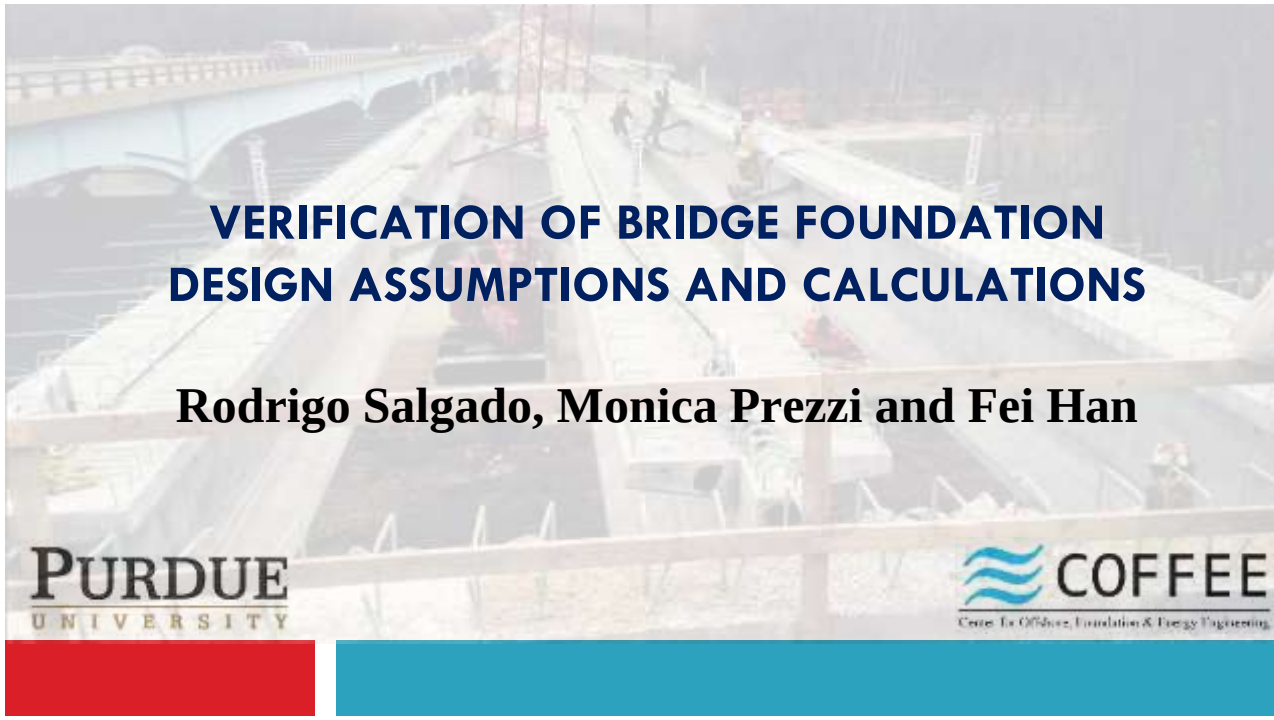

1

Acknowledgments

- Jeremy Hunter
- Athar Khan
- Mir Zaheer
- Tim Wells
- Barry Partridge
- Mahmoud Hailat
- Matthew Kohut, Sean Porter and Derek Barnes
- Superior Construction Company

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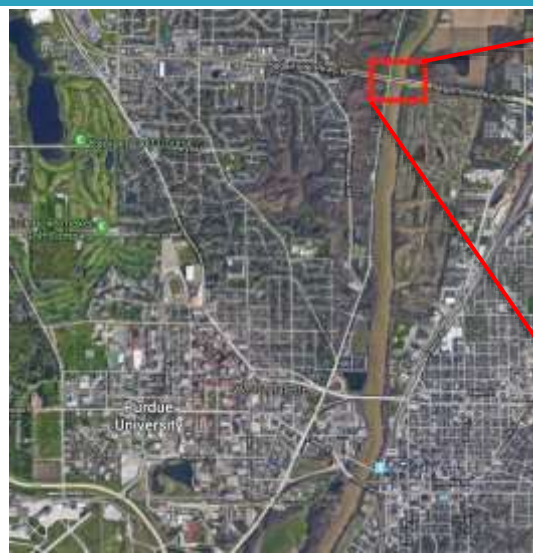
2

Project Background

3

Location - Lafayette, IN, USA



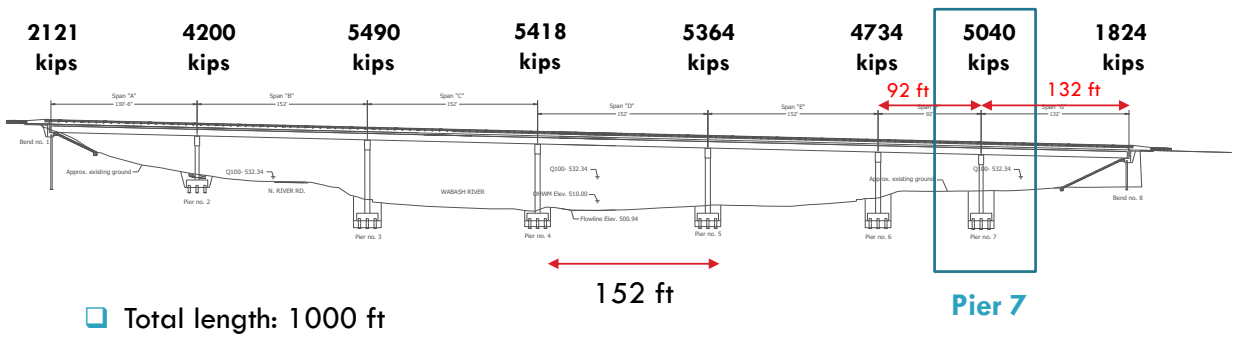
4

Old timber piles

Built 1936; rehabilitated 1984

5

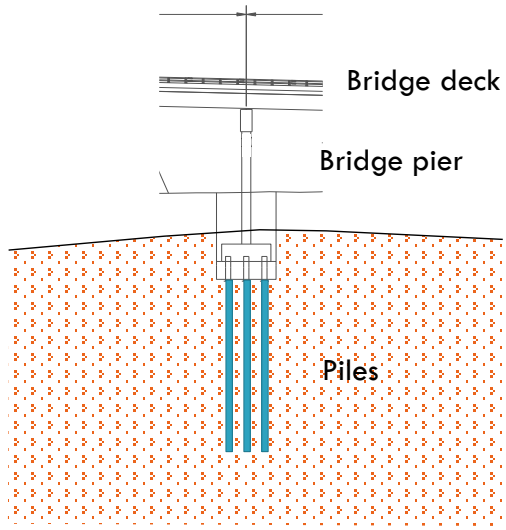
Dead loads at foundation level and span lengths



- Total length: 1000 ft
- 7-span bridge
- Typical span length: 152 ft
- Budget estimate: $ 18 million

6

New bridge



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Foundation loads (per pile)

	Bent 1	Pier 2	Pier 3	Pier 4	Pier 5	Pier 6	Pier 7	Bent 8
Number of piles	7	15	18	18	18	18	15	8
Type of piles	CE	CE	OE	OE	OE	OE	OE	CE
Dead load (kips)	303	280	305	301	298	263	336	228
Live load (kips)	151	187	267	220	196	257	185	115
Lateral load (kips)		10	12	12	11	10	11	

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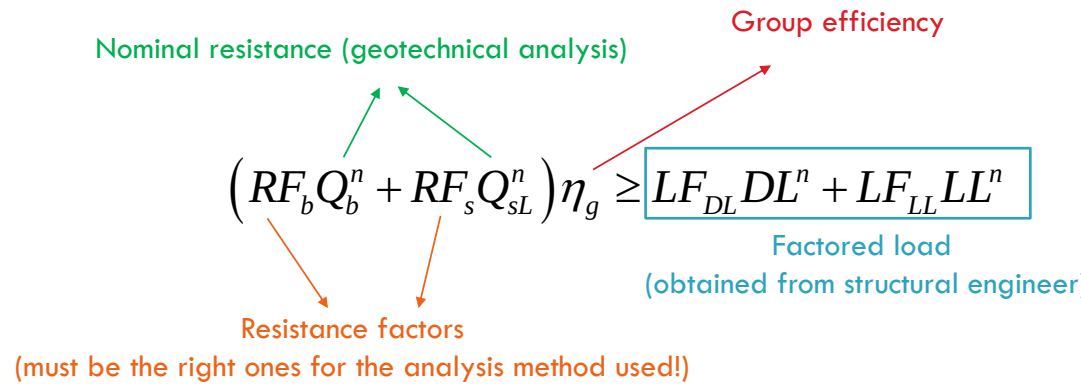
8

LRFD design for pile group



This approach is general and could be used both for ULSs and SLSs but so far resistance factors have been developed only for specific analyses and ULSs

9

Where are the Questions?

$$\left(RF_b Q_b^n + RF_s Q_{sL}^n\right)\eta_g \geq LF_{DL} DL^n + LF_{LL} LL^n$$

Calculated with Purdue Pile Design Method - Verified in JTRP SPR 4040 research project

Group efficiency: One of the greater uncertainties in such calculations: for a given soil profile, it depends on type of pile, c-c spacing, cap resistance, settlement

From structural design: conservative?

Studied in JTRP SPR 4165 research project

10

Where are the Questions?

$$\left(RF_b Q_b^n + RF_s Q_{sL}^n\right)\eta_g \geq LF_{DL} DL^n + LF_{LL} LL^n$$

For what settlement are these calculated?

11

Tolerable Movement of Bridge Foundations

- Ultimate limit states of a bridge are fundamentally similar to those that would be observed in structures that have been better studied, such as frame buildings
- Serviceability is defined differently, relating to ride quality and maintenance preferences

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Bridge Foundations

- **SLS in bridges are related to the riding conditions**
  - Uncomfortable/dangerous ride if pavement is wavy or cracked
  - Settlements or horizontal displacements of the foundations causing such conditions are clearly not tolerable
- **Lower initial cost or lower maintenance costs?**
  - It may be advantageous to save on the foundations (an initial cost) even if it means more frequent repair and maintenance of pavements (delayed costs)
  - Defects caused by vertical movements are easier to correct than those caused by lateral movements, which may lead to an undesirable closing of expansion joints

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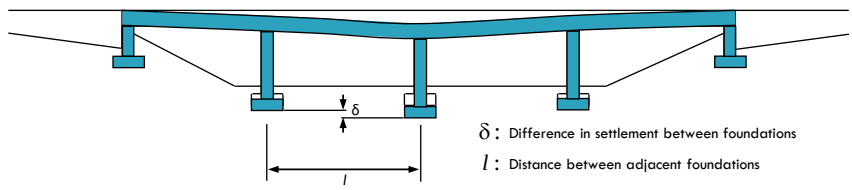

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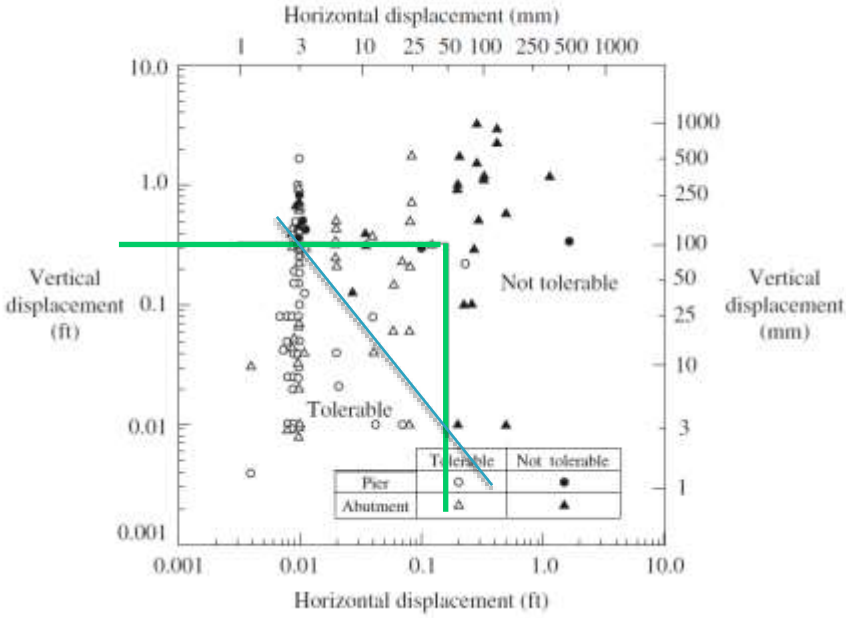

Bozozuk (1978)

15

Empirical limits on vertical settlement

Settlement magnitude	Basis for recommendation	Reference
50 mm	Not harmful	Bozozuk (1978)
60 mm	Ride quality	Walkinshaw (1978)
>60 mm	Structural distress	Walkinshaw (1978)
100 mm	Ride quality and structural distress	Grover (1978)
100 mm	Harmful but tolerable	Bozozuk (1978)
>100 mm	Usually intolerable	Wahls (1990)

Barker, R. M., Duncan, J. M., Rojiani, K. B., Ooi, P. S. K., Tan, C. K., and Kim, S. G. (1991). "Manuals for the design of bridge foundations: Shallow foundations, driven piles, retaining walls and abutments, drilled shafts, estimating tolerable movements, and load factor design specifica- tions and commentary." NCHRP Rep. 343, Transportation Research Board, Washington, DC.

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Tolerable Horizontal Movements of Bridges

Horizontal movement (mm)	Basis for recommendation	Reference
25	Not harmful	Bozozuk (1978)
38	Tolerable in most cases	Moulton, et al. (1985)
51	Structural distress	Walkinshaw (1978)
51	Harmful but tolerable	Bozozuk (1978)
51	Usually intolerable	Wahls (1990)

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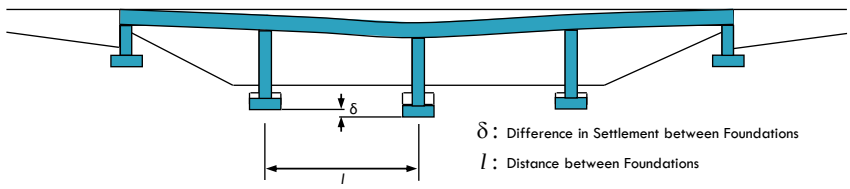

'Standard specifications for highway bridges 2000 interim version.'

Maximum Angular Distortion, δ / l	Basis for Recommendation	Recommended by
0.004	Tolerable for multiple-span bridges	Moulton, et al. (1985)
0.005	Tolerable for single-span bridges	Moulton, et al. (1985)

'LRFD bridge design specifications 2005 interim version'

Maximum Angular Distortion, δ / l	Basis for Recommendation	Recommended by
0.004	Tolerable for multiple-span bridges	Moulton, et al. (1985) Barker, et al. (1991)
0.008	Tolerable for single-span bridges	Moulton, et al. (1985) Barker, et al. (1991)

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Tolerable Angular Distortion for Bridges

Value of Angular Distortion	Percent of 119 continuous-span bridges for which this amount of angular distortion was considered to be tolerable	Percent of 56 simple-span bridges for which this amount of angular distortion was considered to be tolerable
0.000-0.001	100%	98%
0.001-0.002	97%	98%
0.002-0.003	97%	98%
0.003-0.004	96%	98%
0.004-0.005	92%	98%
0.005-0.006	88%	96%
0.006-0.008	85%	93%

MOULTON ET AL. (1985)

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Allowable angular distortion by AASHTO (2018)

- Continuous-span bridges
  - 0.004
- Simple-span bridges
  - 0.008

(AASHTO. (2018). *AASHTO LRFD bridge design specifications*. American Association of State Highway and Transportation Officials, Washington, D.C.)

