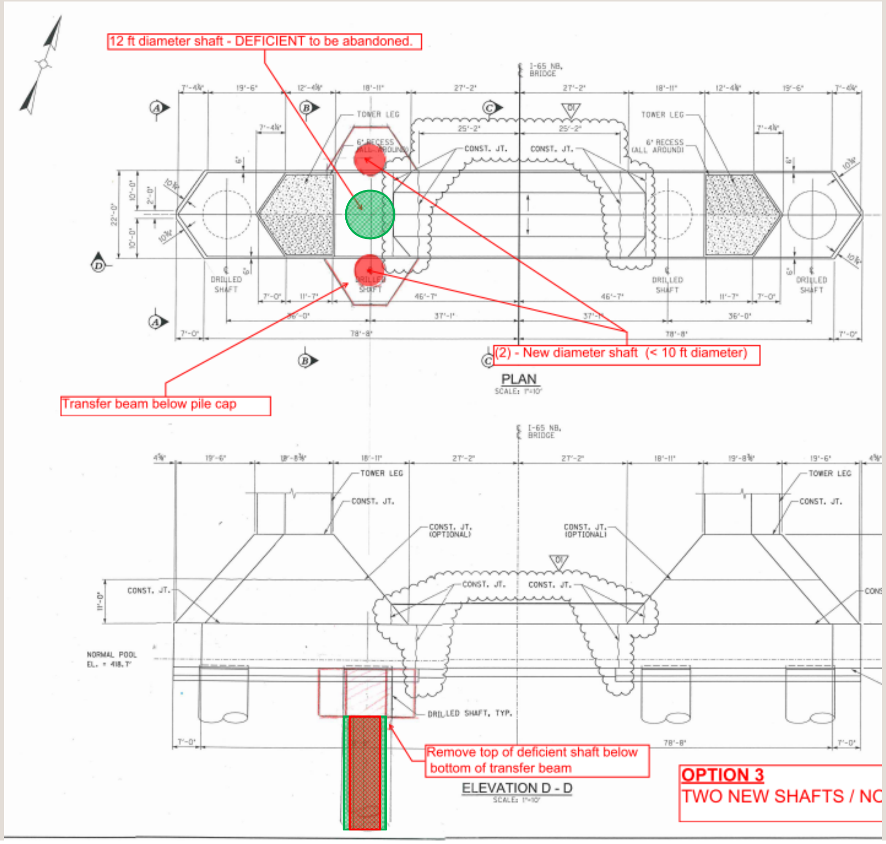
5. Solutions Considered (cont.)

Two new shafts normal to CL of Tower



- Pros
  - Limited impact to original pile cap design
  - Preserves pilecap outline
  - Conventional construction (less risk)
- Cons
  - Can not match original stiffness
  - Requires large transfer beam

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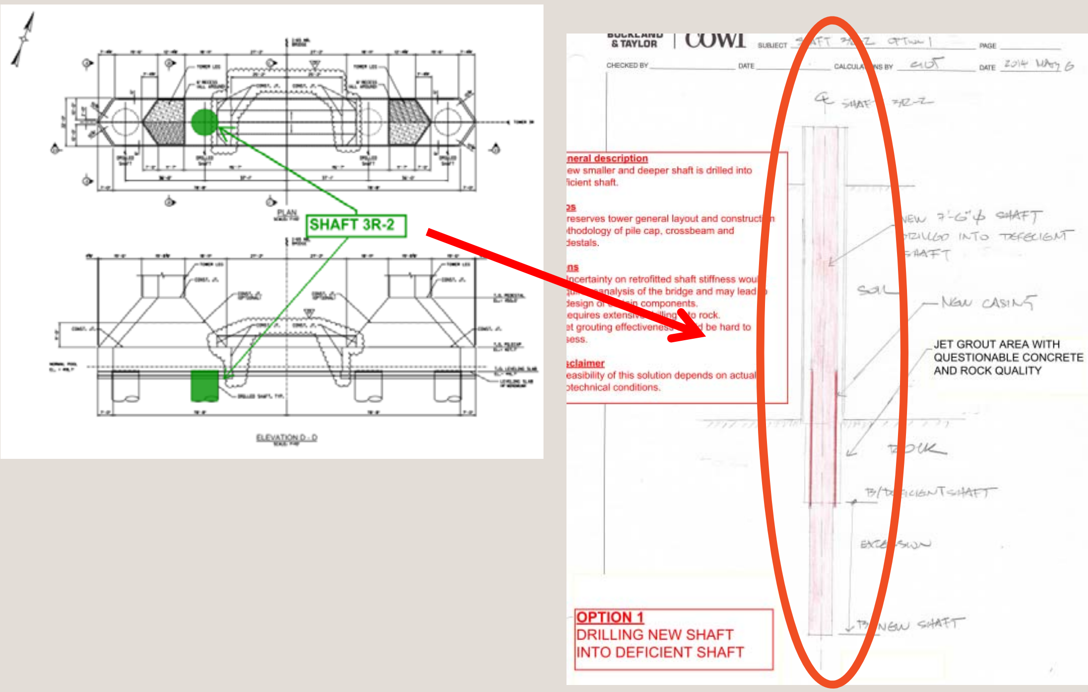
5. Solutions Considered (cont.)

Constructing shaft inside existing shaft (retrofit)



- Pros
  - Can matches original stiffness
  - No pilecap redesign required
  - **Faster solution**
- Cons
  - Non-conventional design
  - **Riskier construction**

SELECTED SOLUTION

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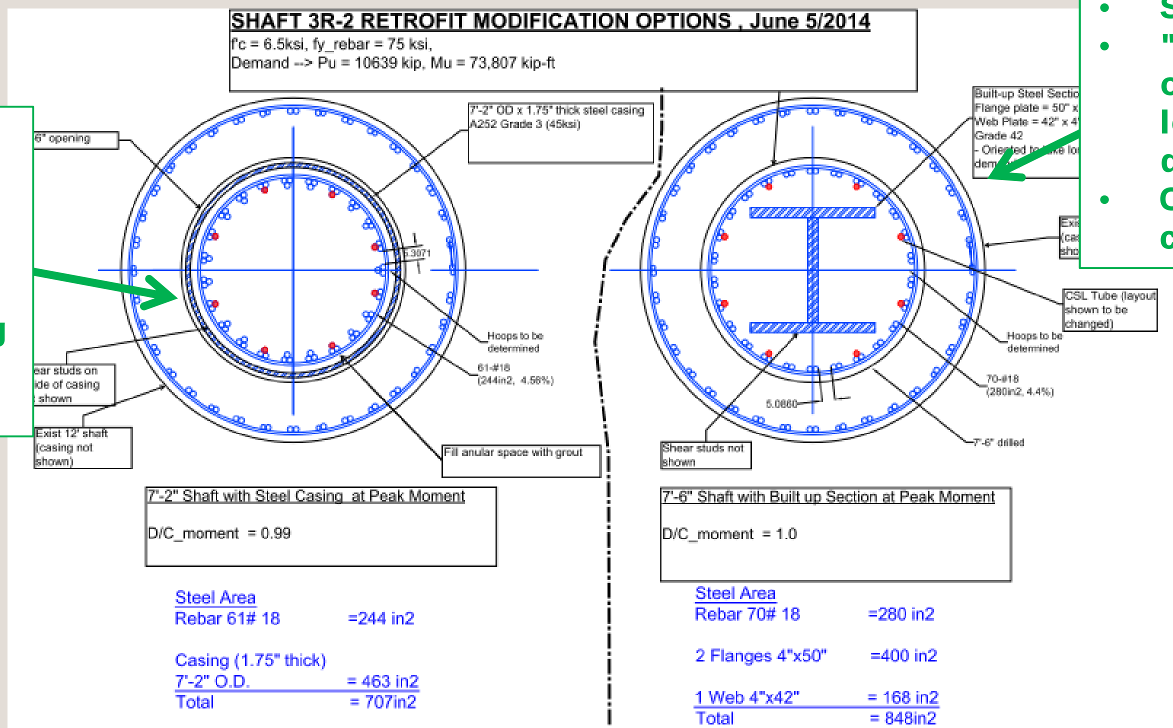
6. Retrofit Design

