Structural Design Related Geotechnical Updates

Derrick Dasenbrock

Geomechanics/LRFD Engineer

Office of Materials and Road Research

Topics:

- Construction Control: Driven Piles
- Static Load Test LRFD Calibration- “MnPile”
- Dragload/Downdrag
- Large Diameter Piles
- Shallow and Geosynthetic Reinforced Soil (GRS) Foundations
- Reports/Recommendations
- Performance Monitoring/Instrumentation

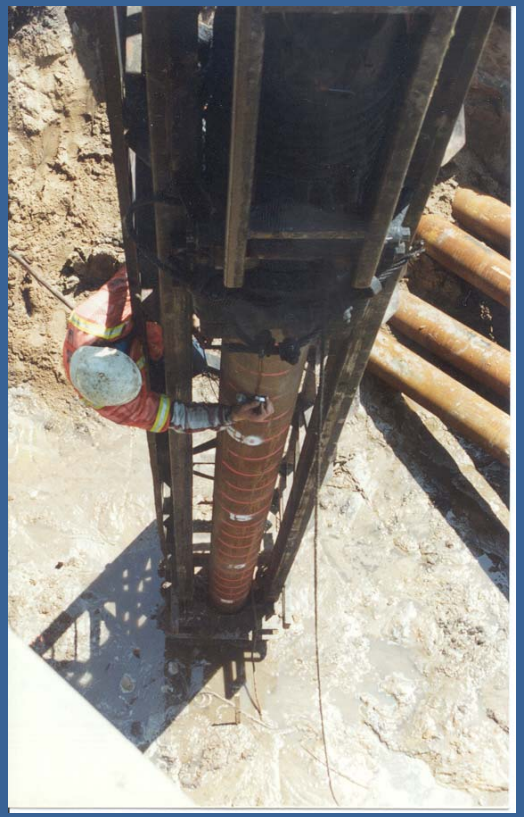
Construction Control: Driven Piles

- Different methods with different LRFD resistance factors
- AASHTO values and/or local calibration

Table 10.5.5.2.3-1—Resistance Factors for Driven Piles

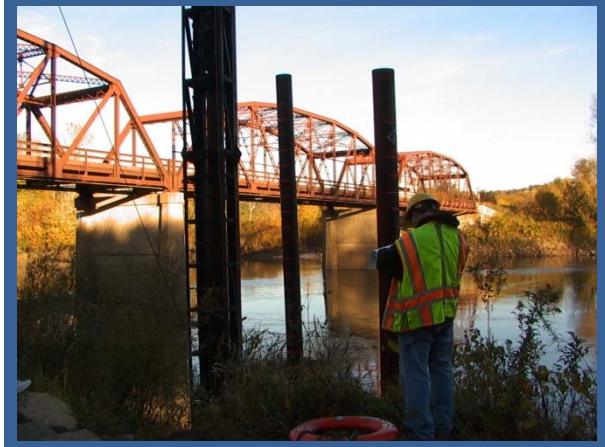
Condition/Resistance Determination Method		Resistance Factor
Nominal Bearing Resistance of Single Pile—Dynamic Analysis and Static Load Test Methods, φ_{dyn}	Driving criteria established by successful static load test of at least one pile per site condition and dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles	0.80
	Driving criteria established by successful static load test of at least one pile per site condition without dynamic testing	0.75
	Driving criteria established by dynamic testing* conducted on 100% of production piles	0.75
	Driving criteria established by dynamic testing,* quality control by dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles	0.65
	Wave equation analysis, without pile dynamic measurements or load test but with field confirmation of hammer performance	0.50
	FHWA-modified Gates dynamic pile formula (End of Drive condition only)	0.40
	Engineering News (as defined in Article 10.7.3.8.5) dynamic pile formula (End of Drive condition only)	0.10

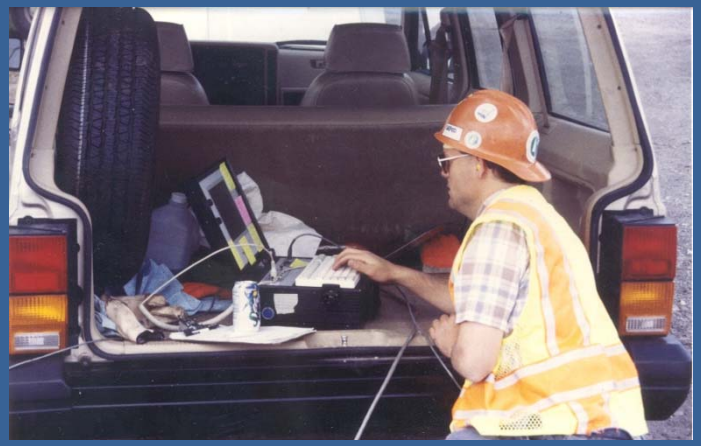
* Dynamic testing requires signal matching, and best estimates of nominal resistance are made from a restrike. Dynamic tests are calibrated to the static load test, when available.



MnDOT Construction Control Methods

- Factored Resistance ≥ Factored Load
  - MnDOT dynamic formula ($\varphi = 0.4$)
  - PDA/CAPWAP ($\varphi = 0.65$)
  - Static Load Test ($\varphi = 0.8$)