20

Allowable settlement for the Sagamore Bridge

- For pier 7 (span length = 92 ft)
  - Allowable differential settlement: 92 ft × 0.004 = 112 mm
  - Assuming: differential settlement/total settlement = 0.75
  - Allowable total settlement = 112/0.75 = 150 mm
- For a typical pier (span length = 152 ft)
  - Allowable differential settlement: 152 ft × 0.004 = 185 mm
  - Assuming: differential settlement/total settlement = 0.75
  - Allowable total settlement = 185/0.75 = 247 mm

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Site Investigation

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Cone Penetration Test (CPT)

23

Standard Penetration Test (SPT)

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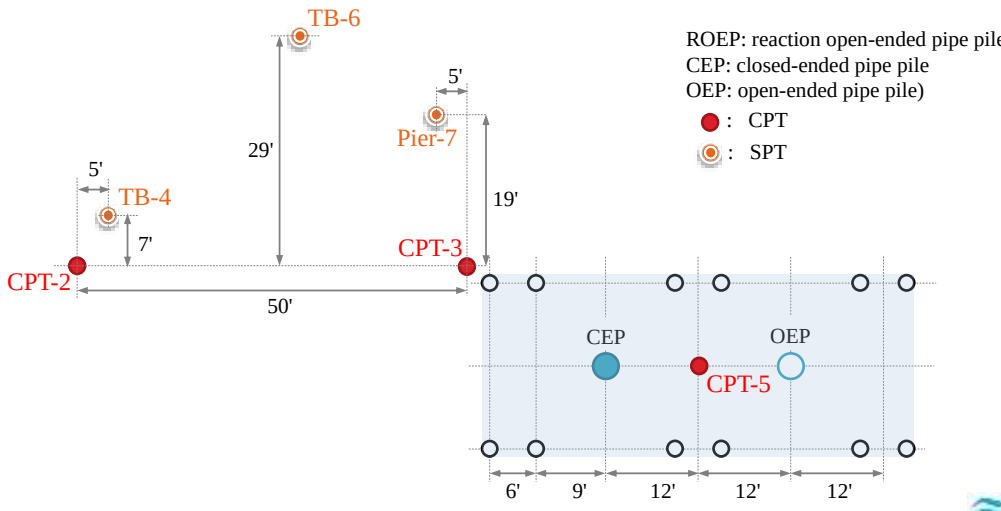
In-situ test locations



25

Soil samples

25 ft

65 ft

80 ft

110 ft

26

Existence of large particles

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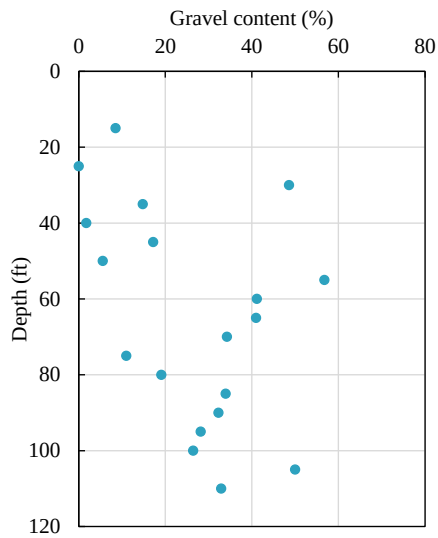
Gravel content



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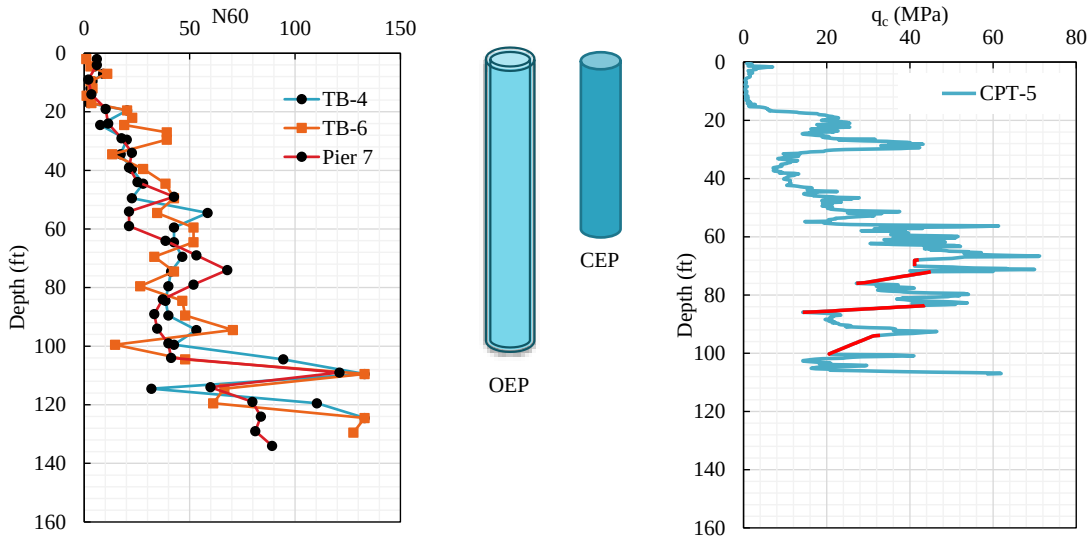
In-situ tests - SPT & CPT



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Pile Instrumentation

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Centre for Offshore Foundation & Energy Engineering

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Bridge Foundations – Test Piles

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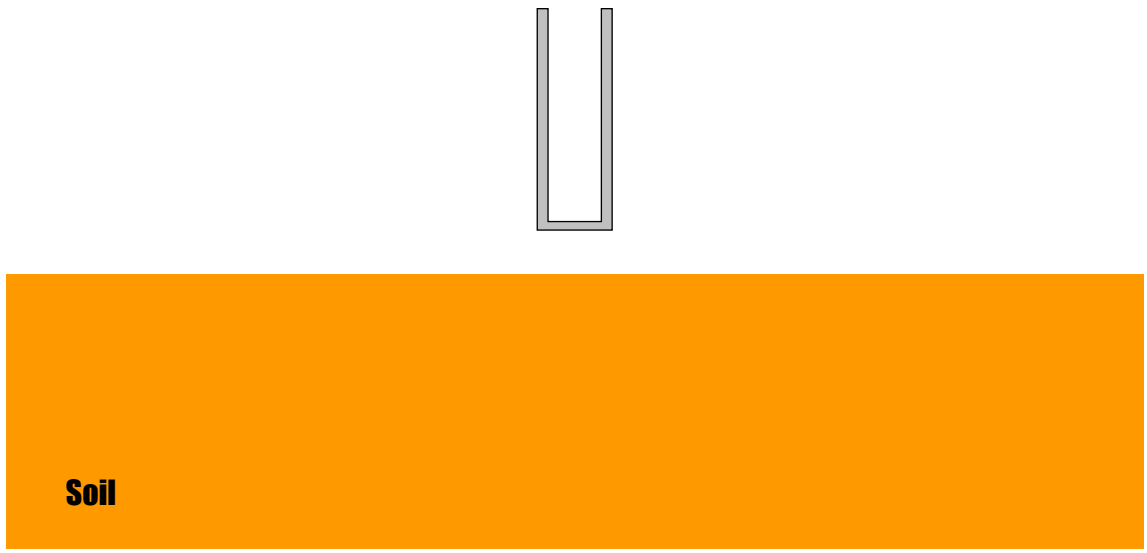
Closed-ended steel pipe pile



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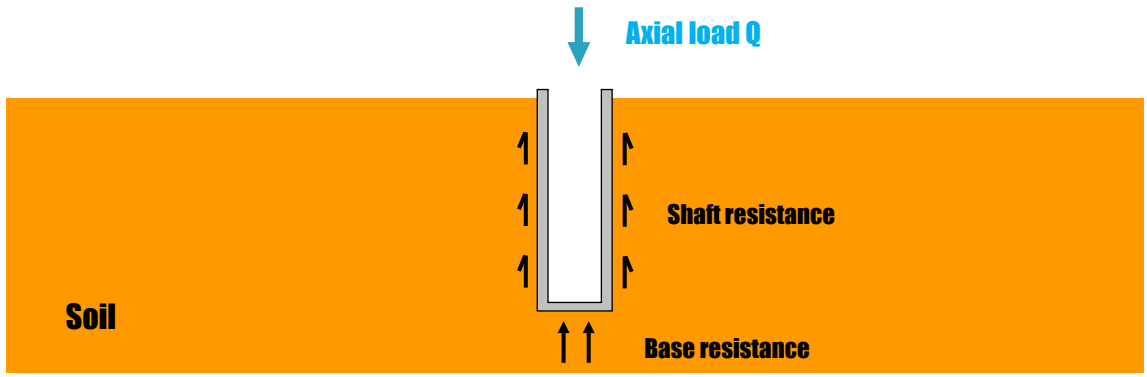
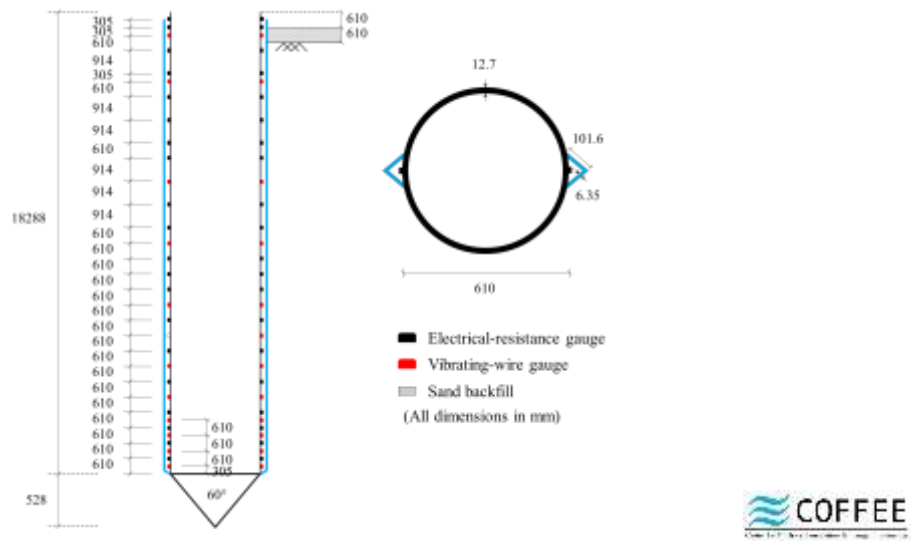
Closed-ended steel pipe pile



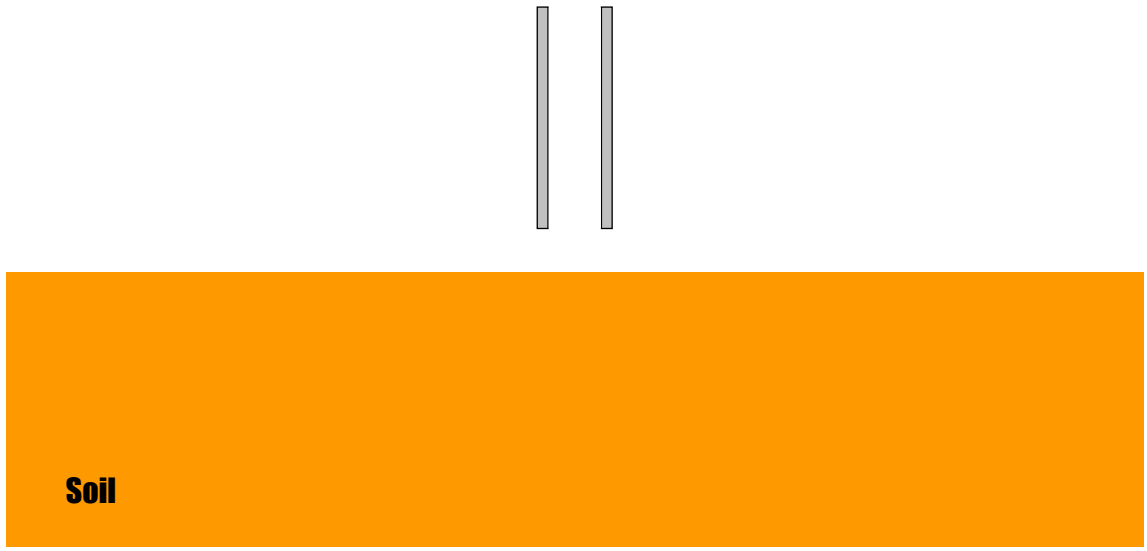
33

Layout of Strain Gauges – closed-ended pile



34

Open-ended steel pipe pile



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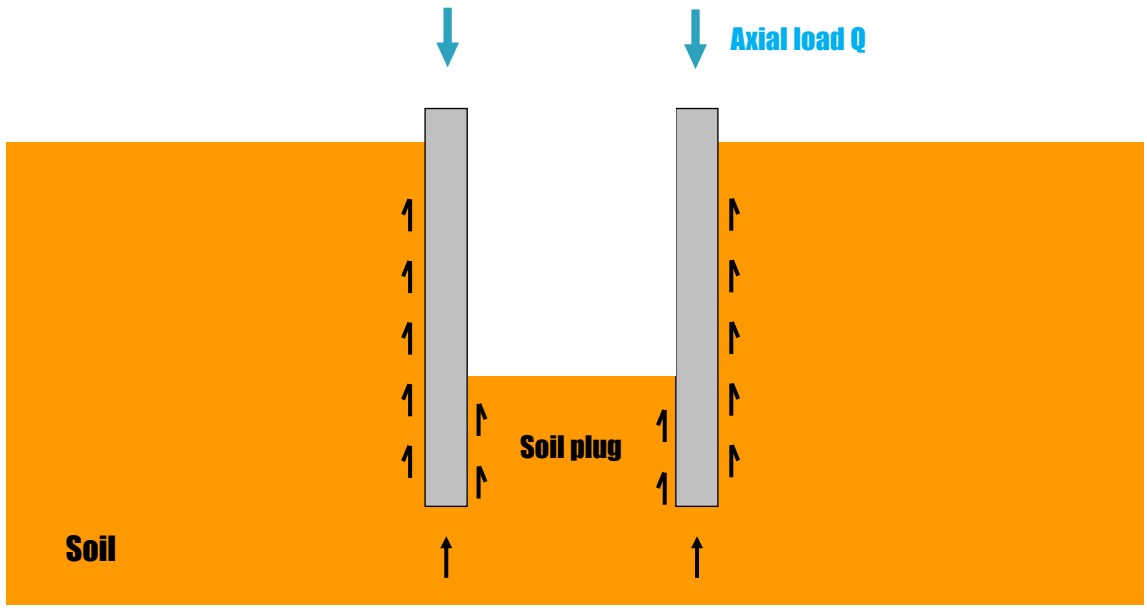
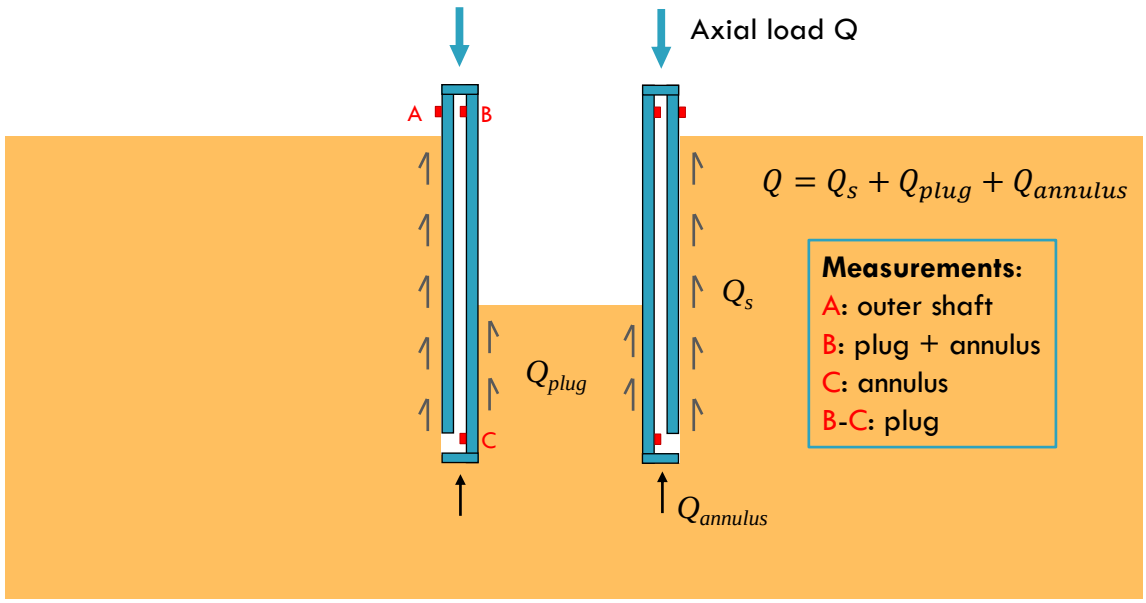
Open-ended steel pipe piles - sands



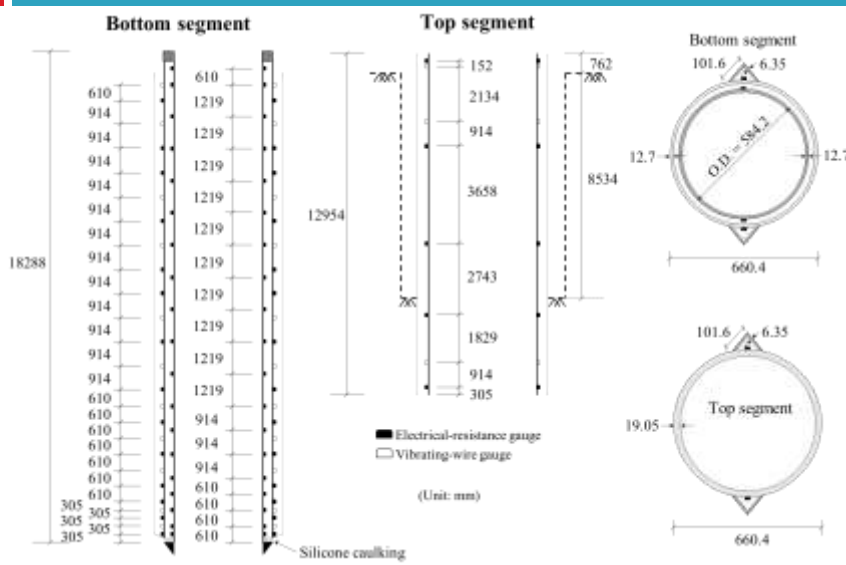
36

Double-wall system for open-ended pile



37

Layout of Strain Gauges – Open-ended pile



Fabricated in two segments:

Double-wall bottom segment

Single-wall top segment

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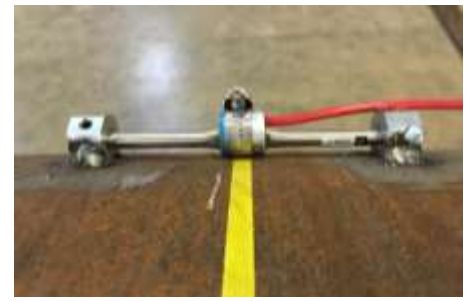
Surface polishing

Electrical-resistance strain gauges

Vibrating-wire strain gauges



Installation of sensors

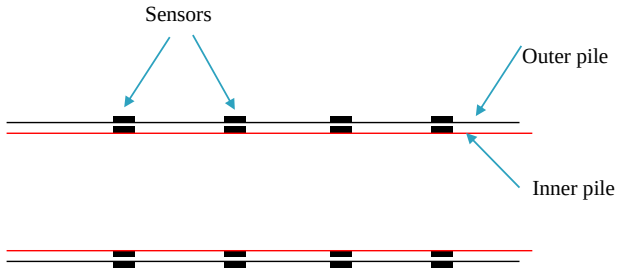
39

Pile instrumentation

- Pile instrumentation
  - 50 VW strain gauges
  - 104 ER strain gauges
  - 5 miles of cables