New 7'-6" shaft section options



Steel casing option
- Not clear it could accommodate coring tolerances
- Requires grouting between the casing and the existing shaft

Steel I-section option
- Selected by COWI
- "I" section best option for longitudinal demand
- Concerns about concrete pouring

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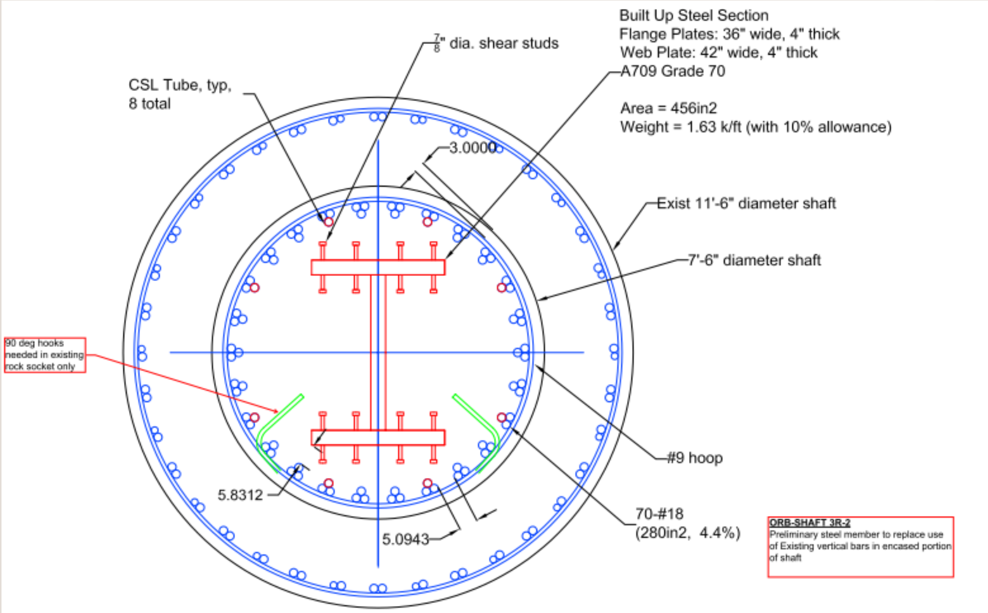
6. Retrofit Design (cont.)

- Presented this concept to Walsh, KYTC and IBT

- Intense coordination to find available steel fabricator, steel material and work out concrete pouring concerns

- Used for evaluation of stiffness change impact in Global model

New 7'-6" shaft – SELECTED CONCEPT



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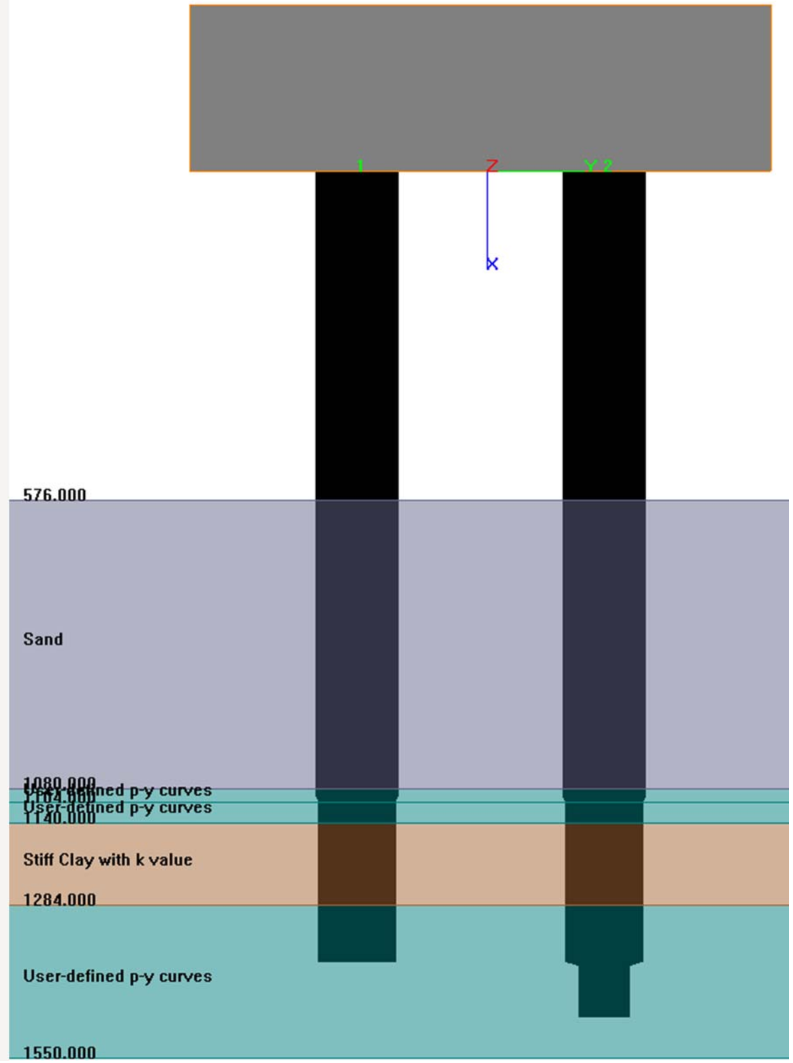
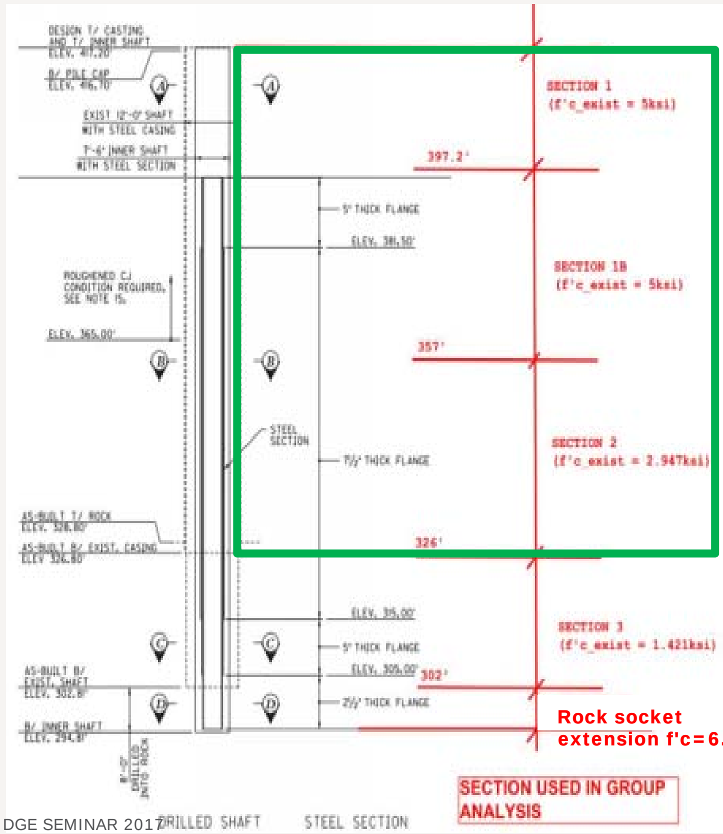
6. Retrofit Design (cont.)