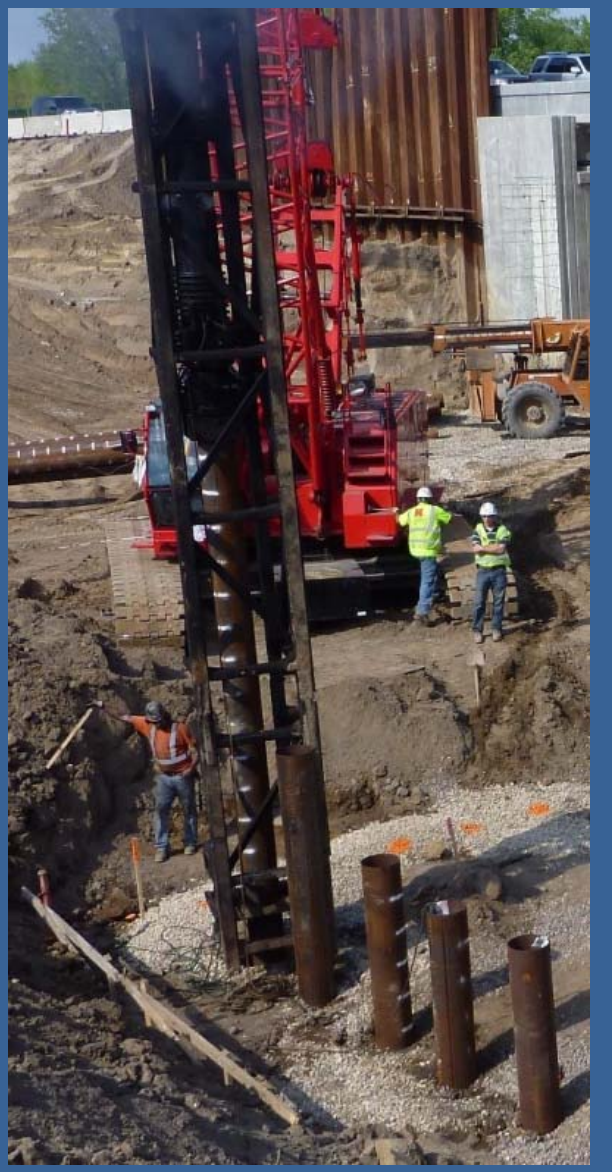
- Nominal Bearing Resistance
  - Geotechnical Failure; Pile Deflection; Static Equilibrium

Construction Control (φ = 0.4)

- "MnDOT formula"
  - Most common control method for state bridge projects in MN
  - Predicts pile capacity

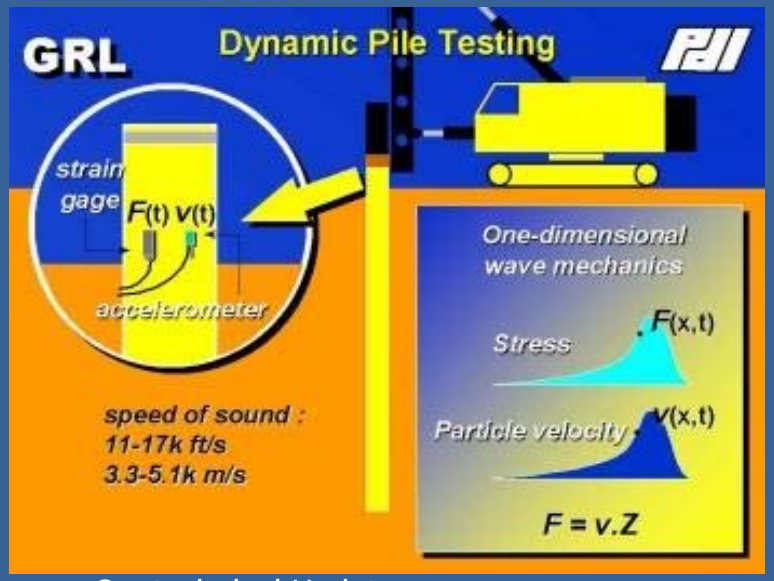
$$R_n = \frac{10.5\,E}{S + 0.2} \times \frac{W + 0.1\,M}{W + M}$$

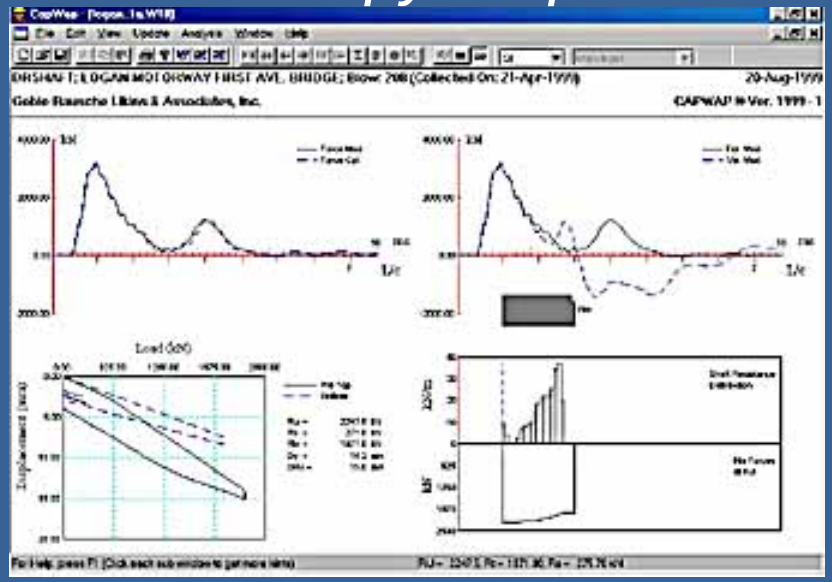
W = Weight of striking part of hammer (pounds)
H = Height of fall (feet)
E = W*H (ft*lb of energy per blow/full stroke)
M = Weight of pile plus driving cap (pounds)
S = Avg. penetration (inches) per blow for the last 10 or 20 blows



Construction Control (φ = 0.65)

- PDA/CAPWAP
  - Pile Driving Analyzer
  - High Strain Dynamic Monitoring and Wave Equation Analysis: Case Pile Wave Analysis Program
  - Predicts pile capacity based on force and velocity
  - *Note: Send ALL electronic/hard-copy output to MnDOT*





Construction Control (φ = 0.8)

- Static Load Test (SLT)
  - Run to geotechnical failure
  - Provide high level of confidence for capacity
  - Measure capacity
  - Davisson Offset Failure Criterion