40

Double wall assembly



Inner pile slid into the outer pile

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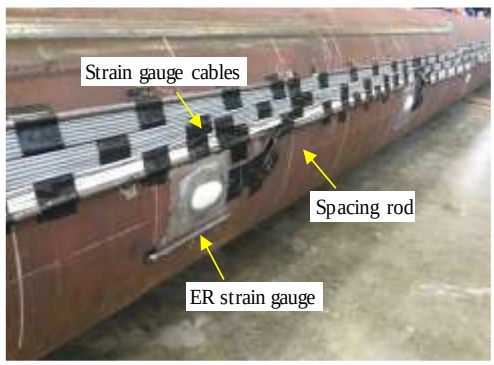
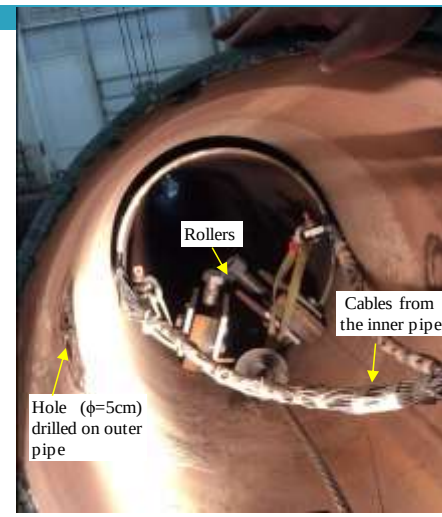
Double wall assembly



Inner pipe



Sliding

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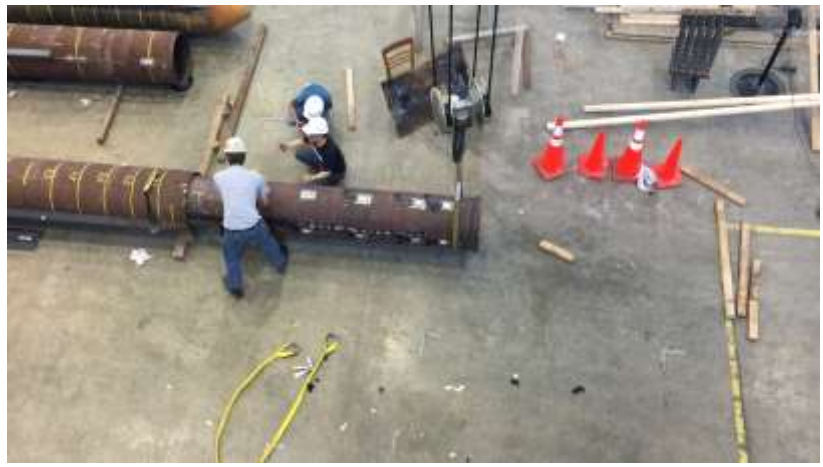
Double wall assembly



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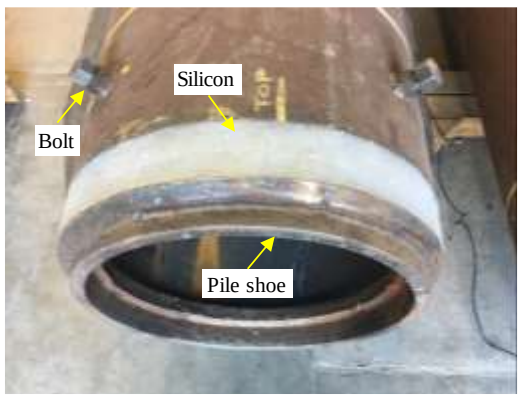
Double wall assembly – driving shoe



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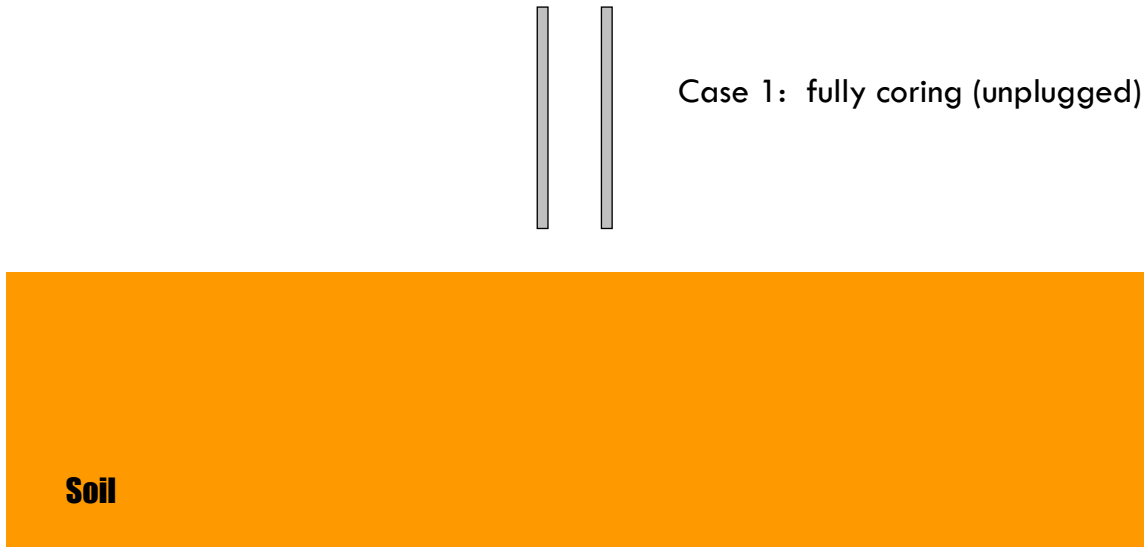
Piles ready for driving

45

Measurement of Plug Formation

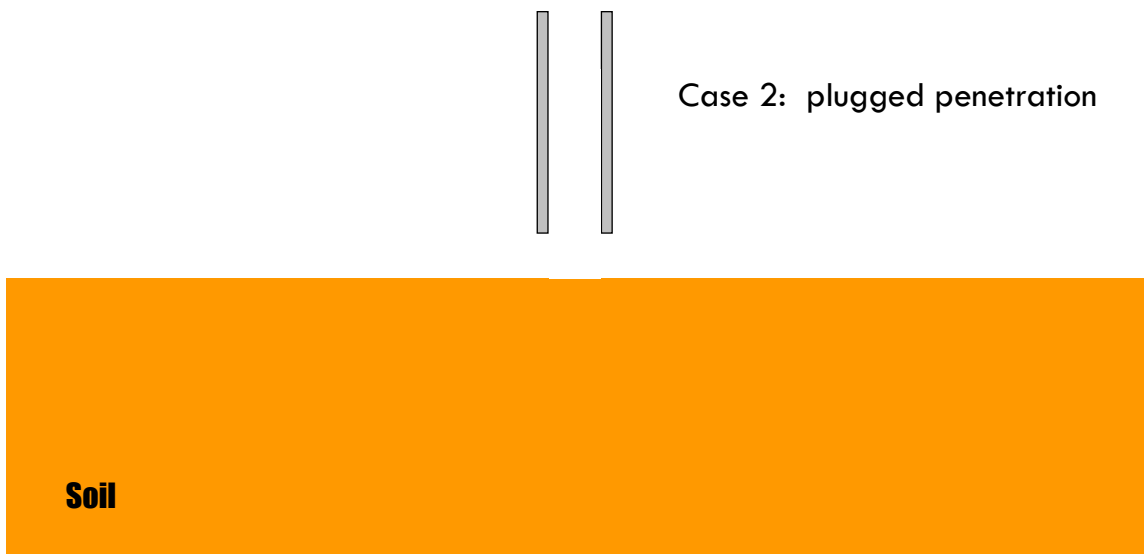
46

Open-ended steel pipe piles - sands



47

Open-ended steel pipe piles - sands



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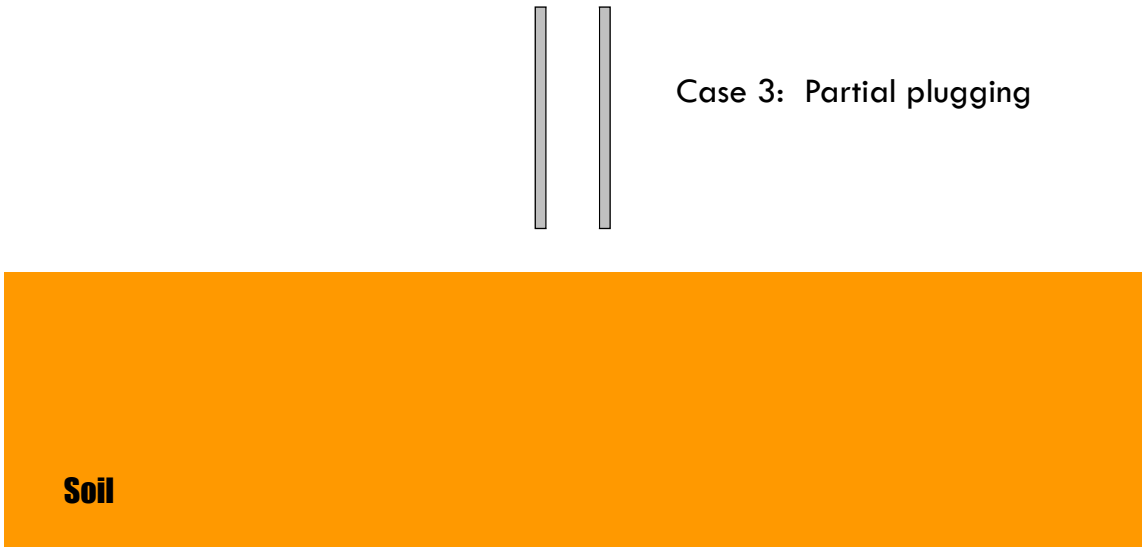
Open-ended steel pipe piles - sands



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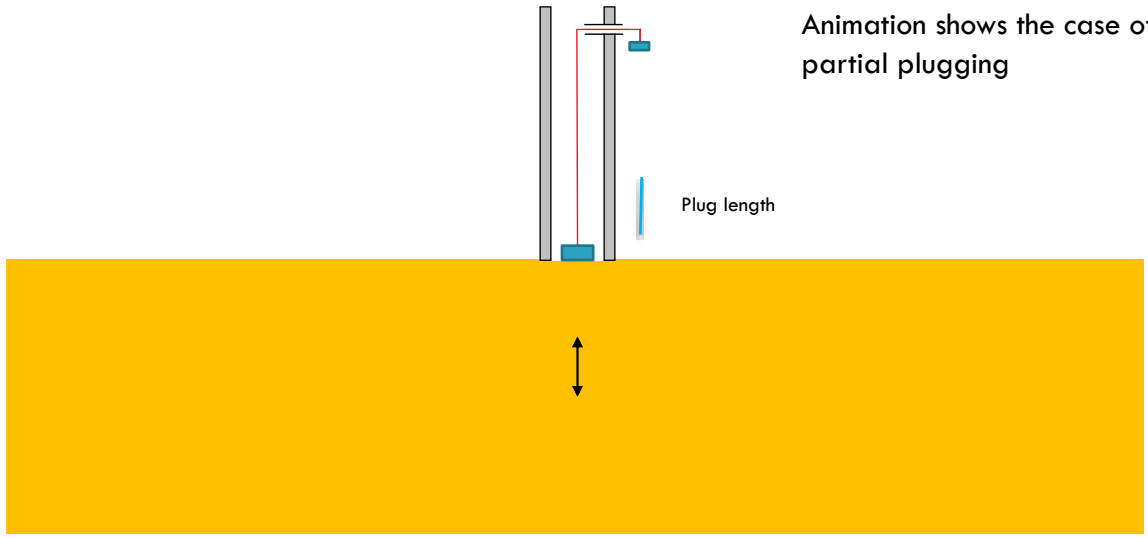
Importance of plug measurement

- IFR and PLR are recognized as the key factors in modern design methods (Purdue method, UWA method) for open-ended piles
- Study is still needed to learn how to predict plug formation and its effect on the pile's resistances

Paik, K., and Salgado, R. (2003). "Determination of Bearing Capacity of Open-Ended Piles in Sand." Journal of Geotechnical and Geoenvironmental Engineering, 129(1), 46–57.
Lehane, B. M., Schneider, J. a., and Xu, X. (2005). "The UWA-05 Method for Prediction of Axial Capacity of Driven Piles in Sand." *Proceedings of the International Symposium. on Frontiers in Offshore Geotechnics (IS-FOG 2005)*, 683–689.

50

Plug measurement



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Pile Driving

52

53

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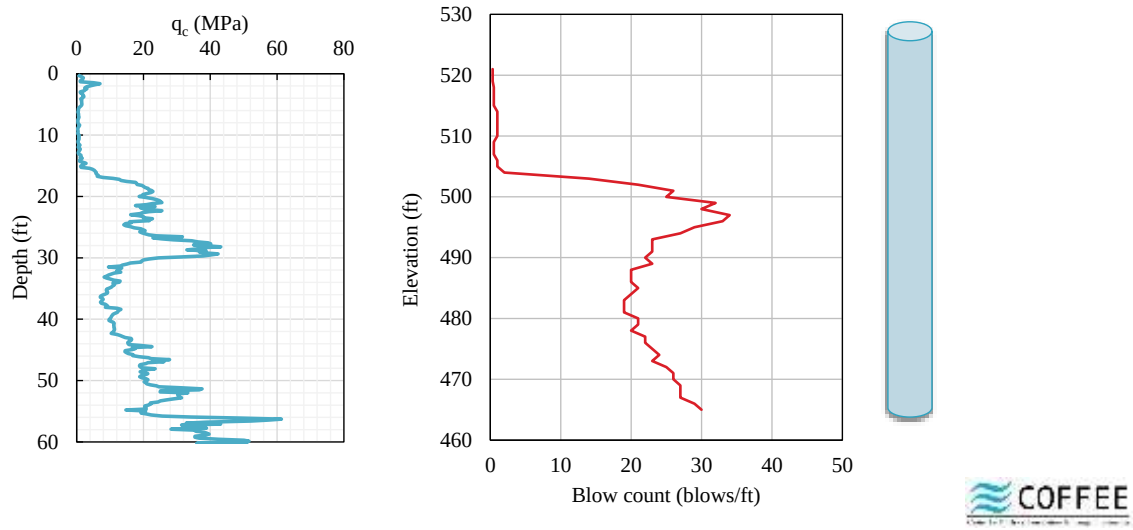
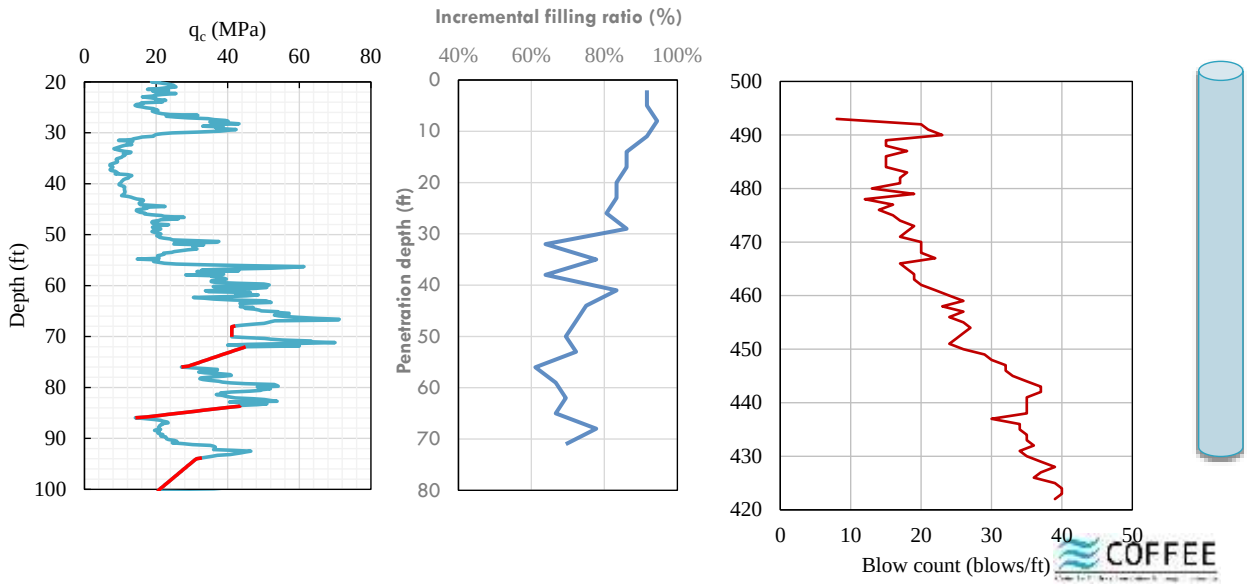
Driving resistance - closed-ended pile