- Goal of retrofit: matching the bending stiffness to the adjacent shaft as closely as possible
- GROUP Model (not LPile as in original design)
- Load redistribution
- Design f'c_new = 6.5 ksi
- Non-uniform section I_long > I_trans
- Deficient I_c +80% new I_c +I Section
- D_shaft = 12'
- D_socket=11.5'
- D_new socket extension=8'



6. Retrofit Design (cont.)



	EI [kip-in2]					
	Longitudinal			Transverse		
	Original	Retrofitted	Ret/Orig	Original	Retrofitted	Ret/Orig
Section 1	9.82E+10	9.97E+10	101%	9.82E+10	9.97E+10	101%
Section 1b	9.82E+10	1.08E+11	110%	9.82E+10	1.01E+11	102%
Section 2	9.82E+10	8.90E+10	91%	9.82E+10	8.15E+10	83%
Section 3	5.80E+10	4.26E+10	73%	5.80E+10	3.51E+10	60%
Section 3b	-	1.55E+10		-	1.25E+10	-

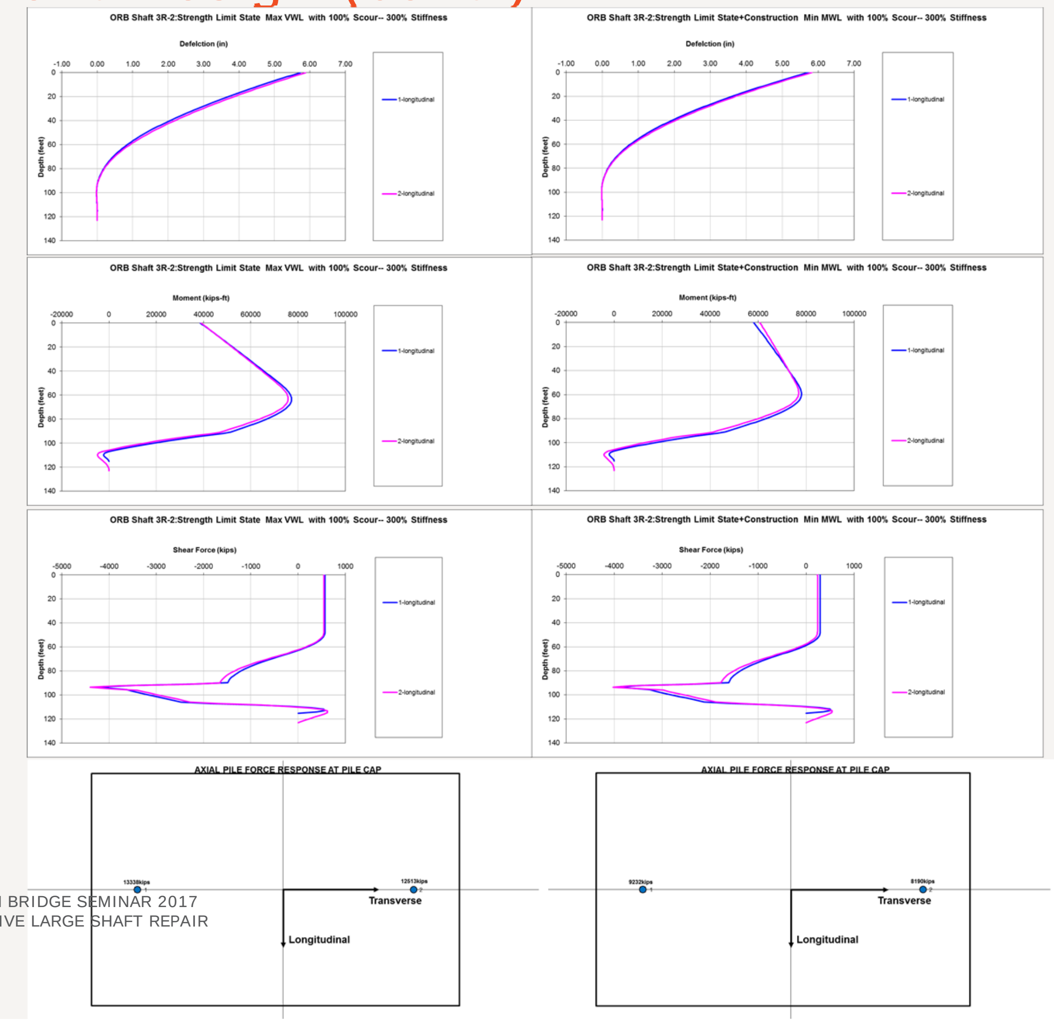
For EI calculations:

- **Retrofit Design Concrete f'c=6.5ksi**
- **Original Concrete f'c= 1.42 to 5 ksi**

For flexural capacity calculations:

- **Retrofit Design Concrete f'c=6.5ksi**
- **Original Concrete f'c=5 ksi (Section 1 above the steel beam)**
- **Original Concrete f'c=0 (Section 1b and Section 2)**

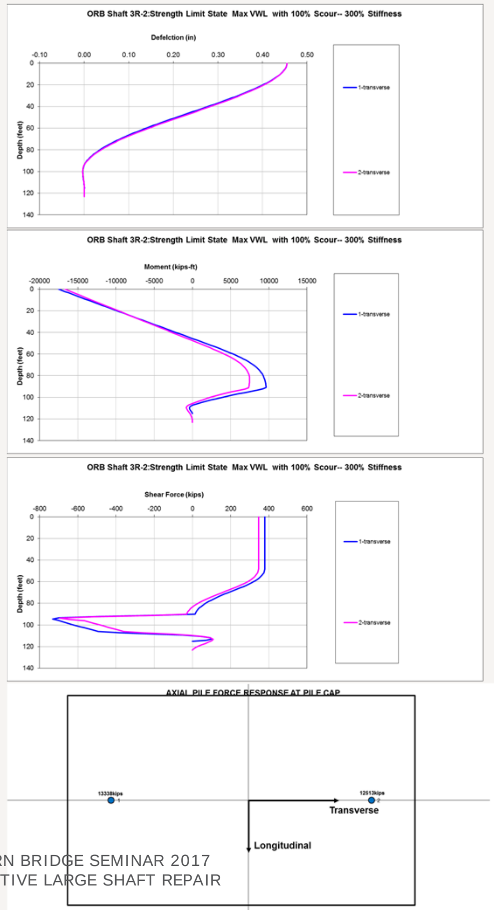
6. Retrofit Design (cont.)