UMASS LOWELL
Where Research Becomes Reality

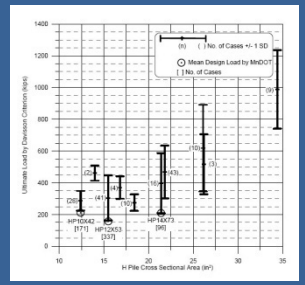
MINNESOTA STATE UNIVERSITY MANKATO

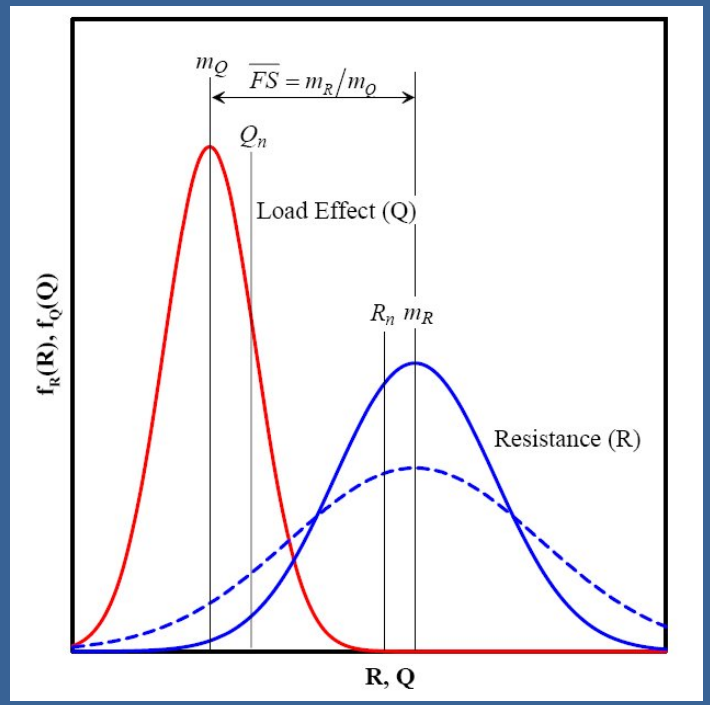
Mn/DOT Research Project:
Developing a Resistance Factor for Mn/DOT's Pile Driving Formula
Final Report

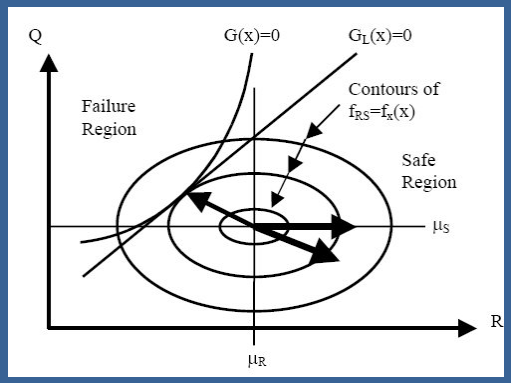
Due to the Mn/DOT dynamic equation **over-prediction** and **large scatter**, the obtained resistance factors were consistently low, and a resistance factor of **φ = 0.25** is recommended to be used with this equation, for both H and pipe piles.

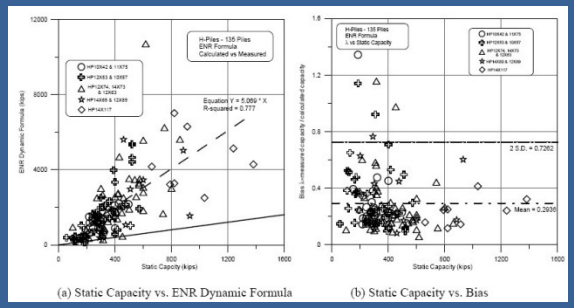
The reduction in the resistance factor from **φ = 0.40** currently in use, to φ = 0.25, reflects a significant economical loss for a gain in a consistent level of reliability. Alternatively, one can explore the use of other pile field capacity evaluation methods that perform better than the currently used Mn/DOT dynamic equation, hence allowing for higher efficiency and cost reduction.

$$\phi = \frac{\lambda_R\left(\gamma_D \frac{Q_D}{Q_L} + \gamma_L\right)\sqrt{\frac{1+COV_{QD}^2+COV_{QL}^2}{1+COV_R^2}}}{\left(\lambda_{QD}\frac{Q_D}{Q_L}+\lambda_{QL}\right)\exp\left\{\beta_T\sqrt{\ln[(1+COV_R^2)(1+COV_{QD}^2+COV_{QL}^2)]}\right\}}$$

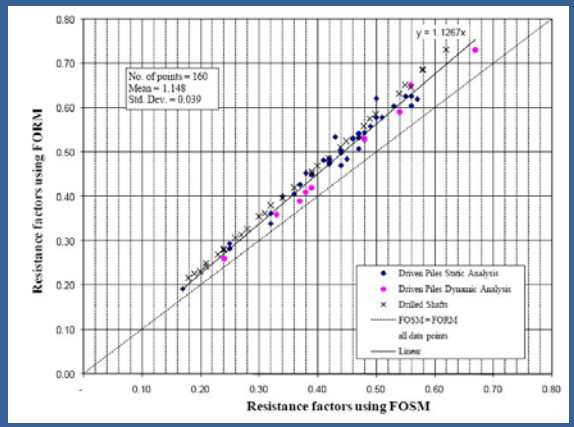


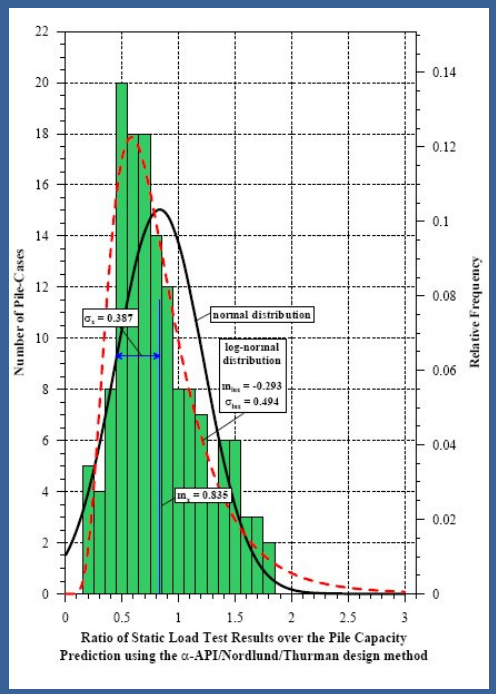


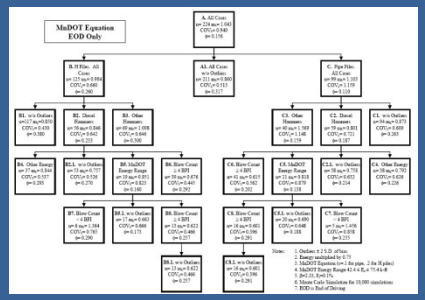


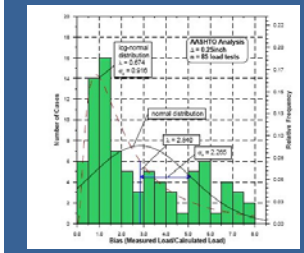


(a) Static Capacity vs. ENR Dynamic Formula (b) Static Capacity vs. Bias









$$\beta = \frac{m_{RN} - m_{QN}}{\sqrt{\sigma_{QN}^2 + \sigma_{RN}^2}} = \frac{\ln\left[(m_R/m_Q)\sqrt{(1+COV_Q^2)/(1+COV_R^2)}\right]}{\sqrt{\ln\left[(1+COV_R^2)(1+COV_Q^2)\right]}}$$