55

Pile driving resistance – open-ended pile



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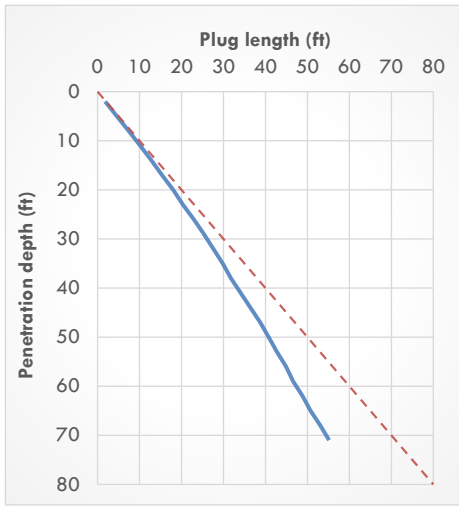
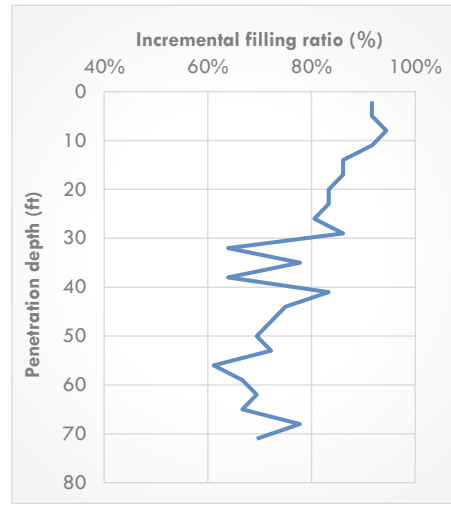
Plug measurement





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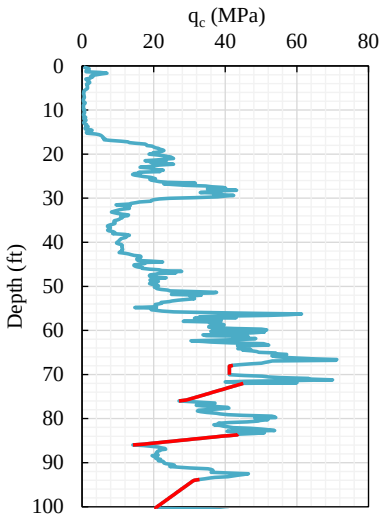
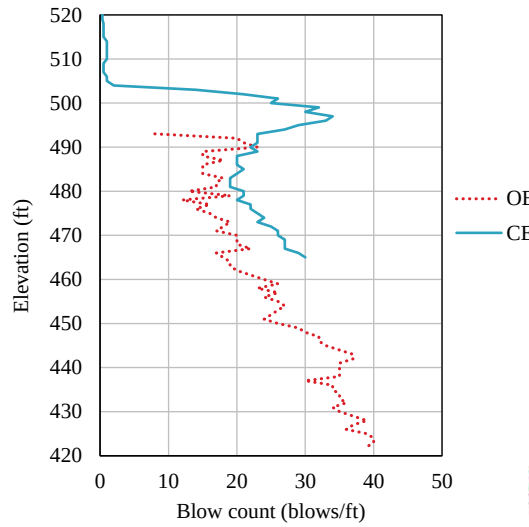
Driving resistance - comparison





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Static Pile Load Test

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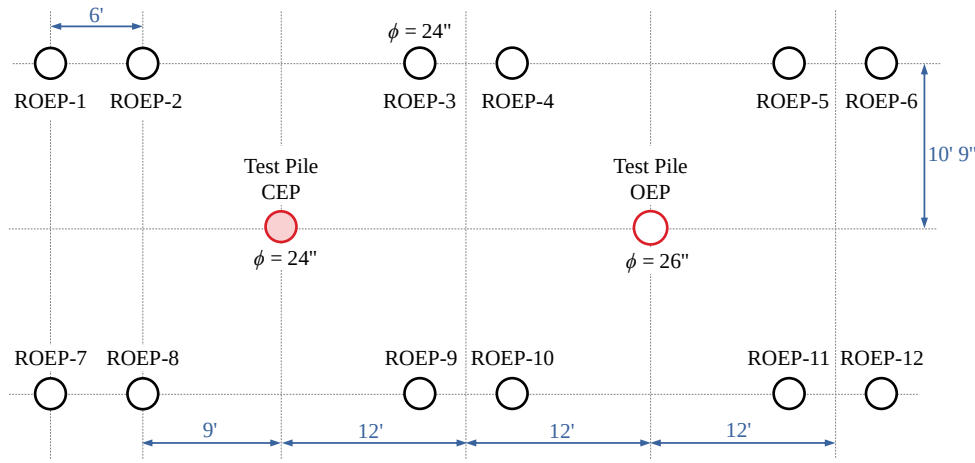
Static load test - layout



(ROEP: reaction open-ended pipe pile; CEP: closed-ended pipe pile; OEP: open-ended pipe pile)

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Static load test

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Static load test

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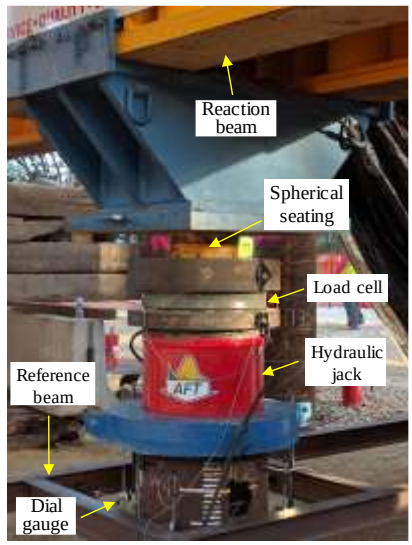
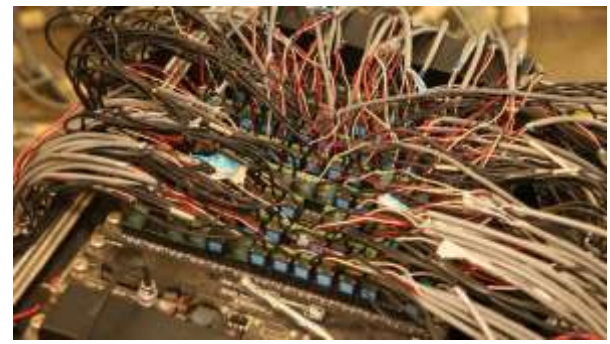
Static load test





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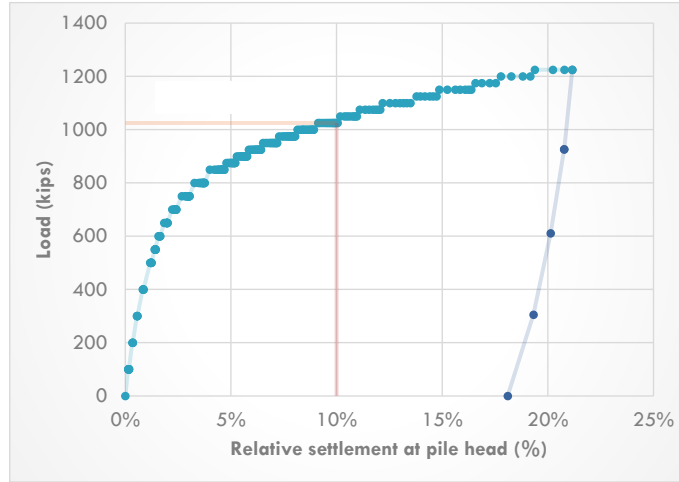
Closed-ended pipe pile

- Load settlement curve
  - Ultimate load: 1025 kips
  - Plunging load: 1225 kips
- Resistance components
  - Shaft: 537 kips
  - Base: 488 kips



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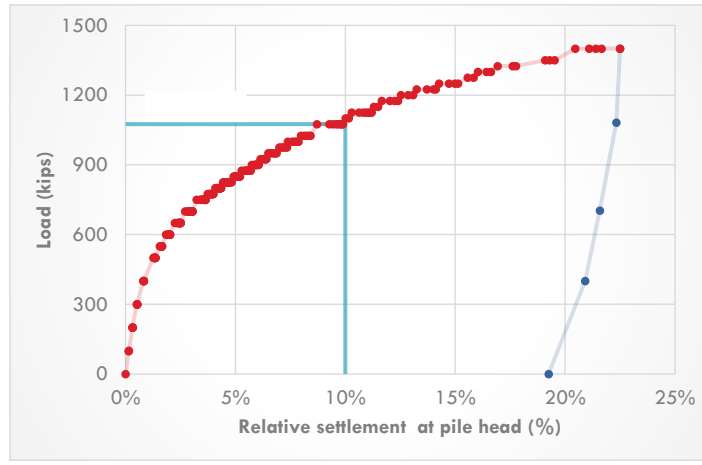
Open-ended pipe pile

- Load settlement curve
  - Ultimate load: 1075 kips
  - Plunging load: 1400 kips
- Resistance components
  - Shaft: 576 kips
  - Plug: 80 kips
  - Annulus: 419 kips



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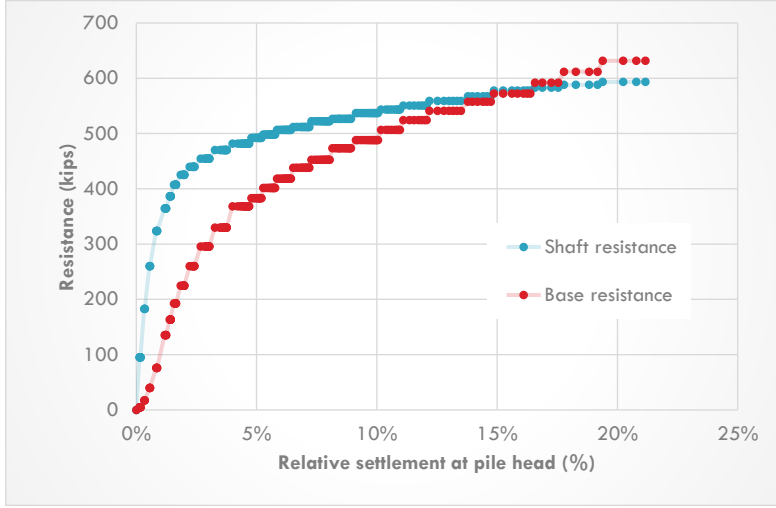
Resistance components - closed-ended pile



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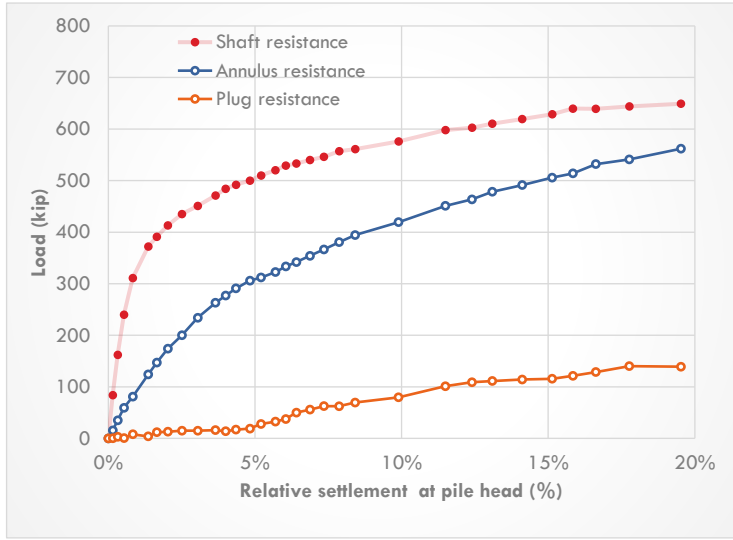
Resistance components - open-ended pile



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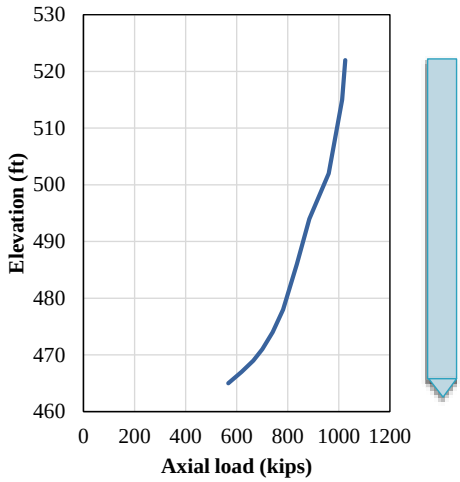
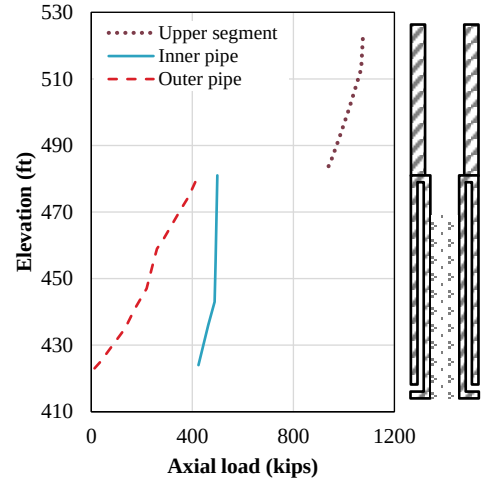
Load transfer curve



Closed-ended pile



Open-ended pile

COFFEE

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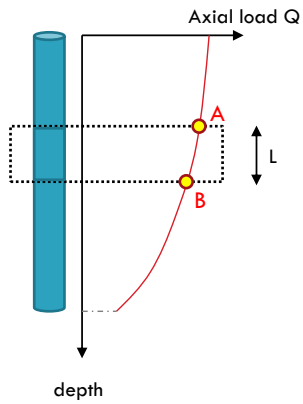
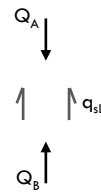
Unit shaft resistance calculation



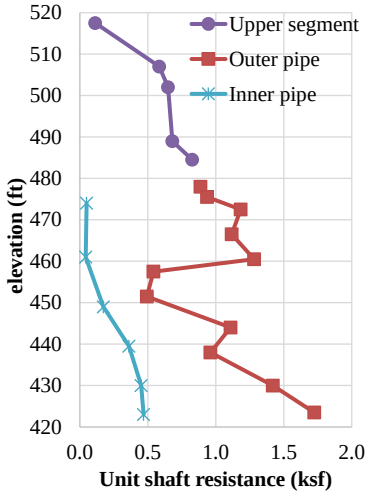


$$q_{sL} = \frac{Q_A - Q_B}{\pi B L}$$

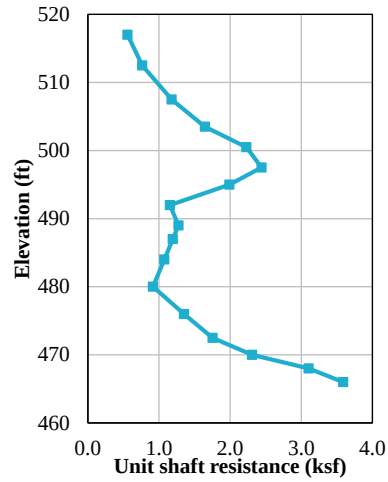
COFFEE

70

Unit shaft resistance



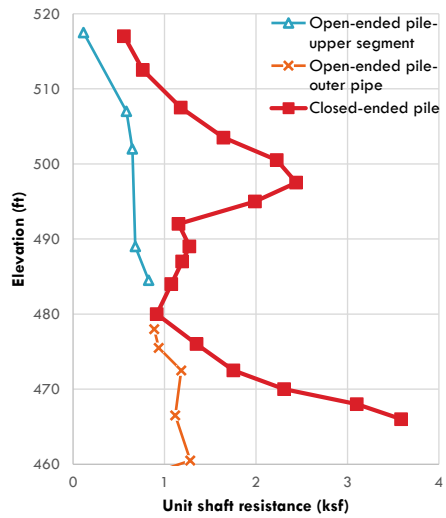
Open-ended pile



Closed-ended pile

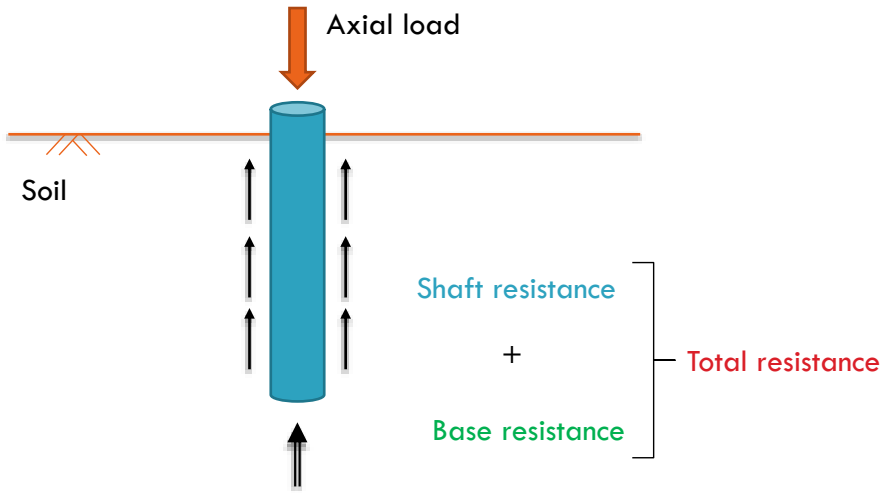
71

Unit shaft resistance - comparisons



72

Components of Pile Resistance



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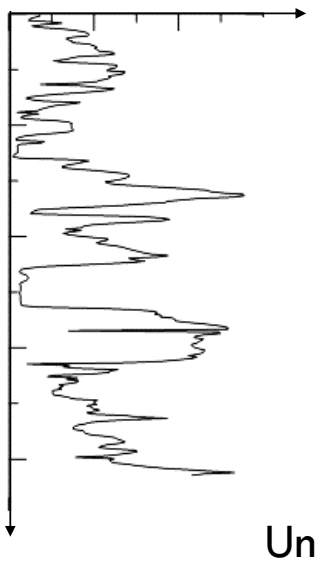
CPT