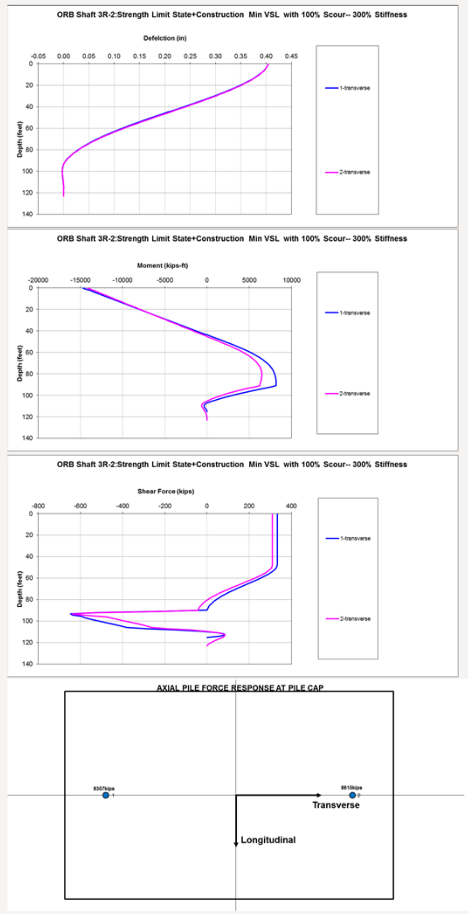


Longitudinal response

- Load redistribution is uniform longitudinally.
- Longitudinal bending stiffness matched closely to the existing adjacent shaft.
- Longitudinal direction is the dominant loading direction.

6. Retrofit Design (cont.)





<u>Transverse Response</u>

- <u>Transversely, there is a slight load redistribution.</u>
- Due to the orientation of the embedded steel beam, the retrofitted shaft bending stiffness is slightly less stiff in transverse direction.
- Transverse direction is <u>not</u> the dominant loading direction.

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6. Retrofit Design (cont.)

Axial response vs Geotechnical resistance

Drilled Shaft ID	Strength Limit State		
	Factored Maximum Axial Compressive Demand [kips]	Factored Axial Compressive Resistance* [kips]	D/C Compression
3R-1	20,665	55,974	0.37
3R-2 (retrofitted)	20,731	22,006	**0.94 OK**

* Resistance factor for compression is 0.7 for the strength limit state.

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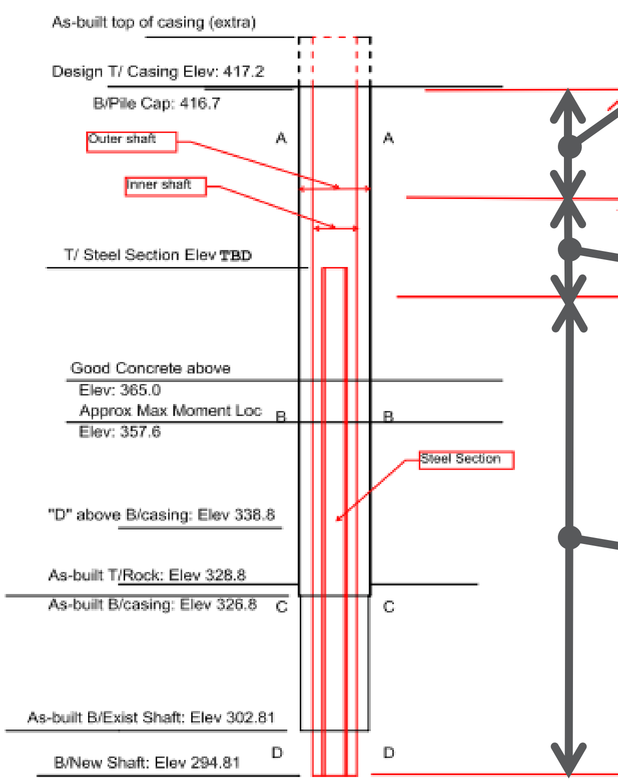
6. Retrofit Design (cont.)

Structural Design



Upper part
-Existing shaft OK
-AASHTO RC Sectional design

Middle part
- Splice zone
- AASHTO Strut and Tie

Lower part
- Rely on new 7'-6" shaft entirely
- AASHTO Composite Sections supplemented with AISC Chapter I

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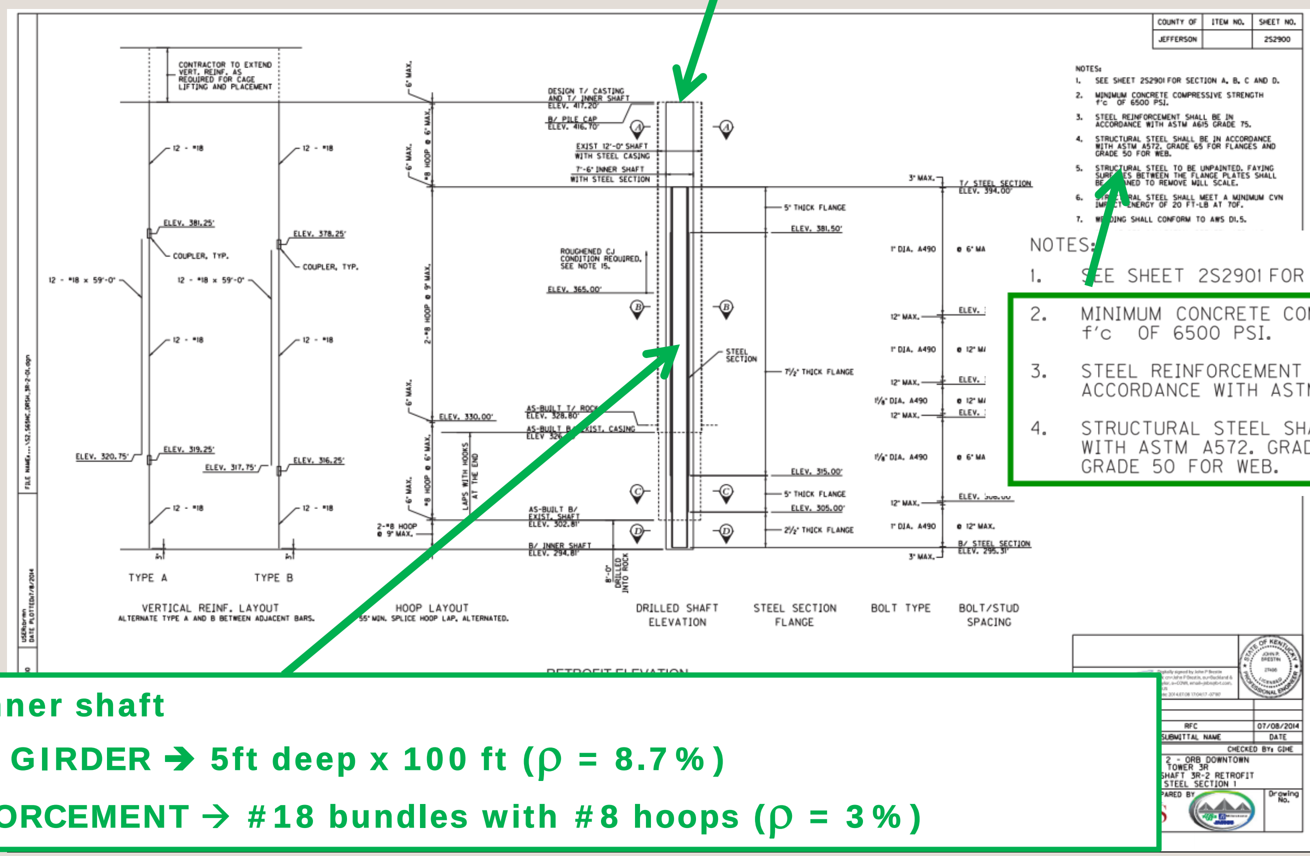
6. Retrofit Design (cont.)