New MnDOT Formula

- Two studies to refine and improve formula
  - Based on SLT database
  - Collection of MnDOT case studies
  - Based on MnDOT pile driving practice/local projects
  - Existing formula could be improved
- Adopt new formula
  - Conduct static load tests to locally calibrate
  - Adjust resistance factors as more data is available

Eq #	Equation	Description	Reference
4.1	$R_u = \frac{12(W_r * h)}{S + 0.1}$	Drop Hammer	Engineering News-Record (1892)
4.2	$R_u = 27.11\sqrt{E_n * e_h}(1 - \log s)$		Gates (1957)
4.3	$R_u = 1.75\sqrt{E_n} * \log(10 * N) - 100$	Modified Gates Equation	FHWA (1982)
4.4	$R_u = 6.6 * F_{eff} * E * Ln(10N)$		Washington State DOT (Allen, 2005)
4.5	$R_u = \frac{10.5E}{S + 0.2} x \frac{W + 0.1M}{W + M}$	Uniform Format for all piles	Minnesota DOT (2006)
4.6	$R_u = 35\sqrt{E_h} \times \log(10N)$	See Chapter 6 for details	First Stage Proposed New Mn/DOT Equation

Notes:

R_u= ultimate carrying capacity of pile, in kips
W= mass of the striking part of the hammer in pounds
M= total mass of pile plus mass of the driving cap in pounds
E= developed energy, equal to W times H, in foot-kips (1.4)
E= energy per blow for each full stroke in foot-pounds (1.5)
e_h= efficiency
E_n= rated energy of hammer per blow, in kips-foot

Ln= the natural logarithm, in base "e"
W_r= weight of falling mass, in kips
s= final set of pile, in inches
N= blows per inch (BPI)
h= height of free fall of ram, in feet
F_{eff}= hammer efficiency factor

New MnDOT Formula

- New MnDOT formula (in final development)
  - Planned for 2013 projects; training this winter
  - Decreases variability (reduced variance/scatter)
  - Improved LRFD resistance factor
- Anticipated for use on most projects:
  - dense soil layers and end bearing piles

$$R_n = [\,35\sqrt{E_h} * \log(10 * \mathrm{N})]$$

E_h = measured hammer energy
N = blows per inch at the end of initial driving

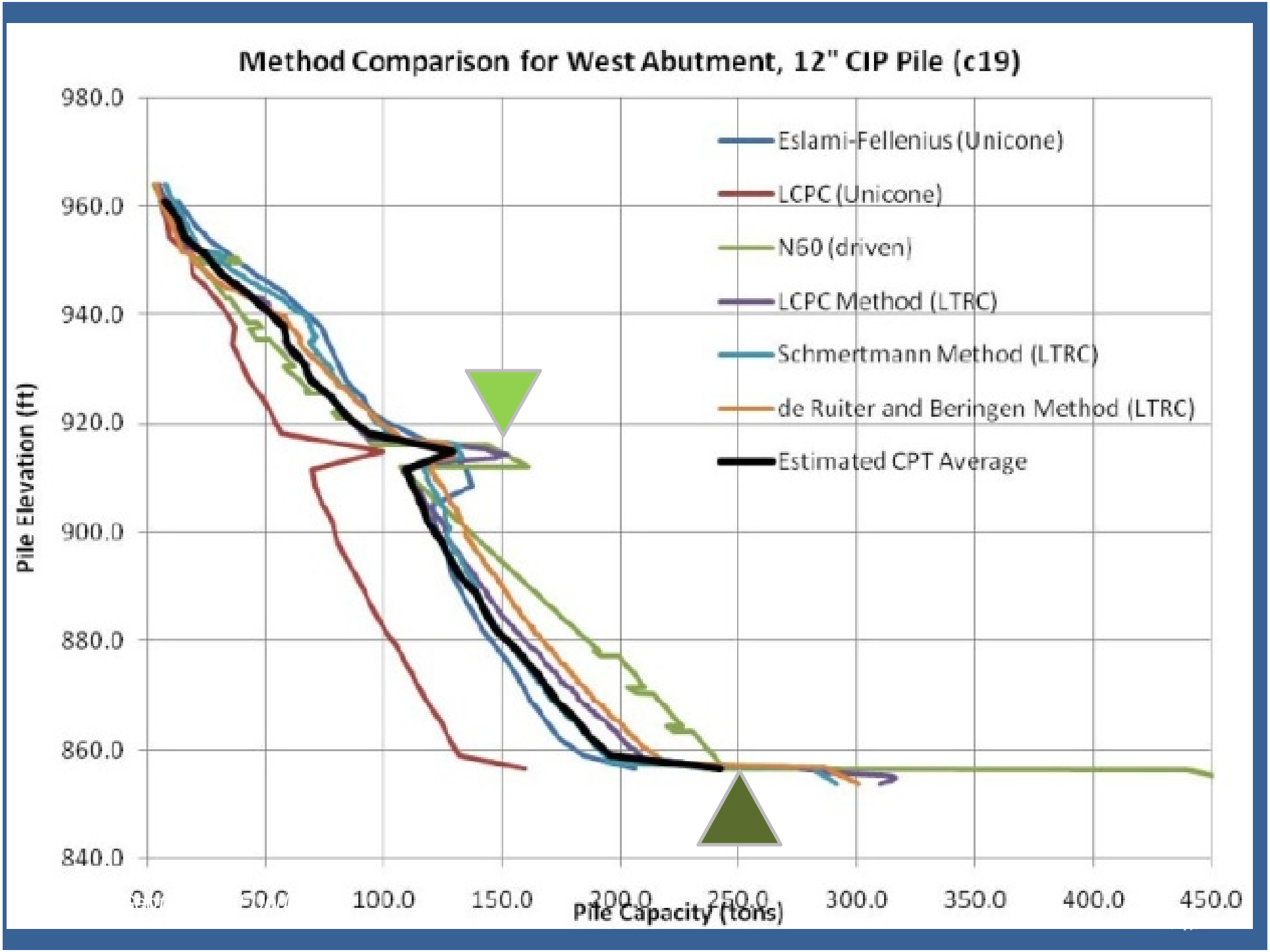
Time, Cost, and Project Value

- Dynamic Formula
  - Shallow bearing layers (common)
  - Small # of Piles
  - Dynamic formula is sufficient in most cases
- PDA/CAPWAP
  - Friction piles
  - Soil set-up
  - Pile damage possible
  - High capacity piles/large # of piles
- Static Load Test (SLT)
  - High value projects; expensive foundations
  - LRFD calibration