Cone resistance q_c

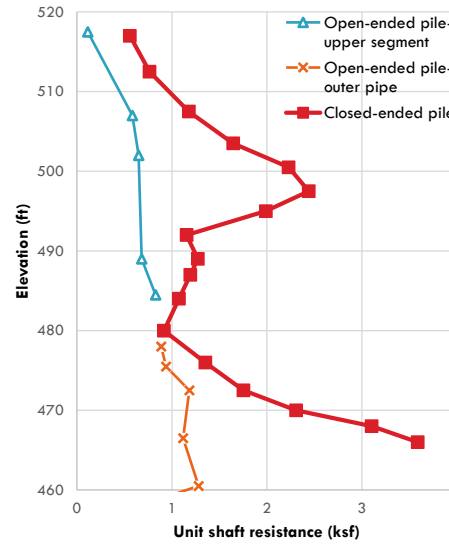


Design Methods

CPT resistances correlated with measured resistances in PLTs

Unit shaft resistance q_{sL}

PLTs



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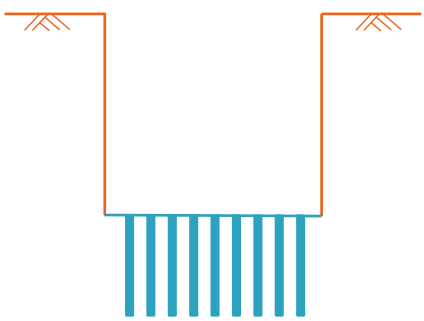
Bridge Monitoring

COFFEE
Center for Offshore Foundation & Energy Engineering

75

Construction stages

Pile installation



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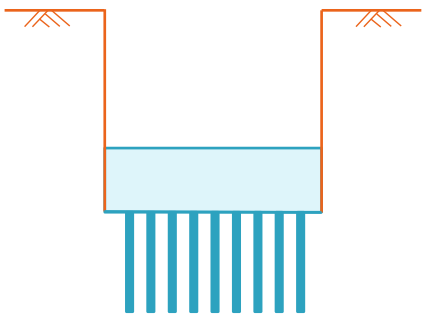
Construction stages

Pile cap pouring



77

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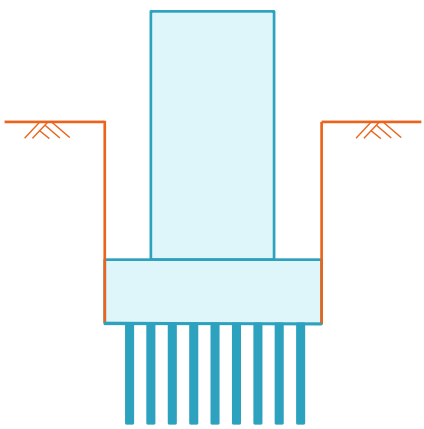
Construction stages

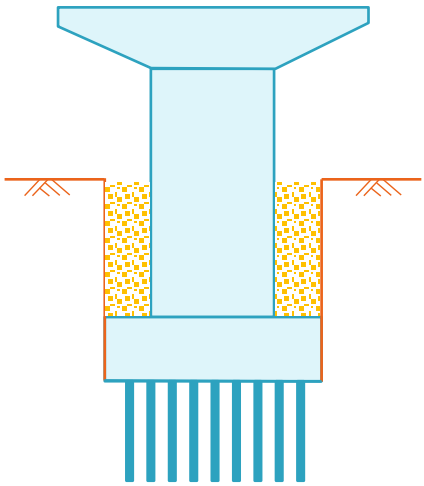
Bridge pier pouring



78

78

Construction stages



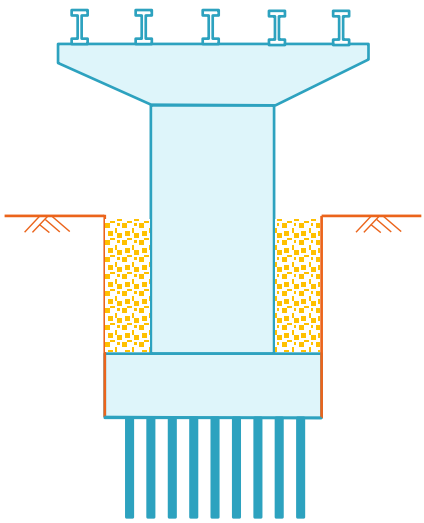
Pier cap
("hammer head")

Backfilling of the cofferdam and pier cap pouring

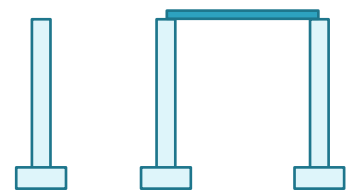
79

79

Construction stages



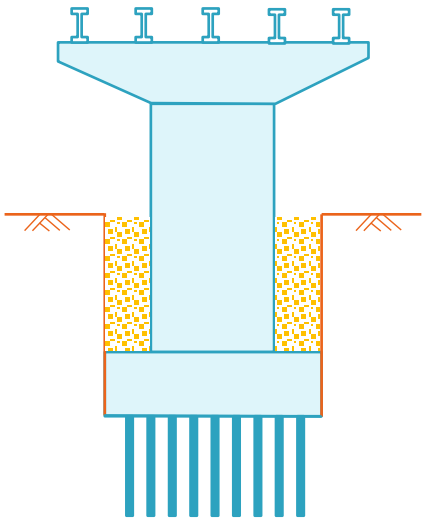
Placement of beams over span 7-8



80

80

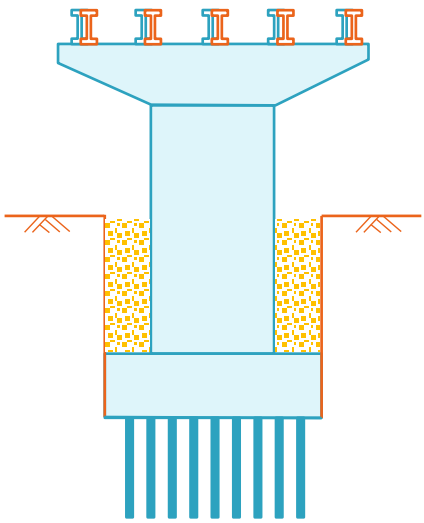
Construction stages



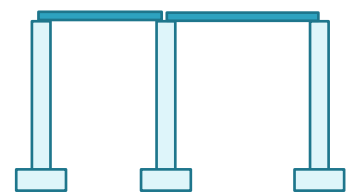
81

81

Construction stages



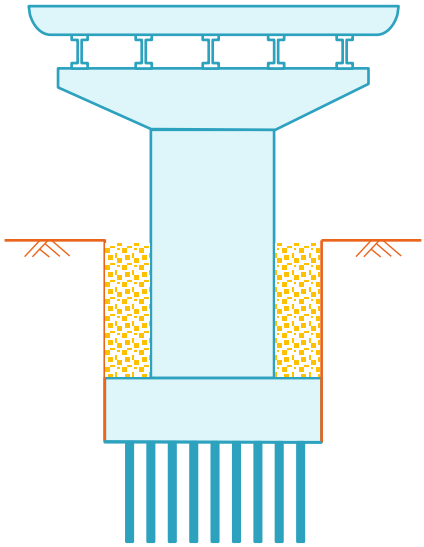
Placement of beams over span 6-7



82

82

Construction stages



Construction of the bridge deck

83

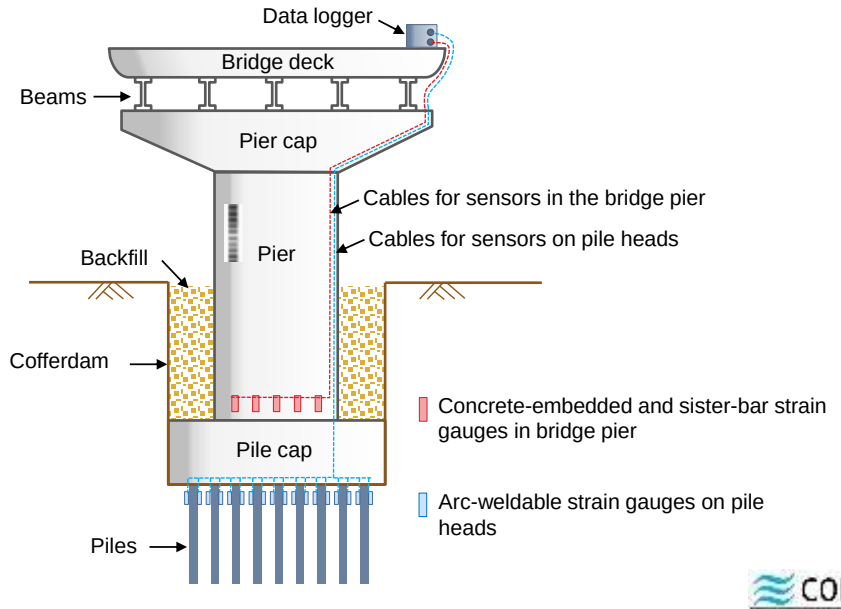
83

Construction completed

84

84

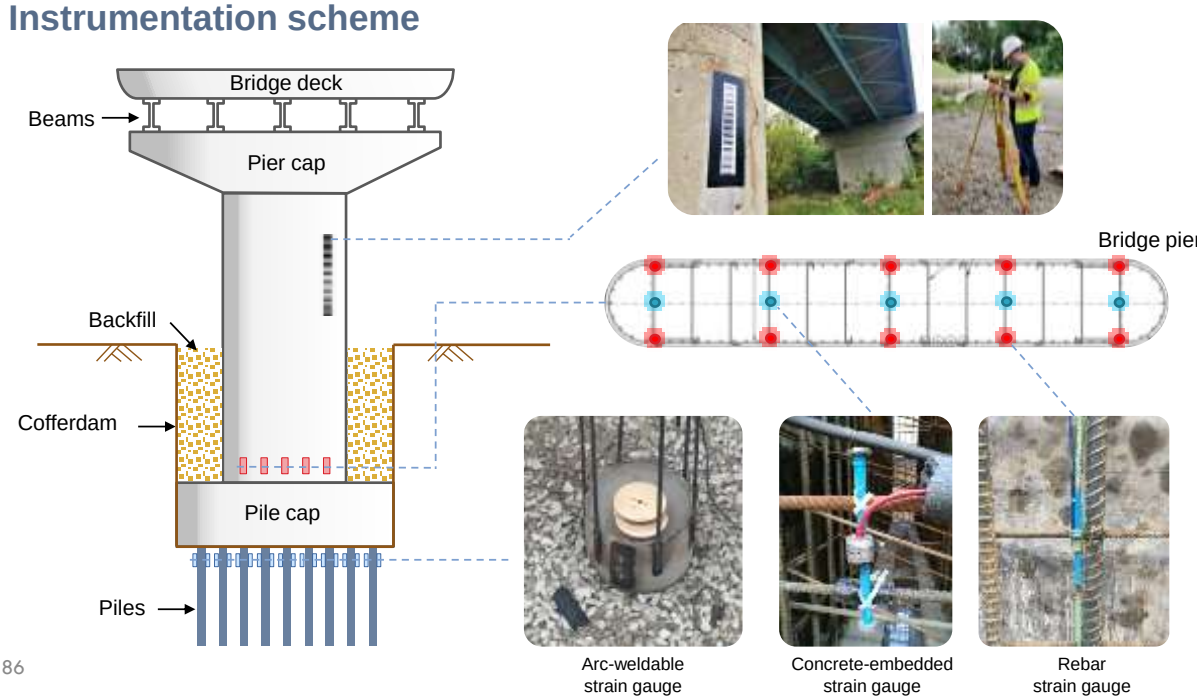
Instrumentation scheme



85

85

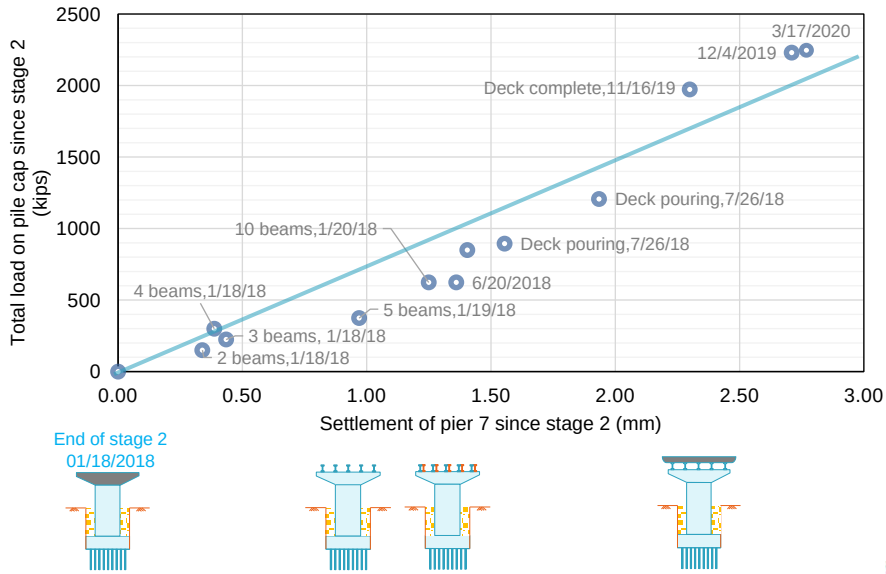
Instrumentation scheme



86

86

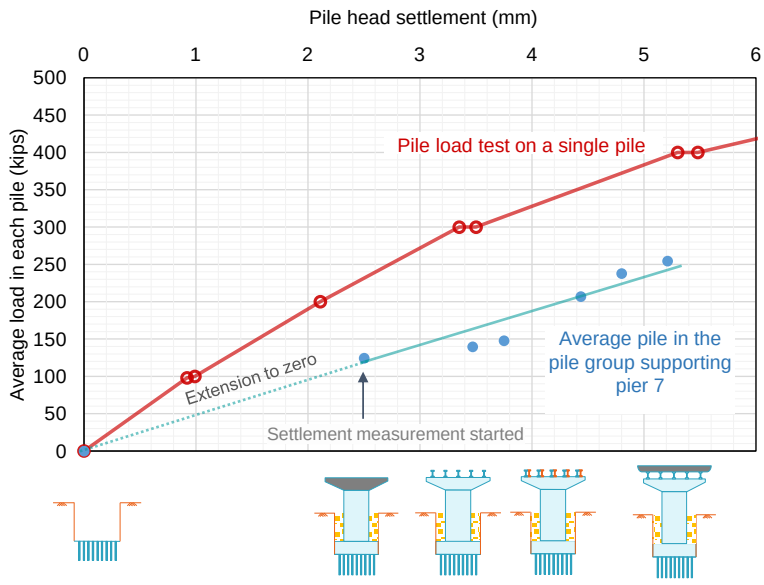
Load-settlement response of bridge pier



87

87

Load-settlement response of piles



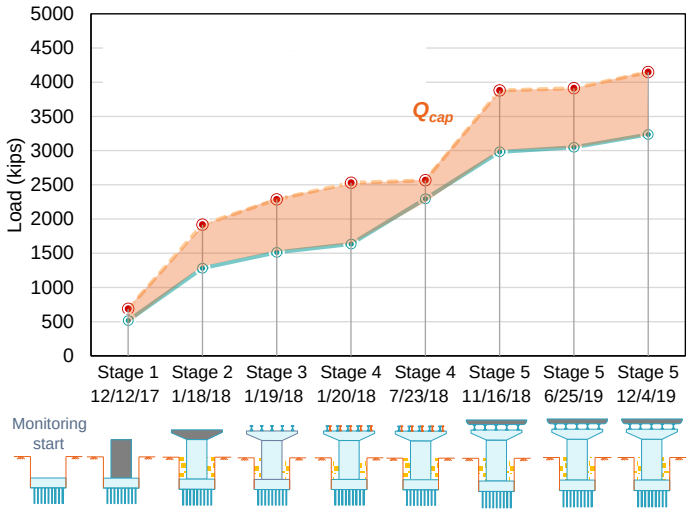
Stiffness of the single test pile at 5 mm
= **76.4 kips/ mm**

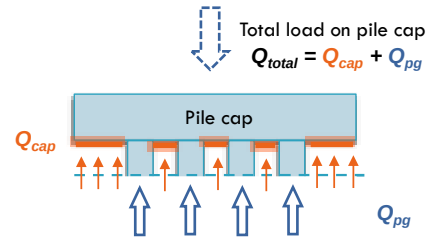
Stiffness of an average pile in the group at 5 mm
= **46.4 kips/ mm**