Original shaft → 12 ft diam x 115 ft long (f'c = 5 ksi)
New inner shaft → 7.5 ft diam x 123 ft long (f'c = 6.5ksi)

Design Drawings 1/2



NOTES:

1. SEE SHEET 2S2901 FOR SECTION A, B, C AND D.
2. MINIMUM CONCRETE COMPRESSIVE STRENGTH f'c OF 6500 PSI.
3. STEEL REINFORCEMENT SHALL BE IN ACCORDANCE WITH ASTM A615 GRADE 75.
4. STRUCTURAL STEEL SHALL BE IN ACCORDANCE WITH ASTM A572. GRADE 65 FOR FLANGES AND GRADE 50 FOR WEB.

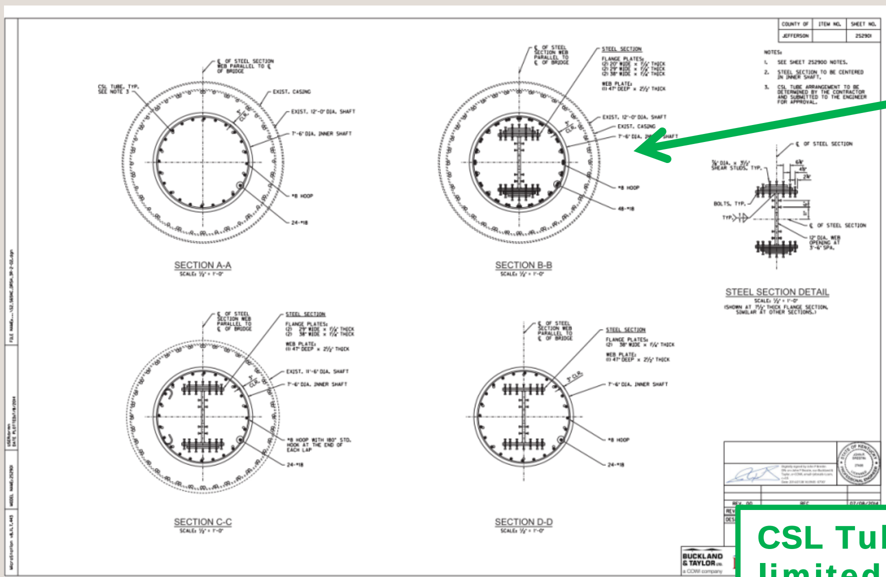
New inner shaft

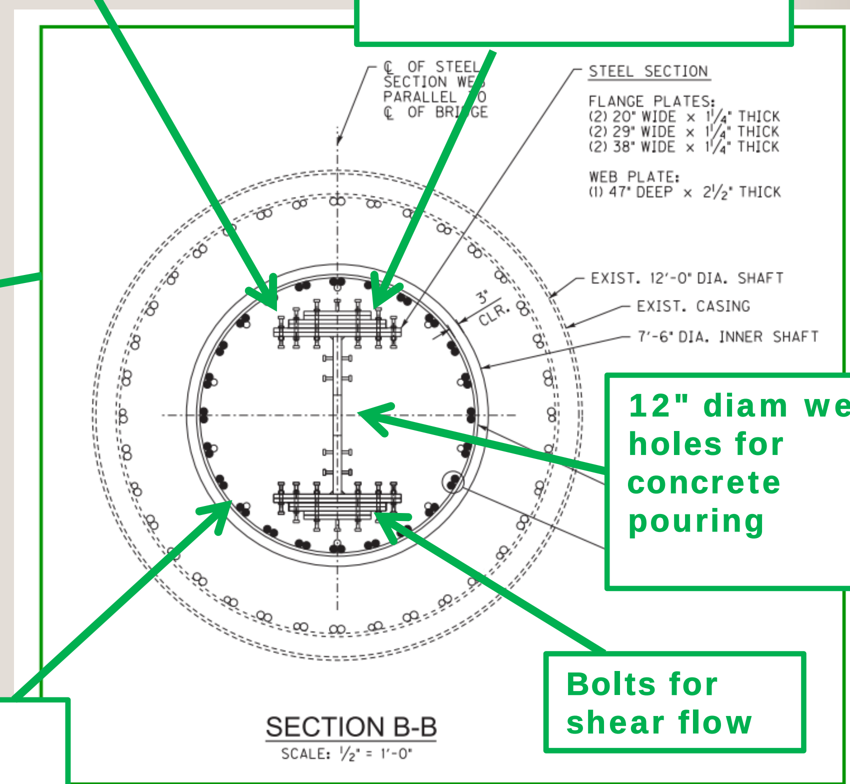
STEEL GIRDER → 5ft deep x 100 ft (ρ = 8.7%)

REINFORCEMENT → #18 bundles with #8 hoops (ρ = 3%)

6. Retrofit Design (cont.)

Design Drawings 2/2





Shear studs for composite action

7.5" flange built with multiple 1.25" plates (bolted)

12" diam web holes for concrete pouring

CSL Tubes, limited application

Bolts for shear flow

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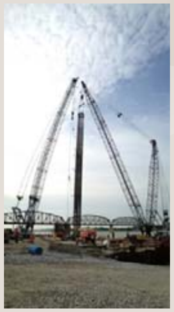
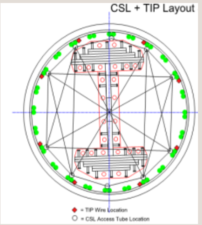
7. Construction

Constructing a shaft into an existing shaft

- Step 1: Core a 7'-6" hole into existing shaft
- Step 2: Place new reinforcing cage
- Step 3: Install massive steel girder inside shaft
- Step 4: Pour concrete
- Step 5: Complete CSL and TIP test