Impact of Construction Control

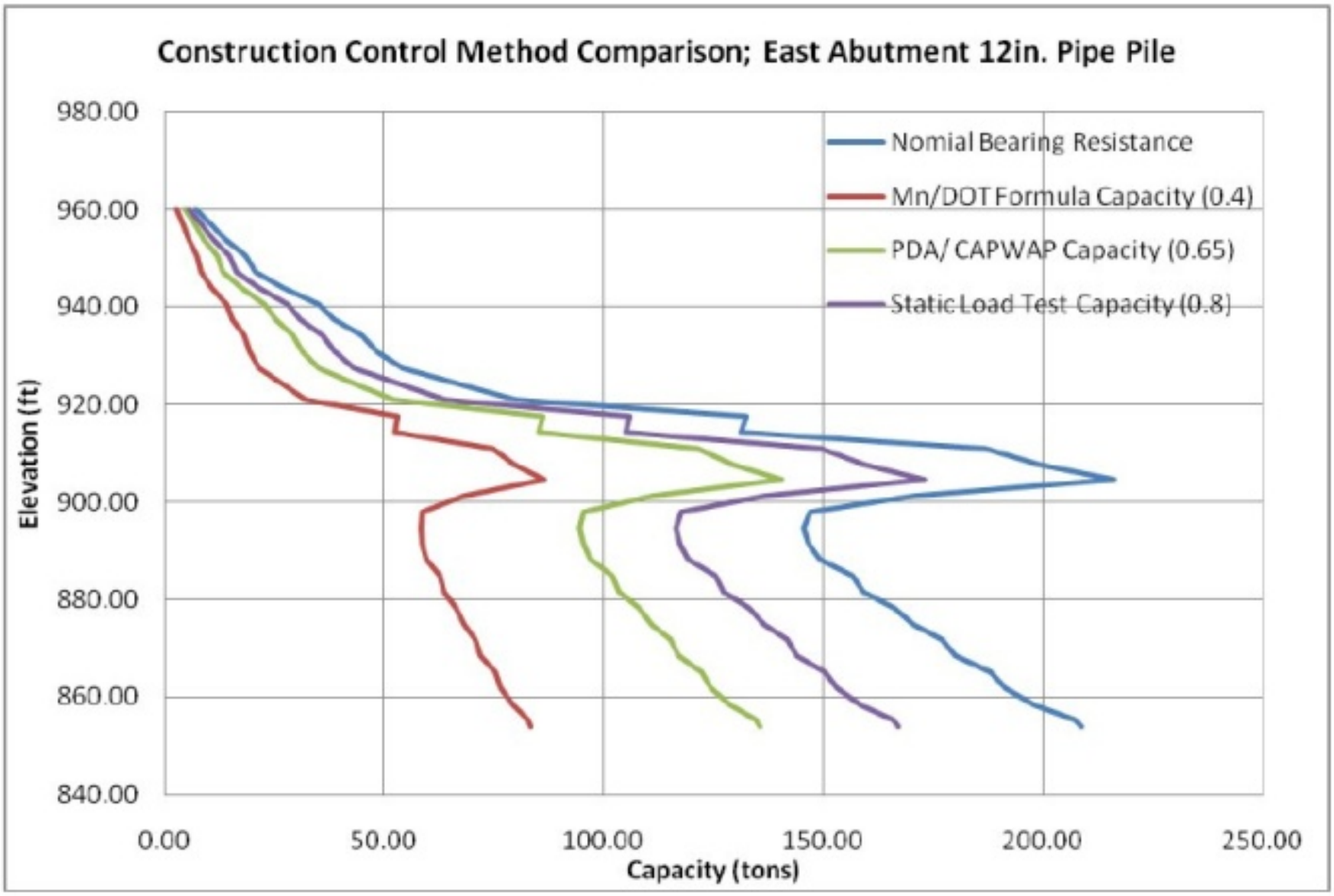
- Resistance Factors
  - Dynamic formula, PDA/CAPWAP, Static Load Test
- 100 tons factored load (for design purposes)
- Field Verification:
  - 100 tons/(φ = 0.4) = 250 tons = R_n
  - 100 tons/(φ = 0.65) = 153 tons = R_n
  - 100 tons/(φ = 0.8) = 125 tons = R_n

Rn = Required 'Nominal Bearing Resistance,' at the Strength Limit State, measured in the field for the SPECIFIED type of construction control method


Method Comparison for West Abutment, 12" CIP Pile (c19)
Pile Elevation (ft)
980.0
960.0
940.0
920.0
900.0
880.0
860.0
840.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
Pile Capacity (tons)
Eslami-Fellenius (Unicone)
LCPC (Unicone)
N60 (driven)
LCPC Method (LTRC)
Schmertmann Method (LTRC)
de Ruiter and Beringen Method (LTRC)
Estimated CPT Average

Impact of Construction Control

- Dynamic Formula vs. SLT
- 100 tons factored load/(φ = 0.4) = 250 tons = R_n
  - 855 elevation
- 100 tons factored load/(φ = 0.8) = 125 tons = R_n
  - 915 elevation; 60 ft. shorter
  - (60' * $30/ft.) = $1,800
  - $1,800 * 30 piles = $54K
  - SLT cost estimate = $24K
  - Project Savings ($54K - $24K) = $ 30K
    - Plus MnPile program benefit
- Consider construction control method "value"



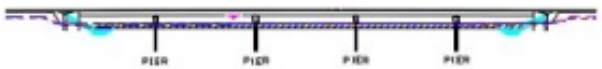
Nominal Bearing Resistance = Geotechnical Capacity = Static Equilibrium