88

88

Load transfer from bridge pier to piles

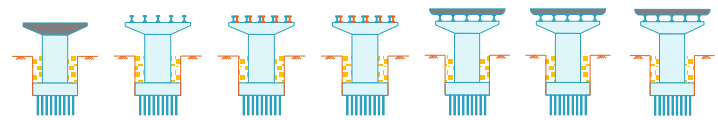


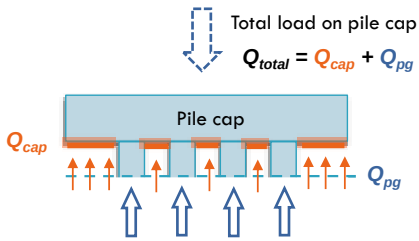


89

89

Load transfer from bridge pier to piles

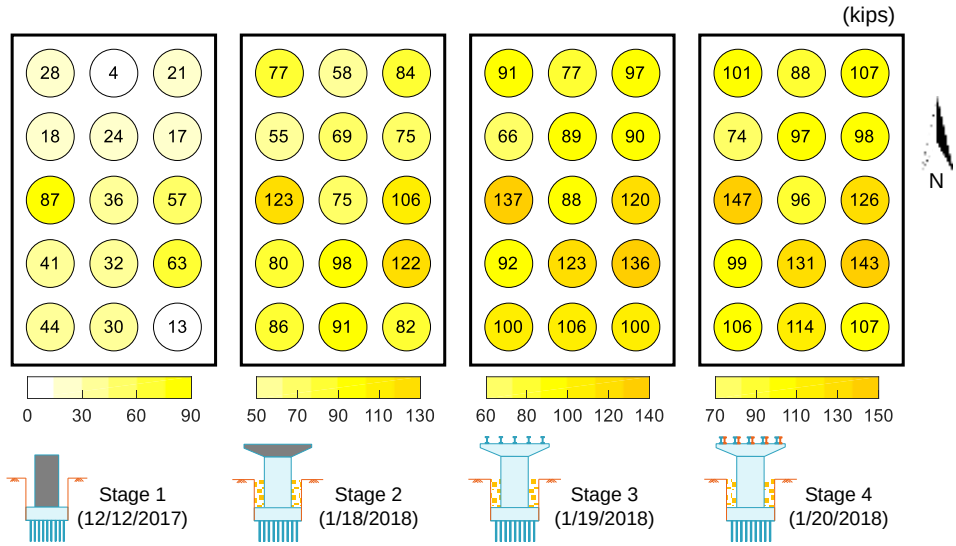




Stage	Stage 2	Stage 3	Stage 4	Stage 4	Stage 5	Stage 5	Stage 5
Date	1/18/2018	1/19/2018	1/20/2018	7/23/2018	11/16/2018	12/04/2019	3/17/2020
Q_{pg}/Q_{total}	67%	66%	65%	89%	76%	78%	78%
Q_{cap}/Q_{total}	33%	34%	35%	11%	24%	22%	**22%**

90

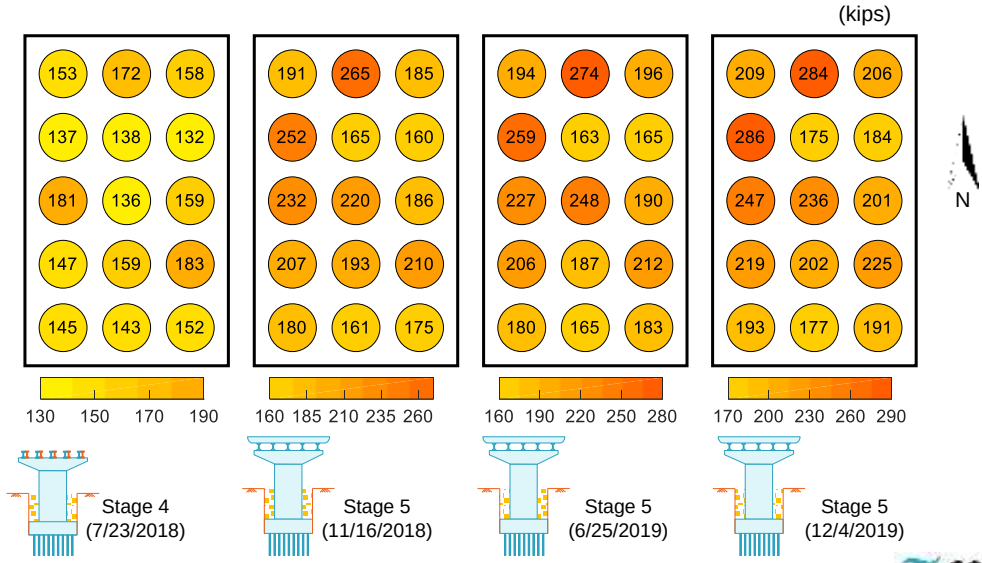
Load distribution among piles in the group