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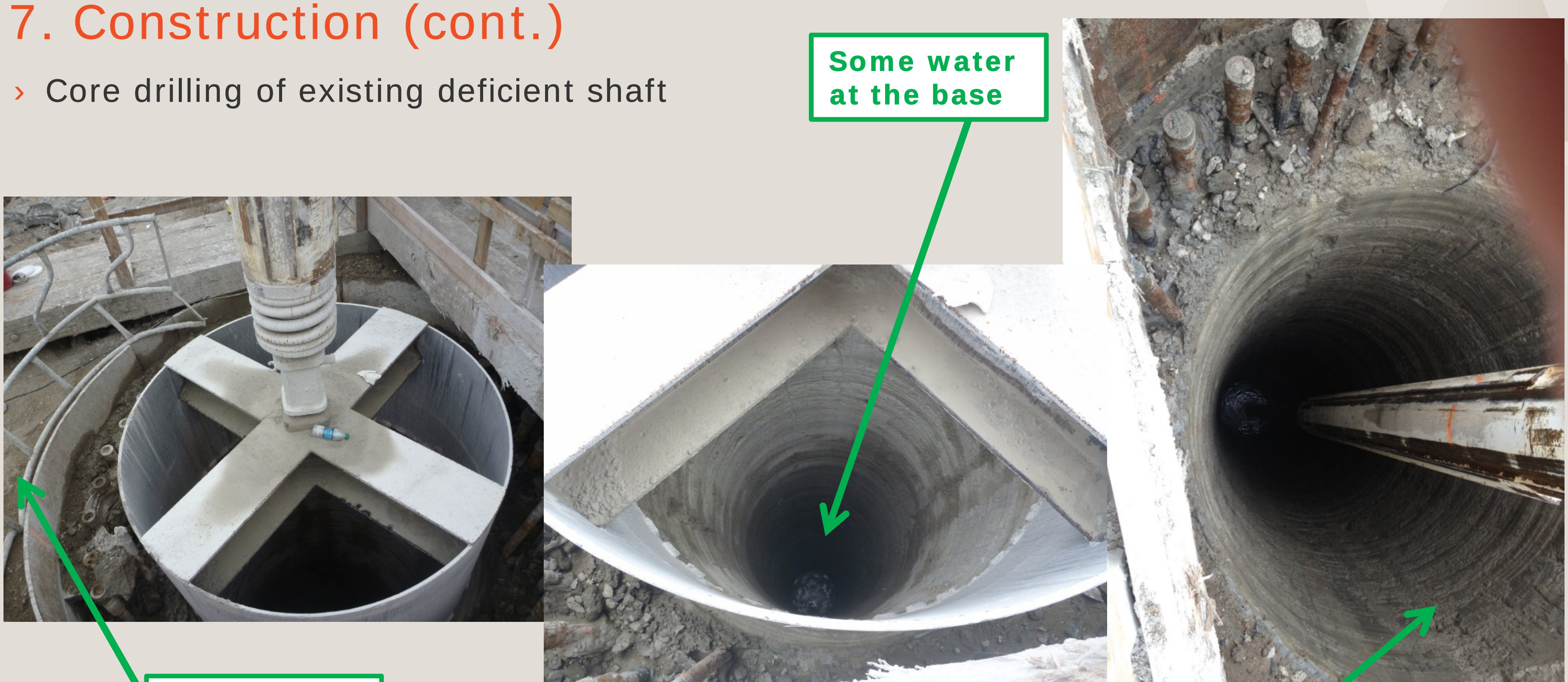
7. Construction (cont.)

› Core drilling of existing deficient shaft



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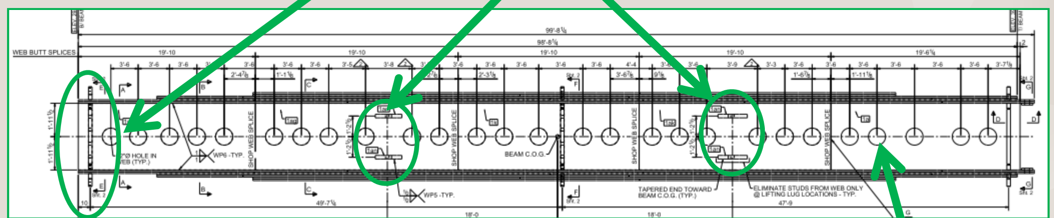
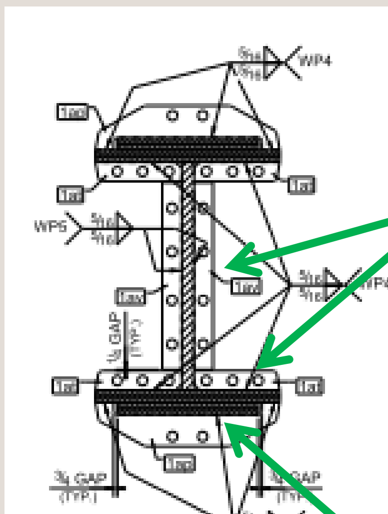
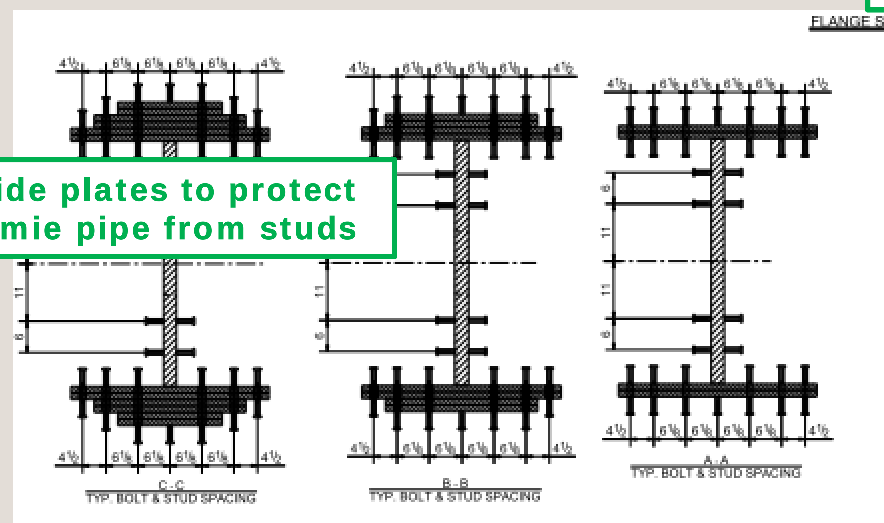
7. Construction (cont.)