"MnPile" SLT Program

Determine actual 'load/deflection' performance

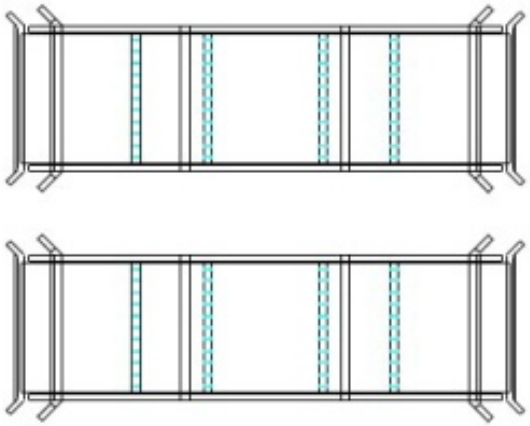
Compare performance results with static predictions, MnDOT formula, and PDA/CAPWAP, based on criteria

- 500 ton and 1000 ton Frames
  - Victoria: BR 10003 (June 2012)
  - Shoreview: BR 62717 (July 2012)
  - Dresbach; Butterfield (2013)

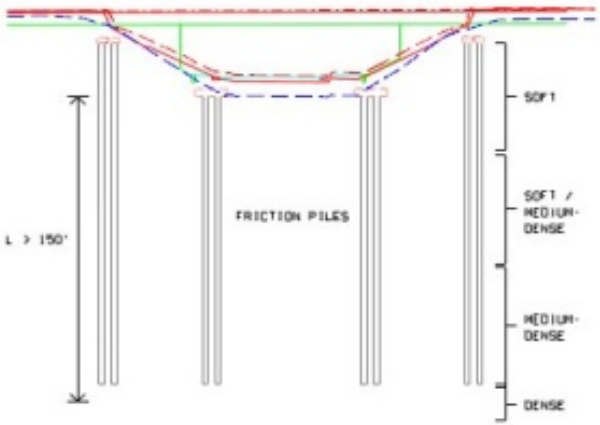


BRIDGE WITH NUMEROUS PIERS/PILES

PILES	Ø	COST/FT	DEPTH	TOTAL
100	0.40	$30	100FT	$300000
75	0.65	$30	100FT	$225000
50	0.80	$30	100FT	$150000

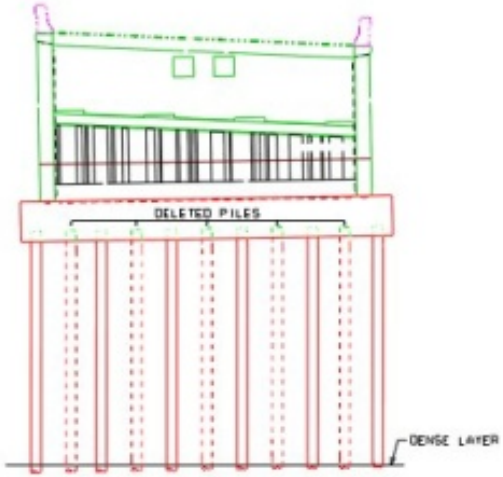


CLOSELY SPACED 'SISTER' BRIDGES
- SMALL SITE
- LARGER NUMBER OF PILES
- LONGER CONSTRUCTION WINDOW

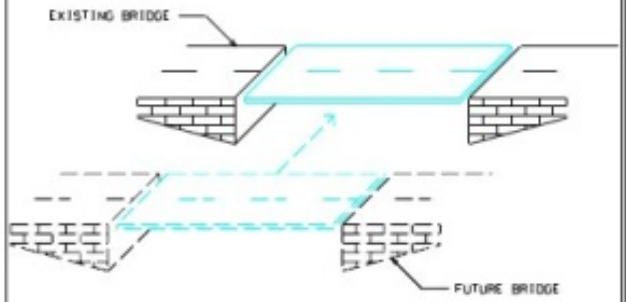


BRIDGES WITH LONG FOUNDATION PILES AND NO END BEARING LAYER

DENSE END BEARING LAYER WITH UPPER MEDIUM-DENSE LAYER



FEWER HIGH CAPACITY PILES WITH A RESISTANCE FACTOR OF 0.8



BRIDGE ON NEW ALIGNMENT
- TIME IS LESS CRITICAL
- MAY NOT BE COST EFFECTIVE FOR PROJECT
- USEFUL FOR CALIBRATION EFFORTS

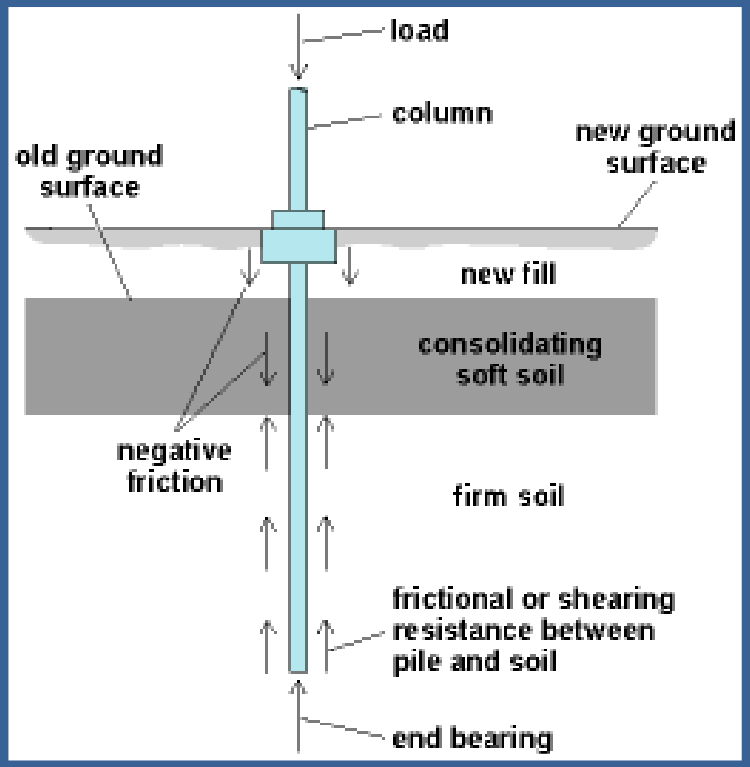
Sample project types for SLT consideration