91

91

Load distribution among piles in the group



92

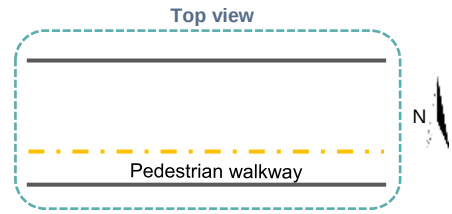
92

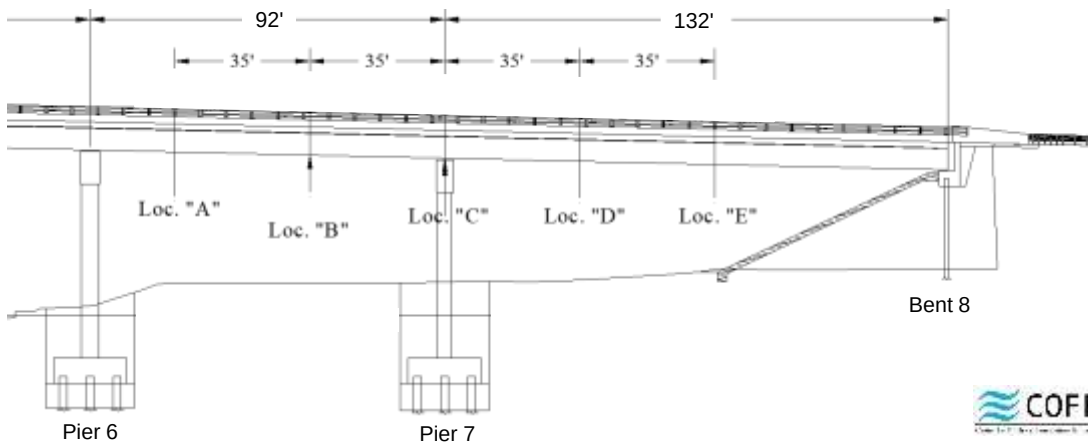
Live Load Test

93

93

Live load test – load step 0

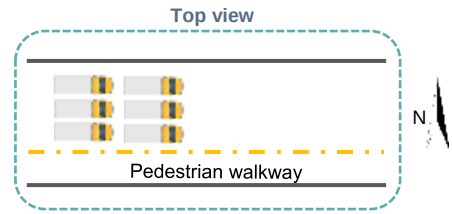


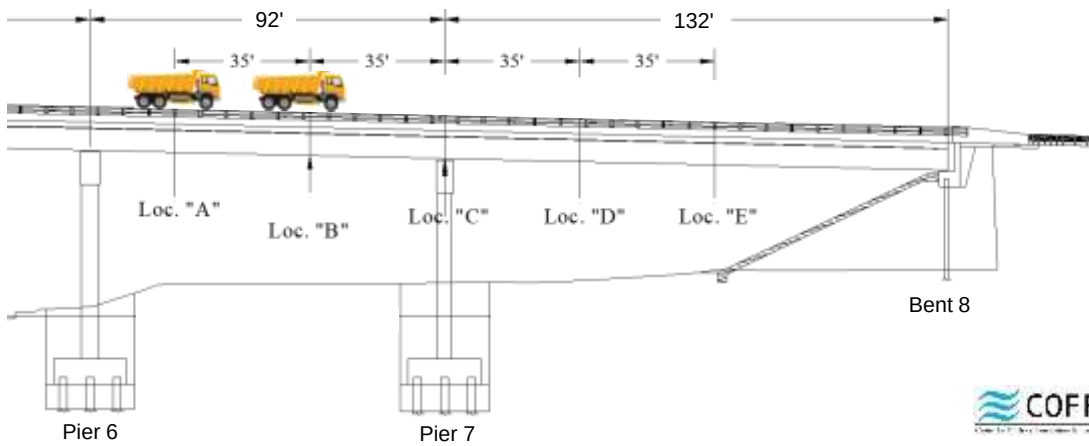


94

94

Live load test – load step 1

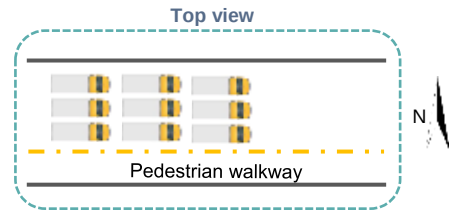


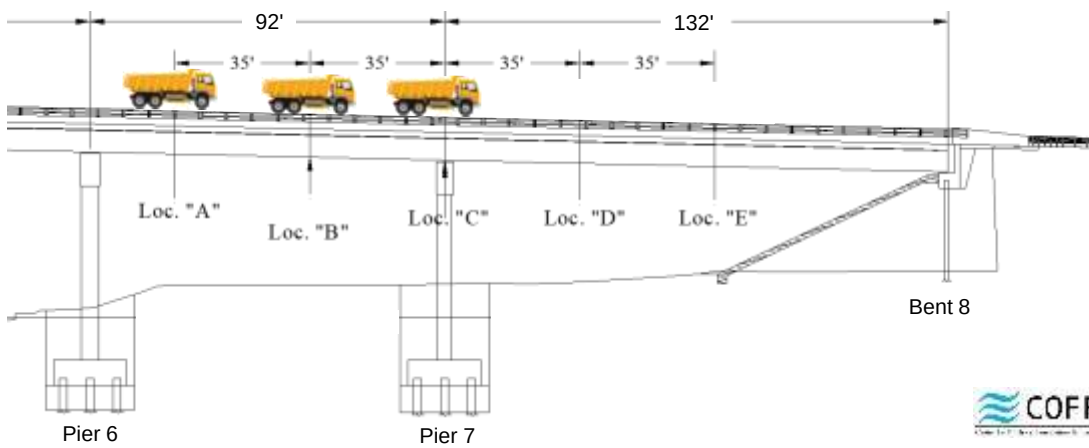


95

95

Live load test – load step 2

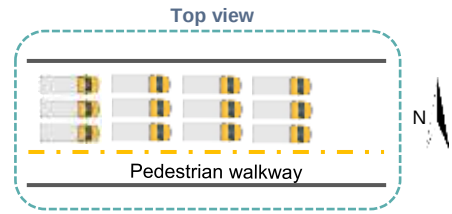


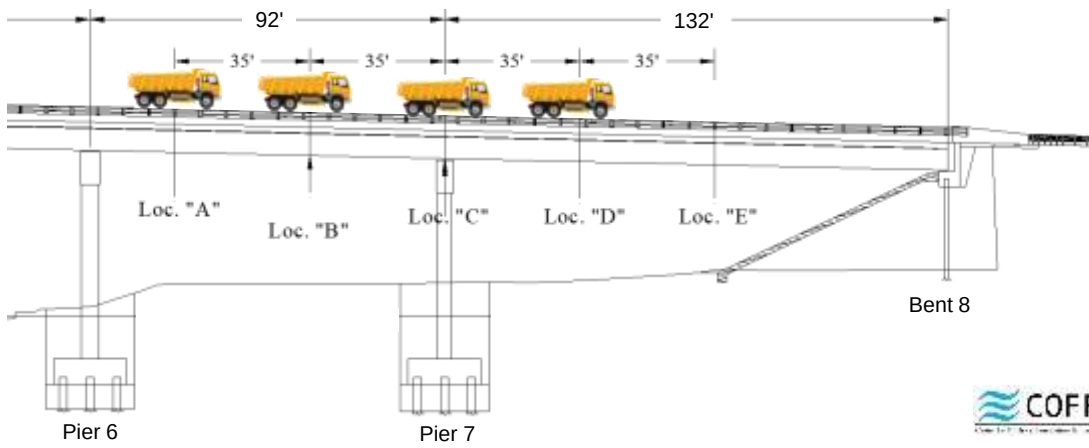


96

96

Live load test – load step 3

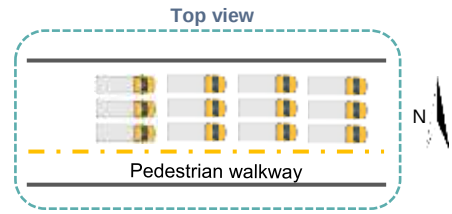


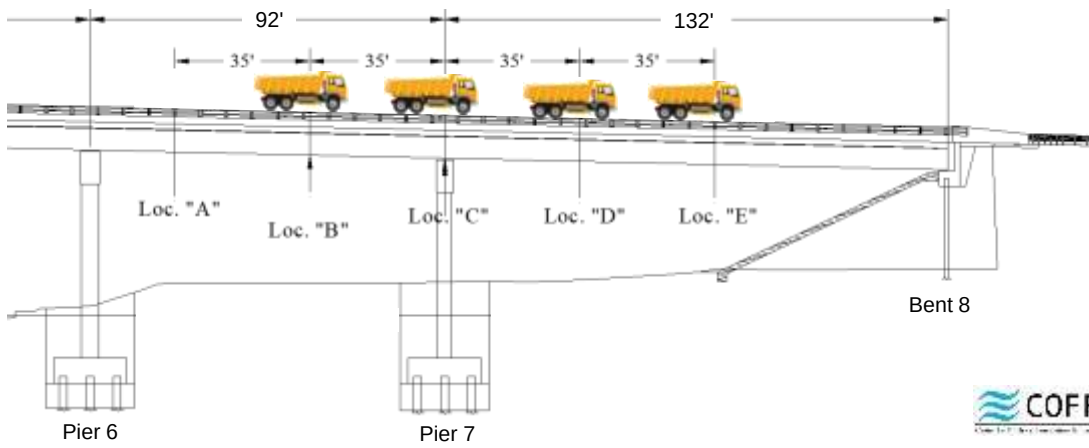


97

97

Live load test – load step 4

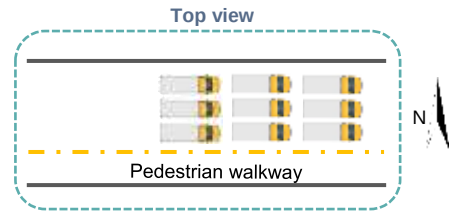


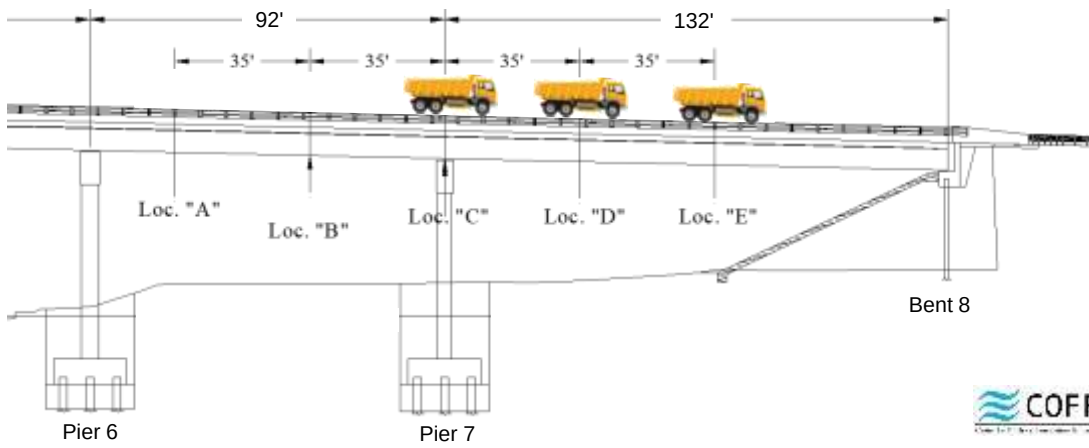


98

98

Live load test – load step 5

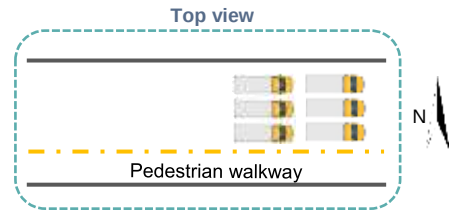


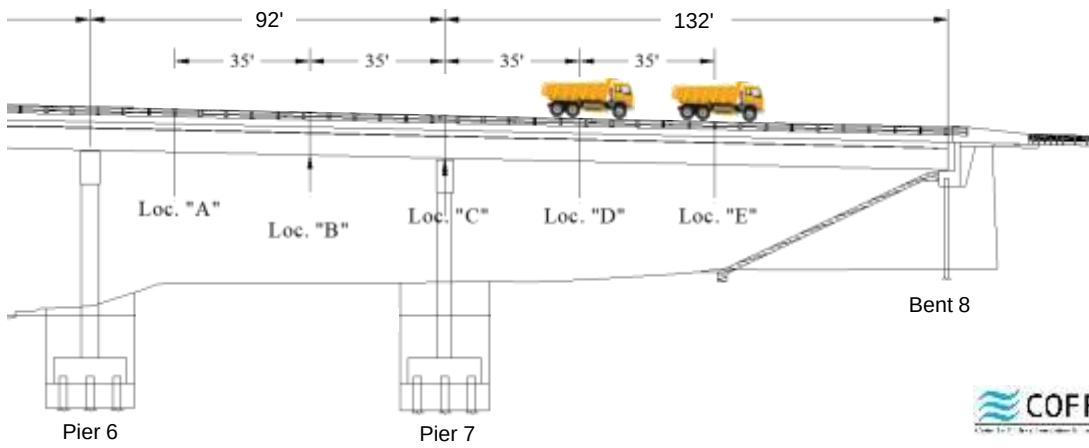


99

99

Live load test – load step 6

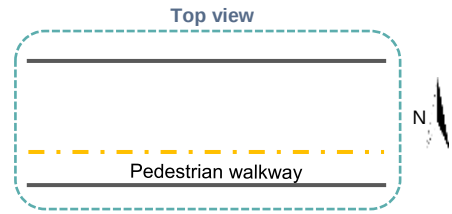


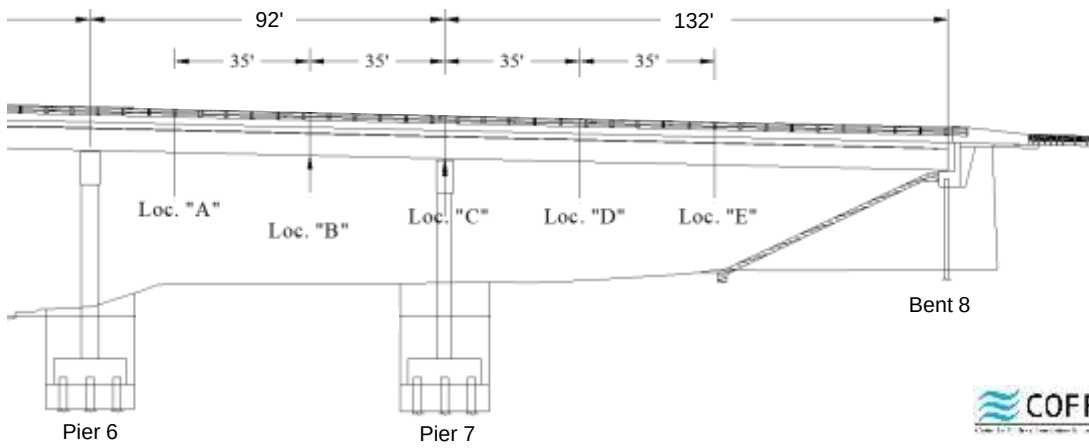


10
0

100

Live load test – load step 7

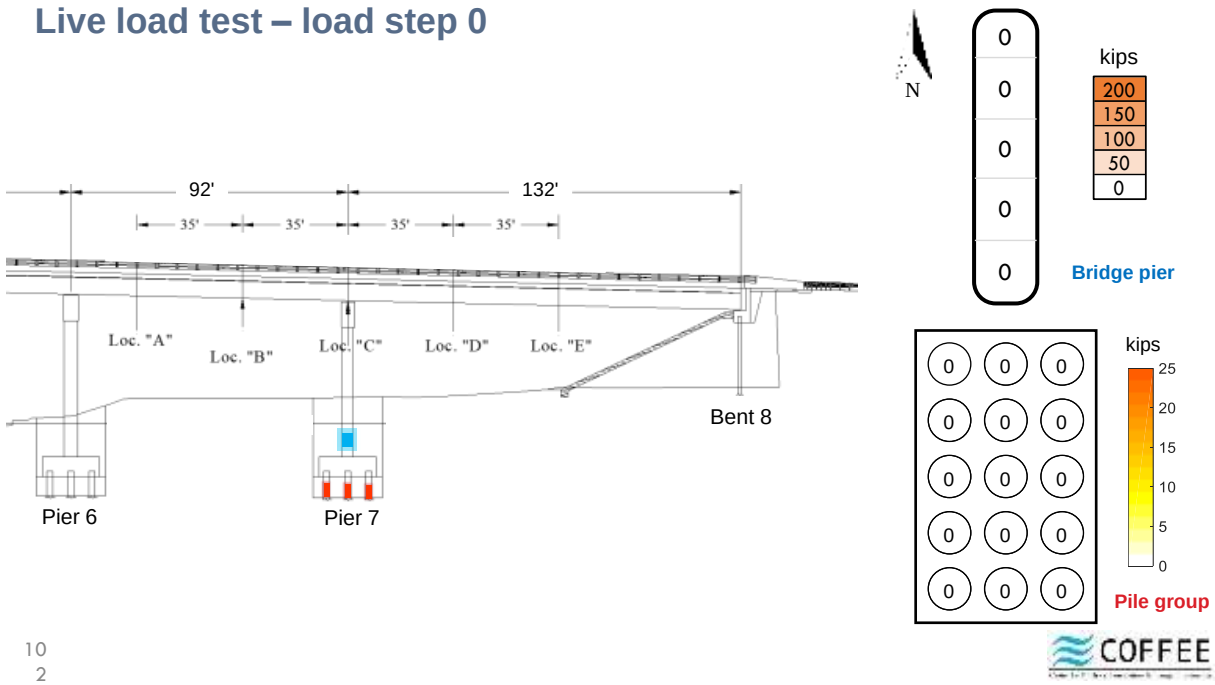




10
1

101

Live load test – load step 0



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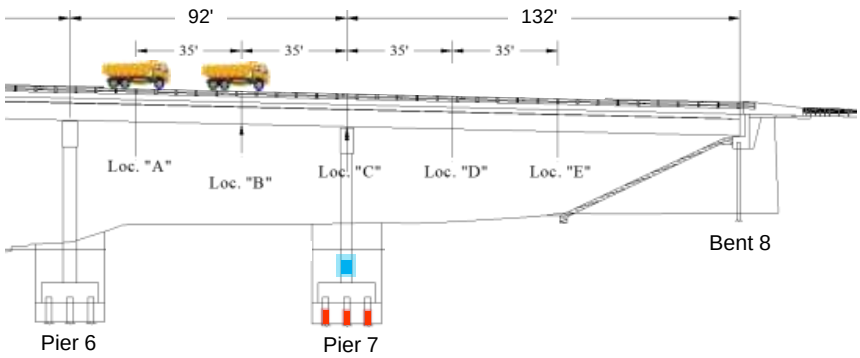
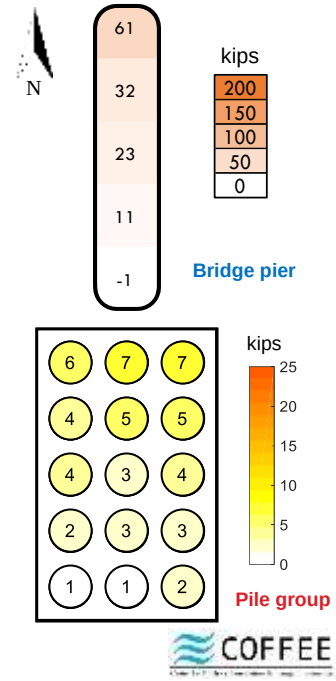
2

102

Live load test – load step 1





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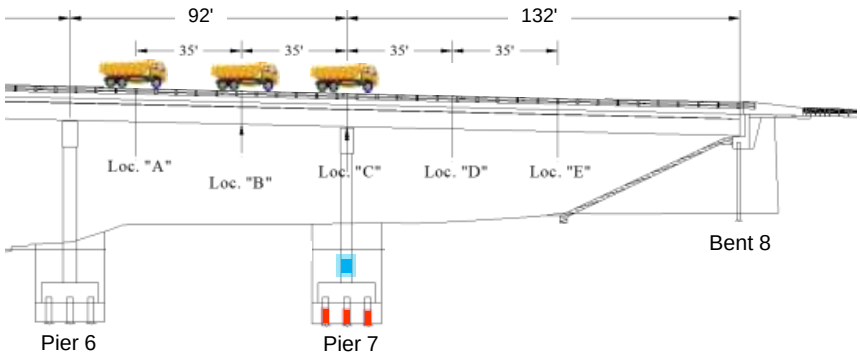
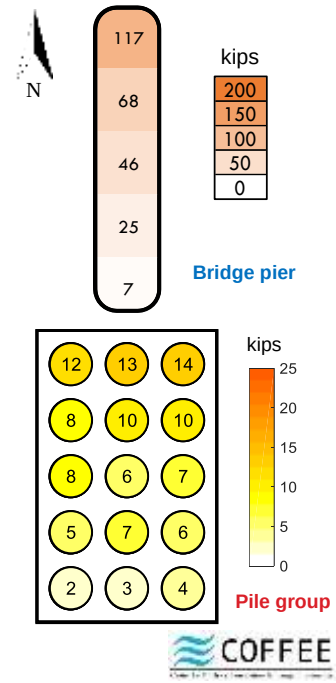
3

103

Live load test – load step 2





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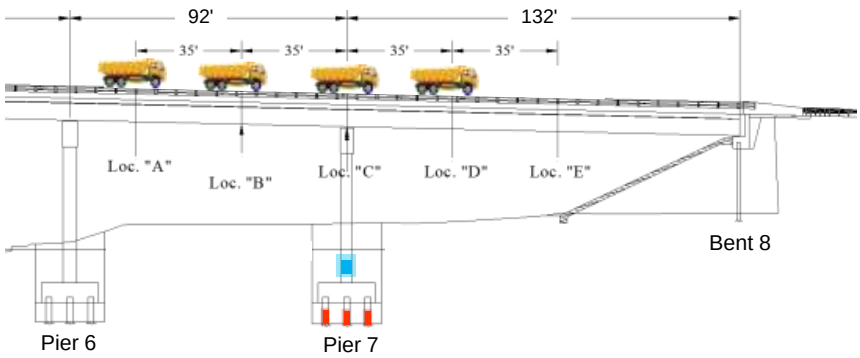
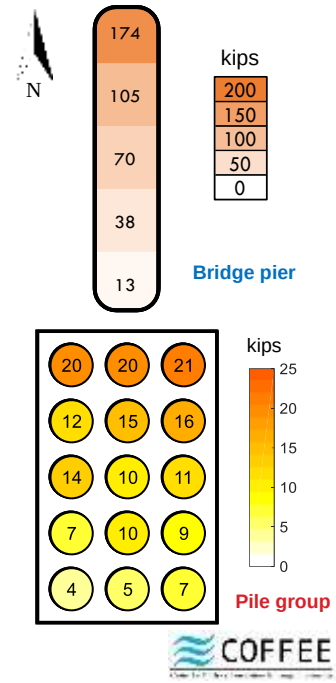
4

104

Live load test – load step 3

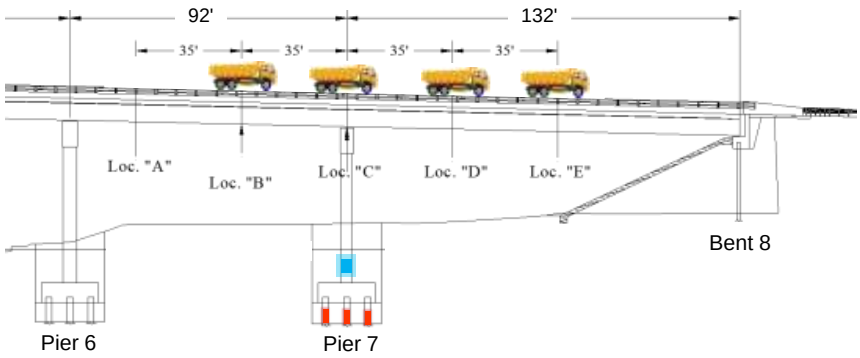


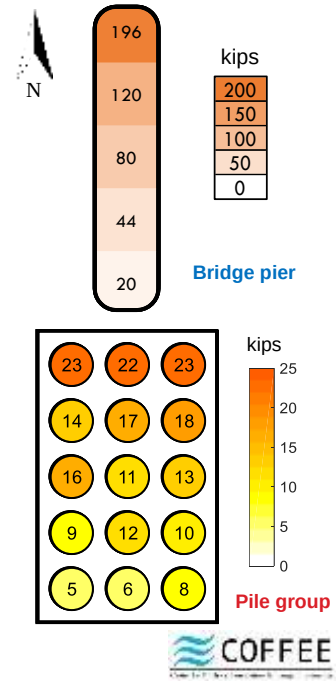


10
5

105

Live load test – load step 4





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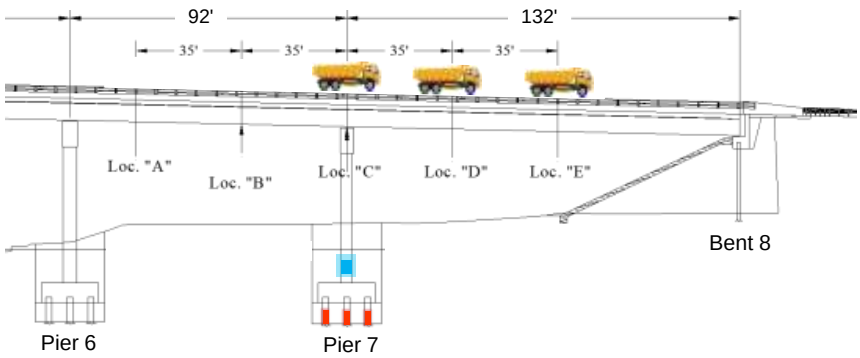
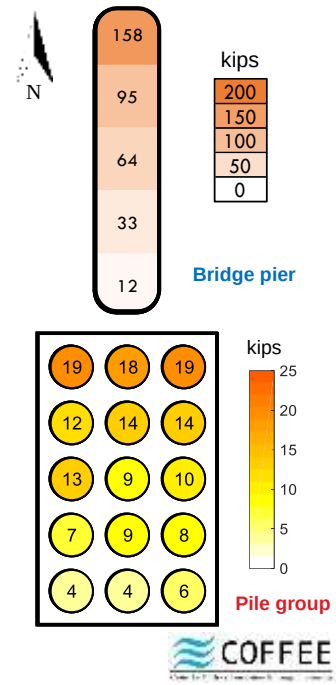
6

106

Live load test – load step 5





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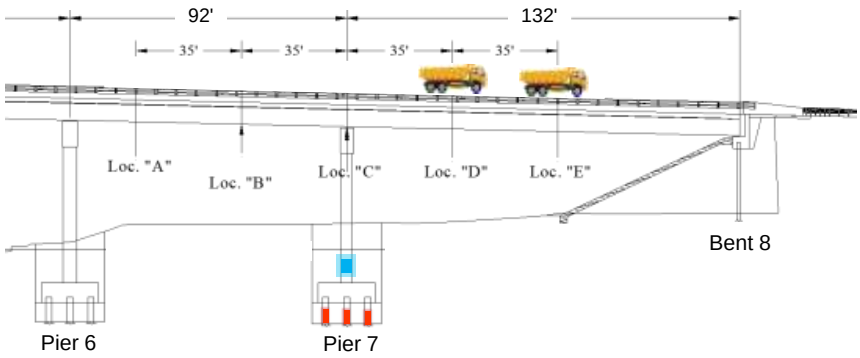
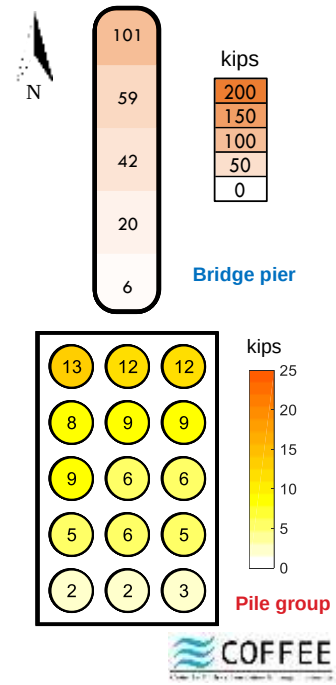
7

107

Live load test – load step 6





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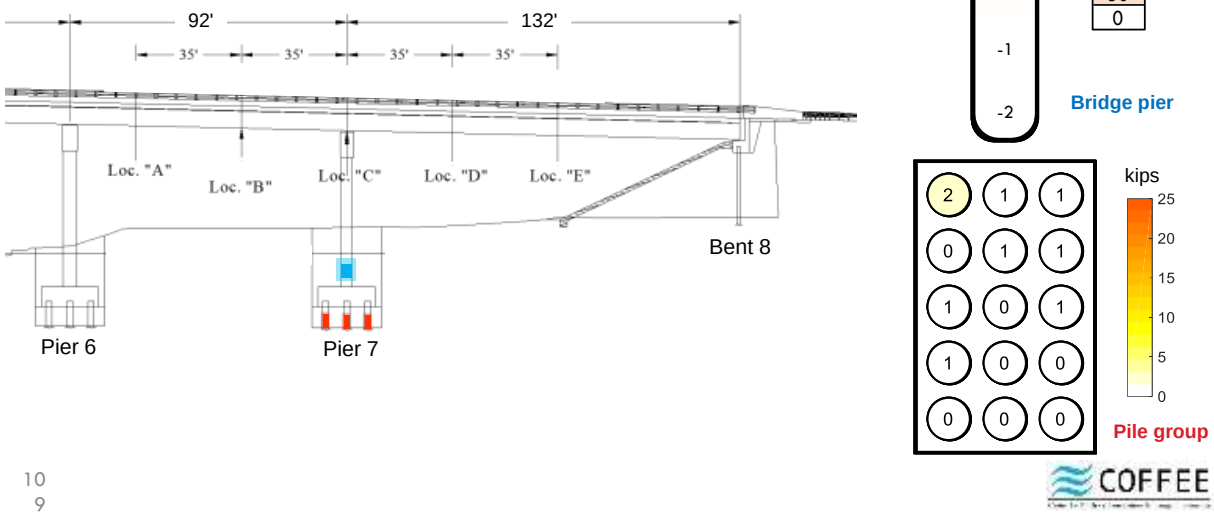
108