› 90 ton steel girder

(~1.8 kip/ft)







Inside plates to protect tremie pipe from studs

Deviators keeping shear studs away from reinforcement cage

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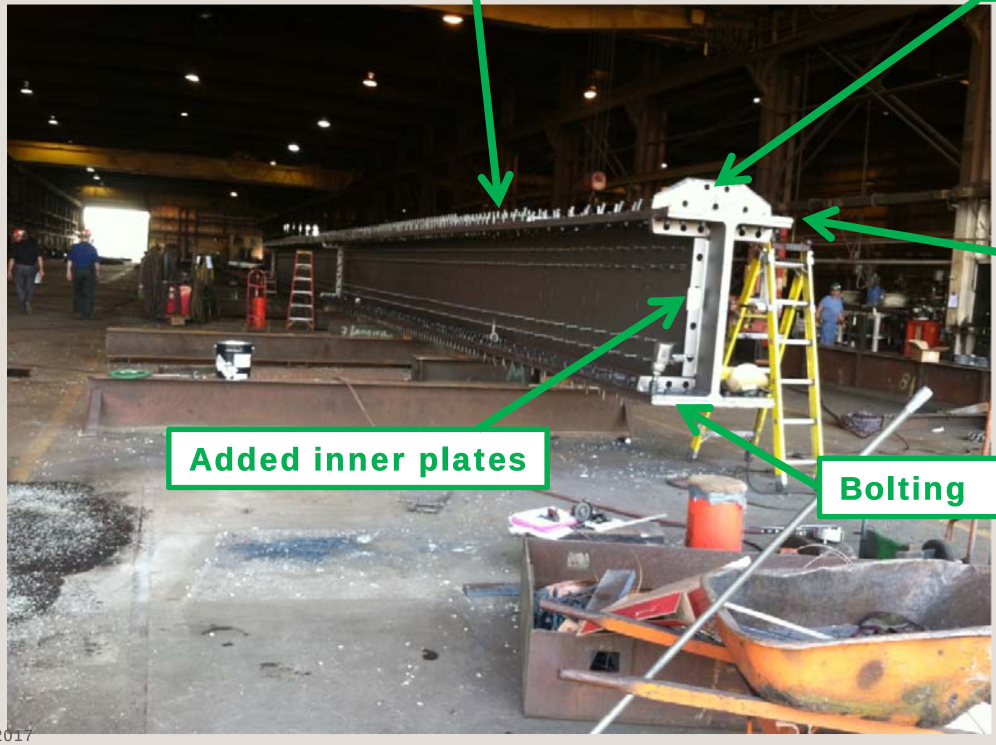
7. Construction (cont.)