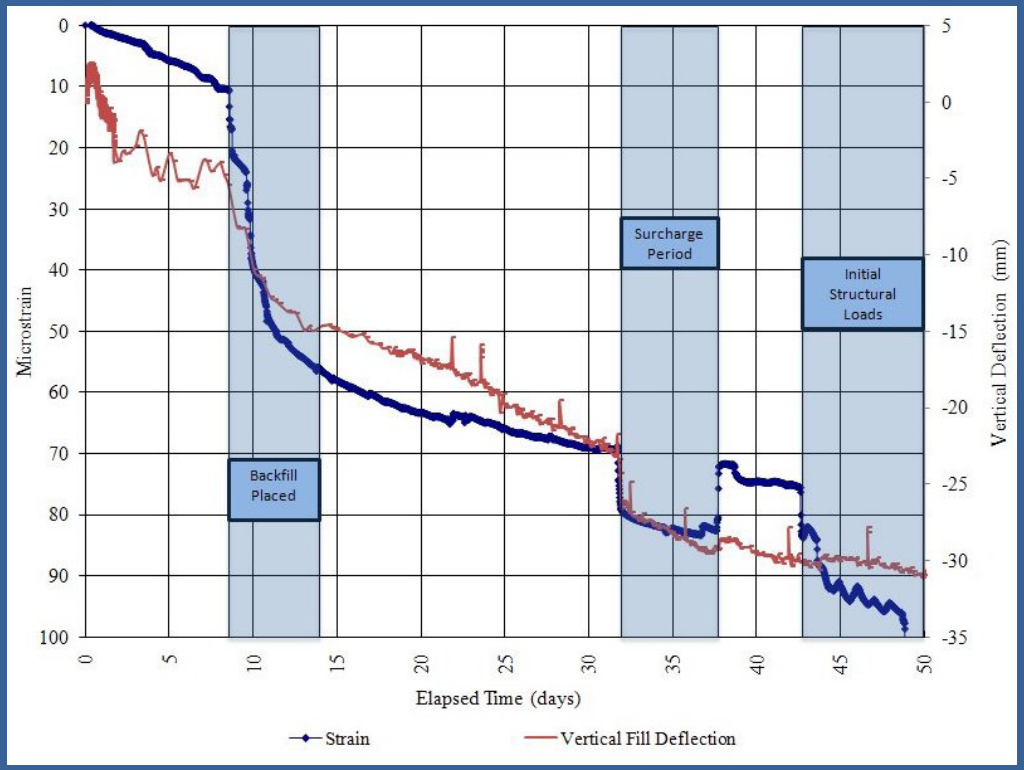
SLT and MnPile

- Additional Investment:
  - Plan details (pile arrangement + piles)
  - Special provisions, sequencing, time
  - Coordination and planning w/Districts
- Benefits:
  - Provides project and program cost savings (φ factor)
    - Sites are pre-selected for project/program benefit
    - Fewer piles or higher capacity
    - Improved quality control
  - Useful for proving high capacity pile strengths
  - Critical component of formula calibration
  - MnDOT provided frames improve efficiency

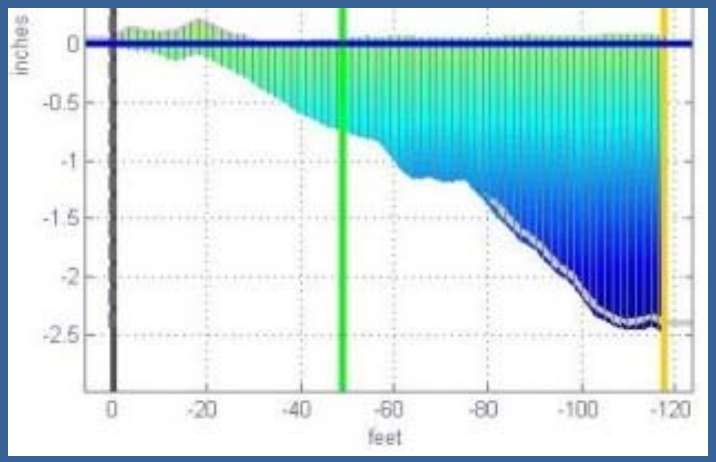
Pile Dragload/Downdrag

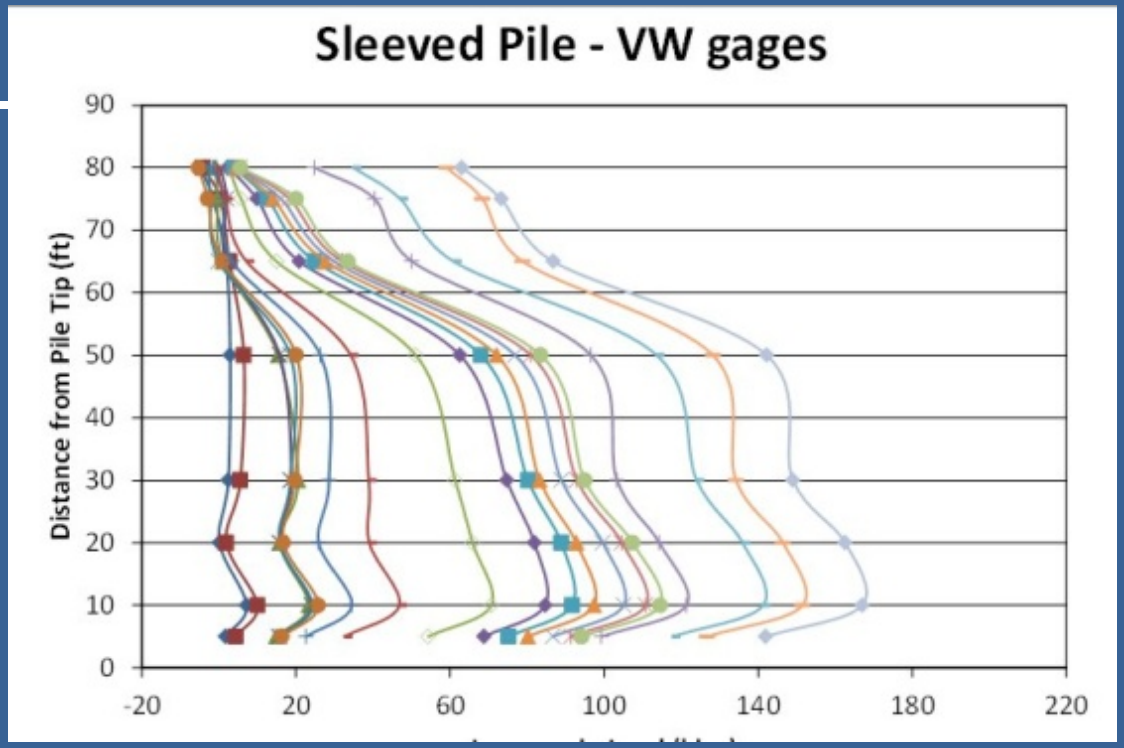
- Large (measured) strains/loads
- Mitigation strategies produce variable results