Live load test – load step 7



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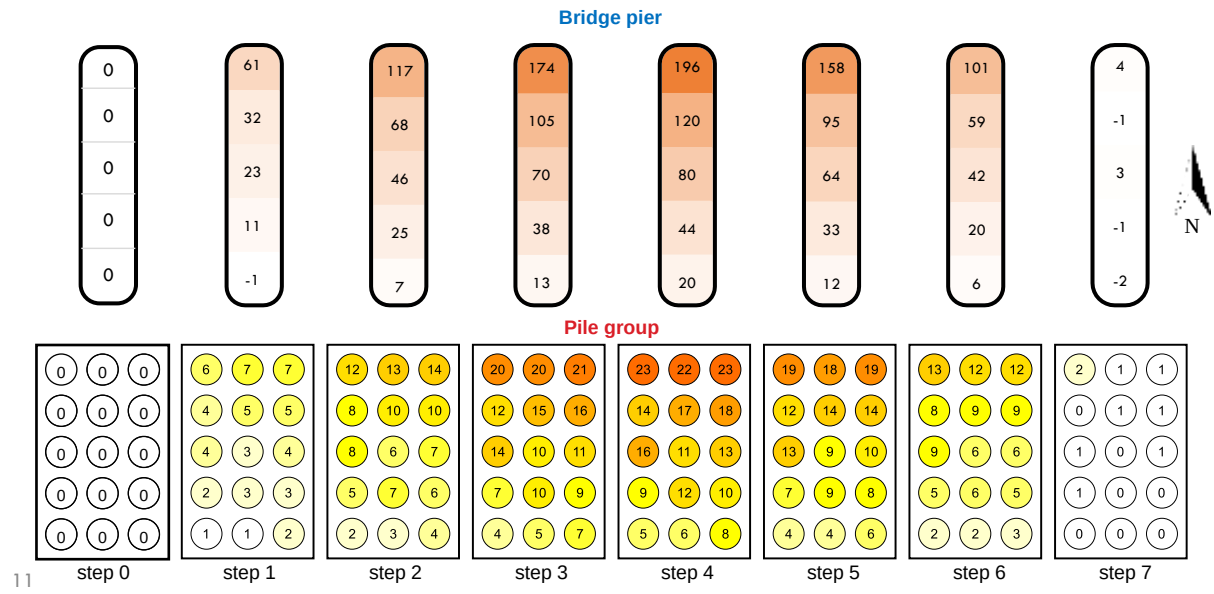
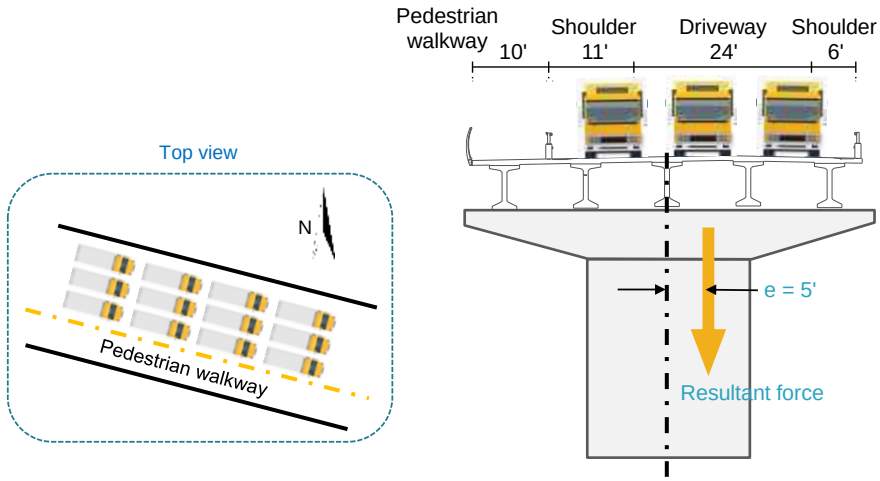
Live load test – load history



110

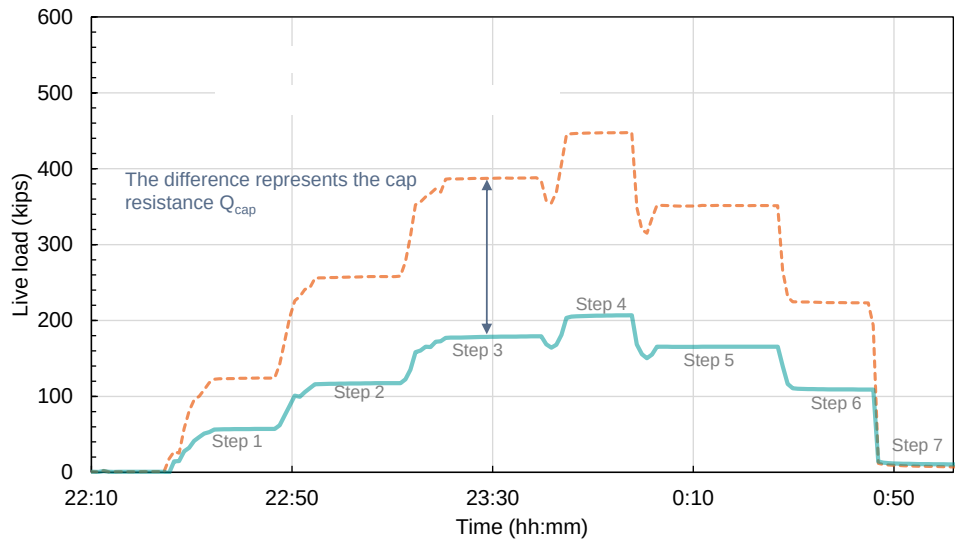
Live load test – load eccentricity



11
1

111

Live load test – load transfer



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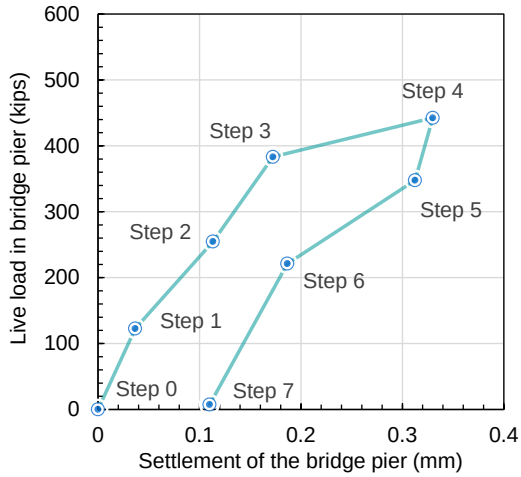
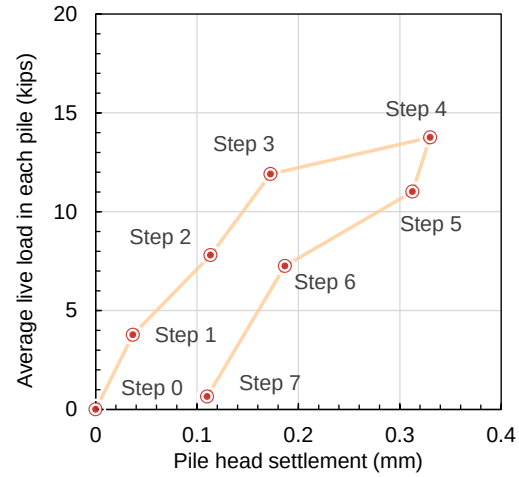
2

112

Live load test – load-settlement response





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Highlights and Implementation

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Rare case history with complete dataset

- Full site investigation and soil characterization
- Dynamic and static load tests on fully instrumented test piles
- Load and settlement monitoring of the bridge pier and its foundation elements under dead and live loads during and after bridge construction

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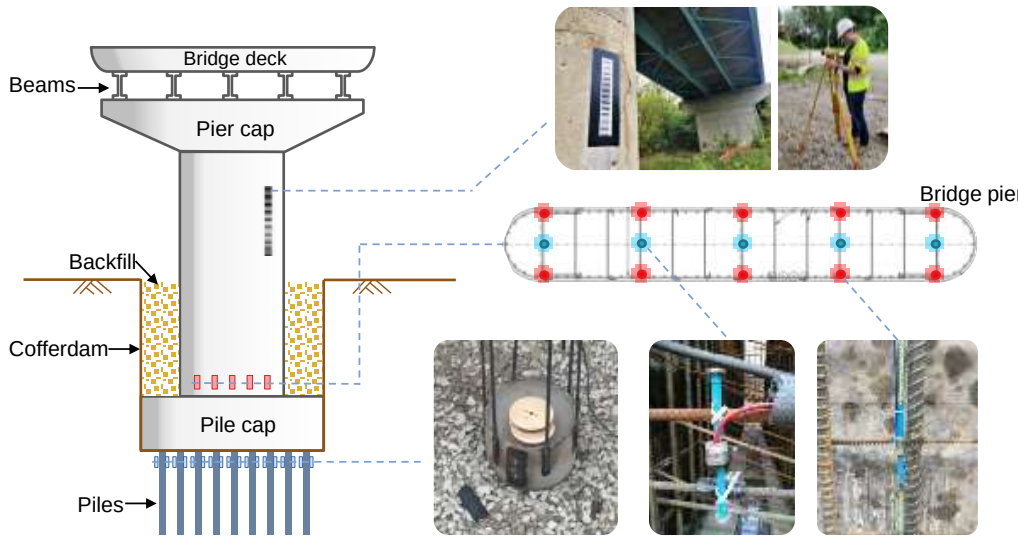
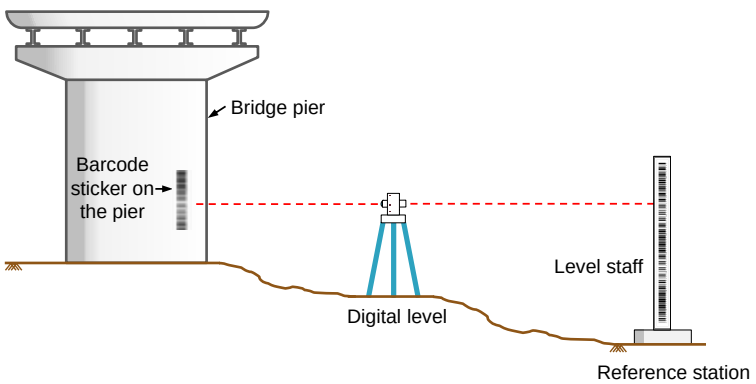
Implementation: instrumentation scheme

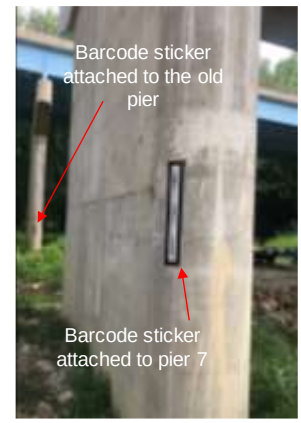


11 7

117

Implementation: instrumentation scheme





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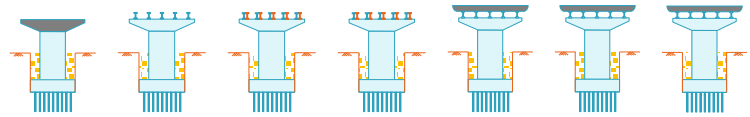
Pile cap contribution



Stage	Stage 2	Stage 3	Stage 4	Stage 4	Stage 5	Stage 5	Stage 5
Date	1/18/2018	1/19/2018	1/20/2018	7/23/2018	11/16/2018	12/04/2019	3/17/2020
Q_{pg}/Q_{total}	67%	66%	65%	89%	76%	78%	78%
Q_{cap}/Q_{total}	**33%**	**34%**	**35%**	**11%**	**24%**	**22%**	**22%**

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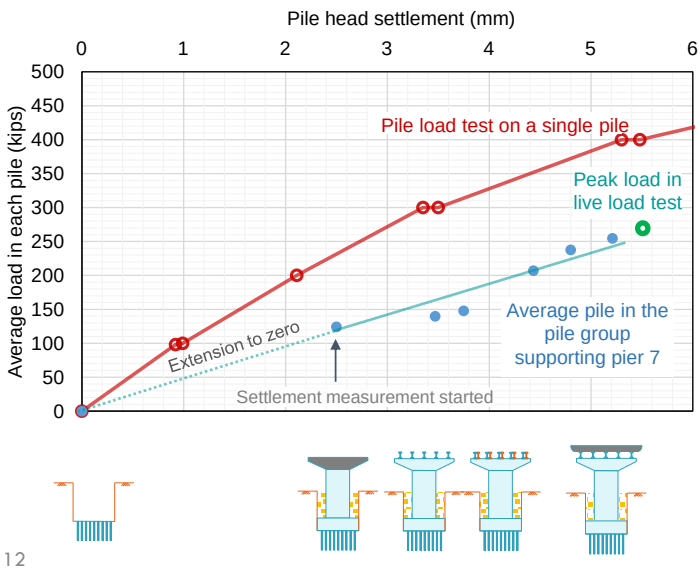
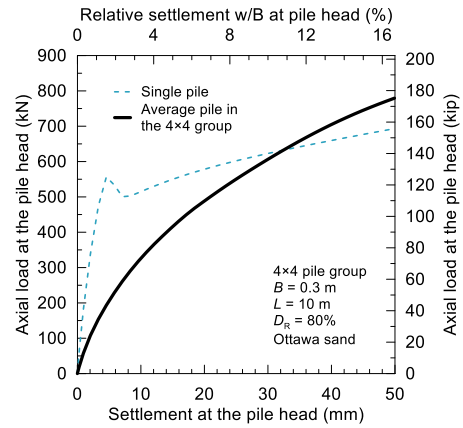
Group pile interactions





FE simulation

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Comparison between measured and estimated loads

- Dead load per pile:
  - Design load = 336 kips
  - Measured at the end of construction (direct measurement) = 248 kips
  - Measured at the end of construction (assuming zero cap resistance) = 325 kips
- Live load per pile:
  - AASHTO design load (vehicular+wind+water…) = 185 kips
  - AASHTO design load (vehicular) = 81 kips
  - Simulation of live load test (assuming continuous-span) = 62 kips
  - Simulation of live load test (assuming simple-span) = 51 kips
  - Measured in live load test (direct measurement) = 23 kips
  - Measured in live load test (assuming zero cap resistance) = 53 kips

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Purdue Method

- Unit shaft resistance (q_{sL}) for closed-ended pipe piles

$$q_{sL} = K\sigma'_{v0}\tan\delta_c$$

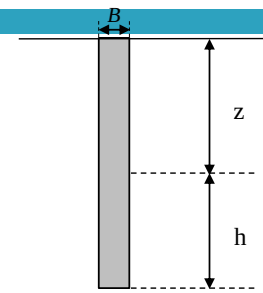
$$K = K_{\min} + (K_{\max} - K_{\min})\exp(-\alpha\frac{h}{B})$$

$$K_{\max} = 0.01(q_c/P_A)\Big/\sqrt{\sigma'_{h0}/P_A}$$

- Unit base resistance ($q_{b,ult}$) for closed-ended pipe piles

$$q_{b,ult} = (1-0.0058D_R)\,q_{cb,avg}$$

$$D_R(\%) = \frac{\ln\left(\frac{q_c}{p_A}\right) - 0.4947 - 0.1041\phi_c - 0.841\ln\left(\frac{\sigma_{h0}'}{p_A}\right)}{0.0264 - 0.0002\phi_c - 0.0047\ln\left(\frac{\sigma_{h0}'}{p_A}\right)} \le 100\%$$



- h = distance from the pile base
- $K_{\min}$ = 0.2
- α = 0.05
- B = pile diameter
- D_R = relative density
- δ_c = interface friction angle
- $q_{cb,avg}$ = average cone resistance near the pile base

Han et al. 2019; Salgado et al. 2011; Salgado & Prezzi 2007

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Purdue Method

- Unit shaft resistance (q_{sL}) for open-ended pipe piles

$$q_{sL} = K\left(1-0.66\text{PLR}\right)\sigma'_{v0}\tan\delta_{cs}$$

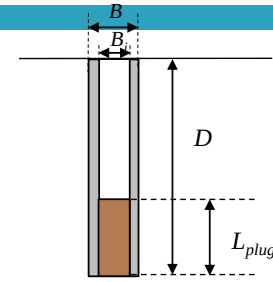
$$K = K_{min} + \left(K_{max} - K_{min}\right)\exp\left(\frac{-\alpha h}{B}\right)$$

$$K_{max} = 0.01\left(q_c / P_A\right)\Big/\sqrt{\sigma'_{h0}/P_A}$$

$$K_{min} = 0.2, \quad \alpha = 0.05$$

- Unit base resistance ($q_{b,ult}$) for open-ended pipe piles

$$q_{b,ult} = 0.21\left(\text{IFR}\right)^{-1.2} q_{cb,avg} \le 0.6 q_{cb,avg}$$



- δ_{cs} = interface friction angle
- D = penetration depth
- L_{plug} = soil plug length
- B = outer pile diameter
- B_i = inner pile diameter

IFR ≈ min[1, $(B_i/1.5)^{0.2}$], B_i in meters (Lehane et al. 2005)

Han et al. 2019; Paik & Salgado 2003

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Bridge foundation design in gravelly sand

Elevation range (ft)	Soil description	Unit shaft resistance (ksf)	**Gravel content (%)**	q_c (ksf)	q_{sL}/q_c
522-513	Clayey silt with sand	0.11	-	20	**0.0056**
513-501	Clayey silt with sand	0.58	**9**	80	**0.0073**
501-486	Sandy gravel	0.55	**24**	390	**0.0014**
486-482	Sand with gravel	0.35	**15**	156	**0.0022**
482-475	Sand with gravel	0.60	**10**	234	**0.0026**
475-464	Gravelly sand	0.95	**27**	427	**0.0022**
464-456	Gravelly sand	0.81	**41**	696	**0.0012**
456-444	Gravelly sand	0.66	**29**	801	**0.0008**
444-432	Gravelly sand	1.11	**27**	565	**0.0020**
432-422	Gravelly sand	1.83	**30**	538	**0.0034**

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Dissemination

- Road School 2019, Purdue University
- TRB 2020, Washington, DC
- Geo-Congress 2020, Minneapolis, MN
- Indiana Bridge Design Conference, 2021
- IFCEE 2021, Dallas, TX
- ICSMGE 2021, Sydney, Australia
- TRB AKG70, Foundations of Bridges and Other Structures, Washington, DC, January 2021

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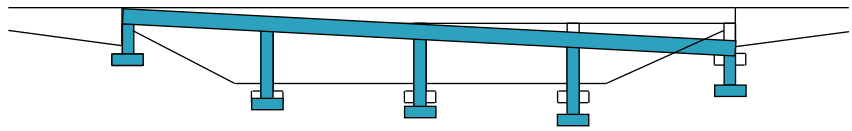

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