- Steel girder fabrication



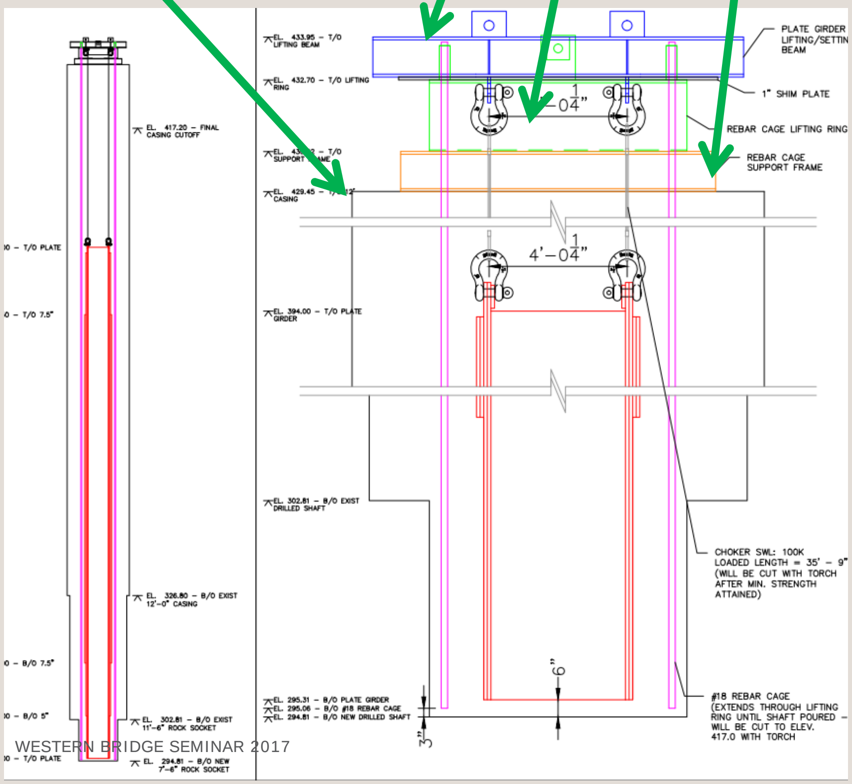
7. Construction

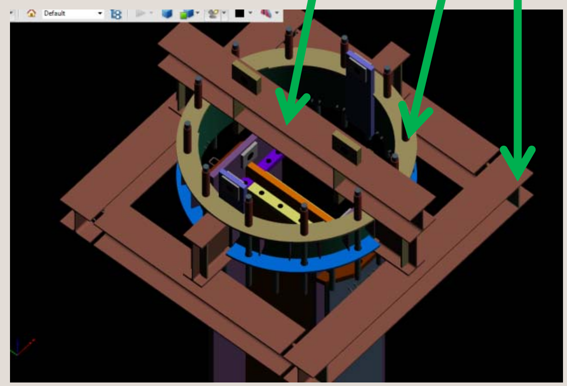
Third – strong beam for Steel girder

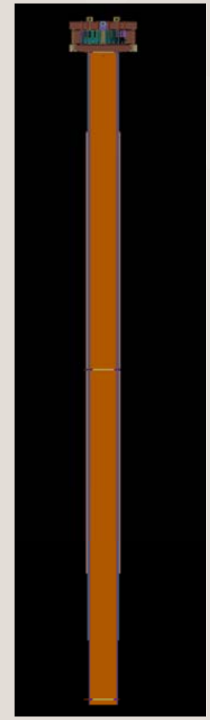
Second - Lifting ring for rebar cage

First - Square frame on exist casing

Existing shaft casing







7. Construction (cont.)

› Installation of the of cage and steel girder

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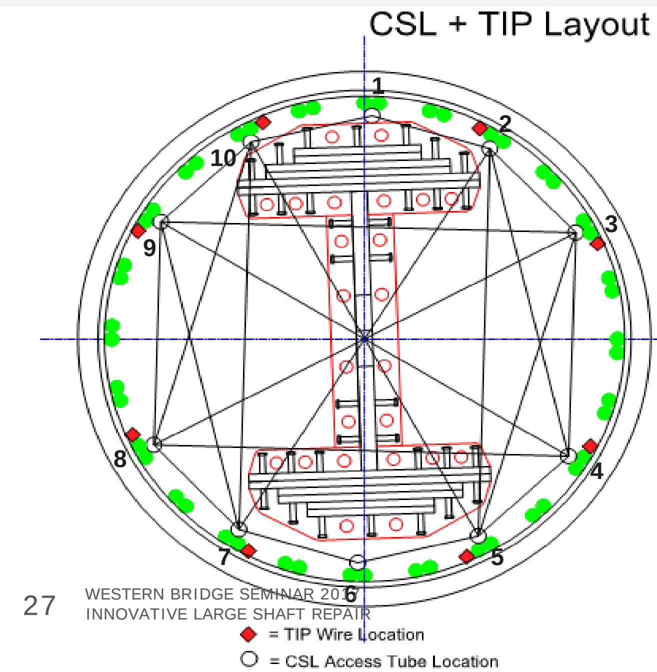
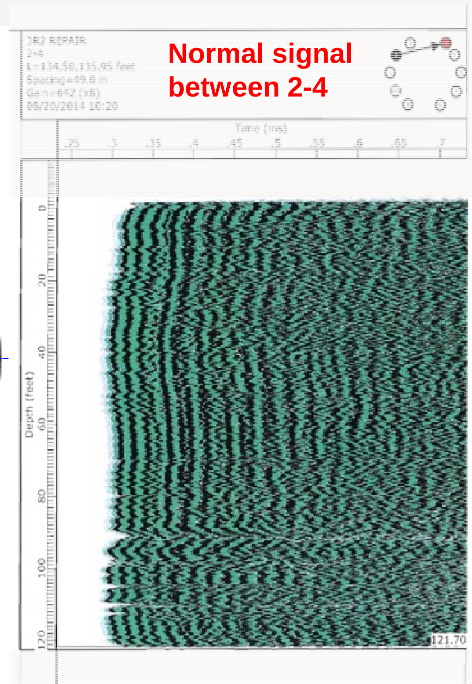
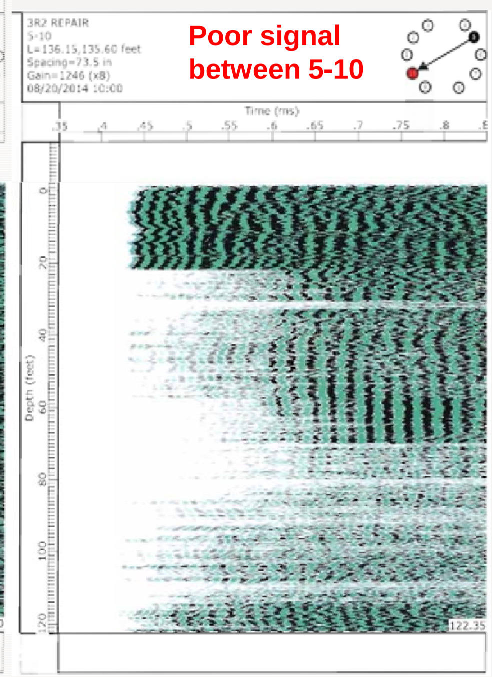
8. Testing - Challenges in crosshole sonic logging tests

- Crosshole Sonic Logging (CSL) on the new shaft.
- Thick flanges blocked sonic signals being transmitted between 1-6, 2-7, 5-10, etc.
- CSL: Inclusive results in those paths intersected by flanges.







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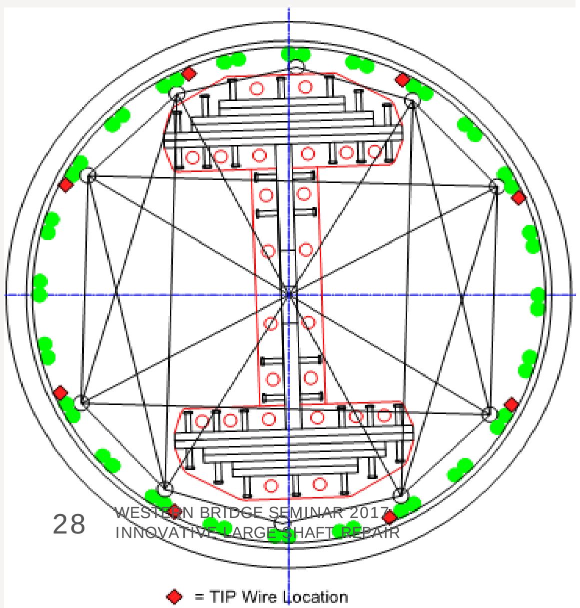
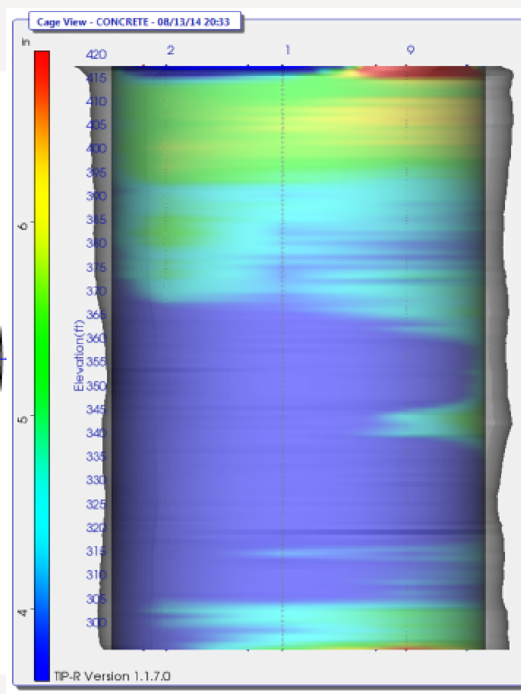
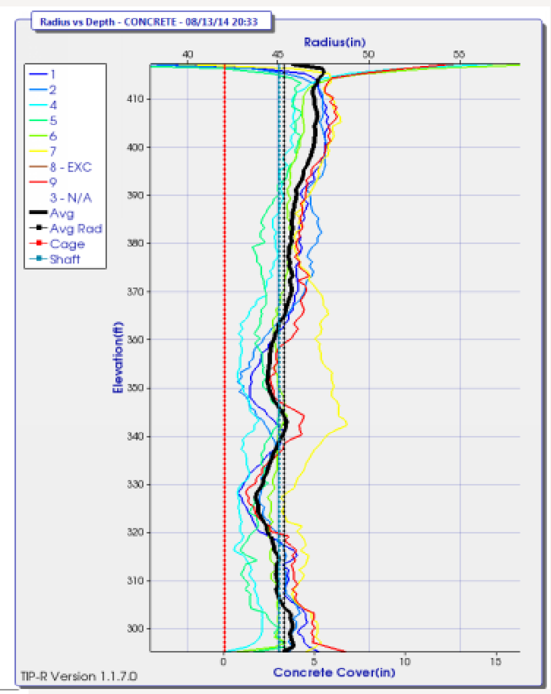
8. Testing - Thermal integrity profiling test

- Thermal Integrity Profiling (TIP) was pre-planned and carried out on the new shaft.
- TIP thermal wire measurements were monitored during concrete pour and over the next 35-hour period.
- TIP: Concrete cure was normal; Detected slight cage tilting; No concerns.

TIP Layout







9. Completed Abraham Lincoln Bridge

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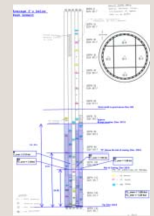
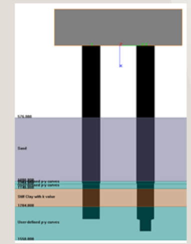
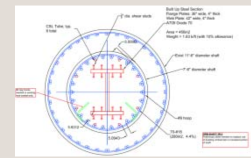
10. Final Remarks




- **Total retrofit cost → $1.9M**
- **Time it took to fix → ~4 months**
- **Lessons learned for Walsh**
  - Monitor concrete volume to depth of concrete more closely
  - Have a crane available to lift cage and airlift concrete if necessary
- **Lessons learned for COWI**
  - Do not attempt to rely on low quality concrete (<2.4ksi AASHTO Limit) for structural capacity
- 14 COWI engineers involved on solving this issue
- **COWI / Walsh Team provided a sound solution that allow the project to move forward meeting all the project requirements to the satisfaction of KYTC**

Questions?

COWI