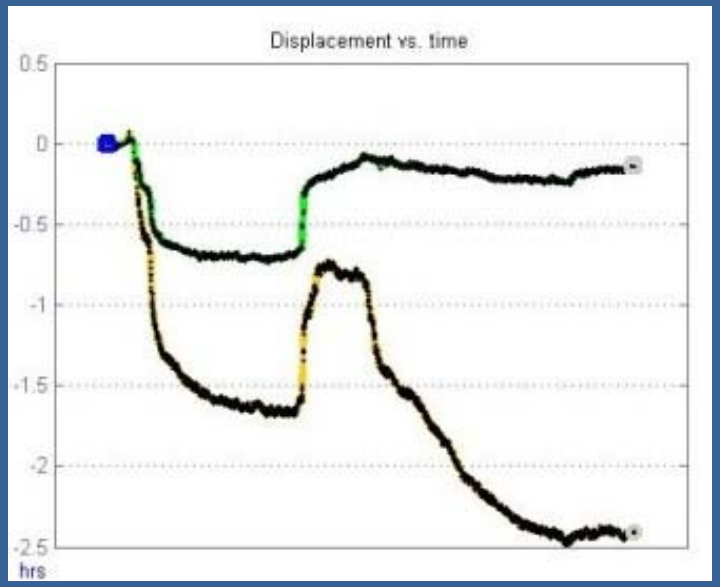




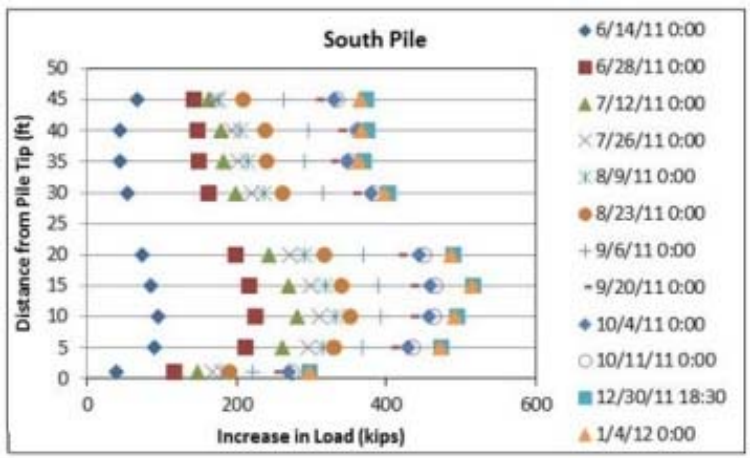
Dragload

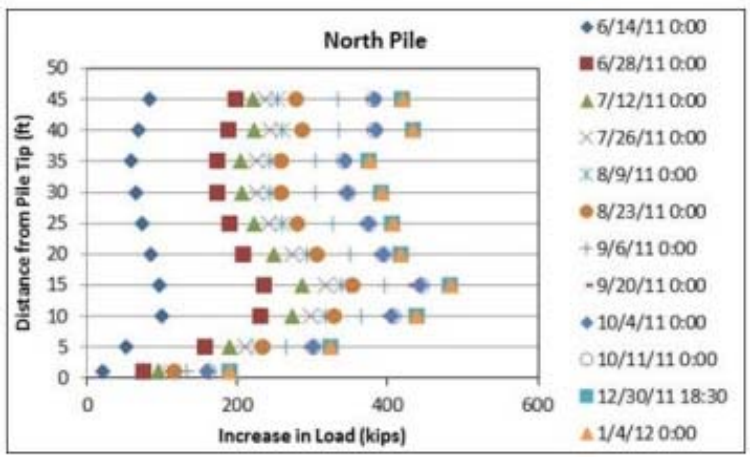

inches
0
-0.5
-1
-1.5
-2
-2.5
0
-20
-40
-60
-80
-100
-120
feet

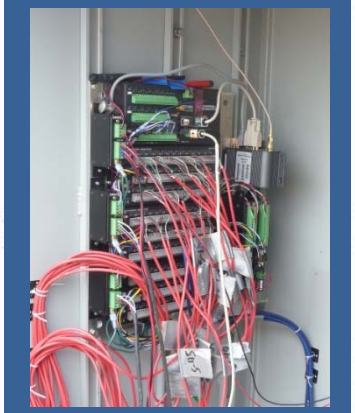

Sleeved Pile - VW gages
Distance from Pile Tip (ft)
90
80
70
60
50
40
30
20
10
0
-20
20
60
100
140
180
220

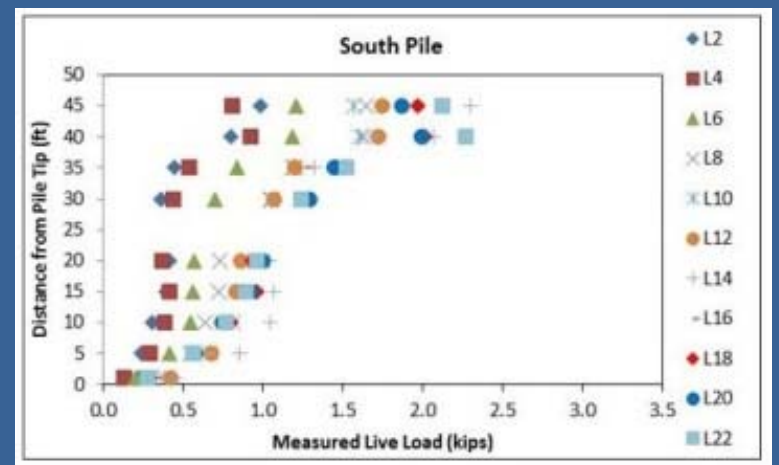

Displacement vs. time
0.5
0
-0.5
-1
-1.5
-2
-2.5
hrs

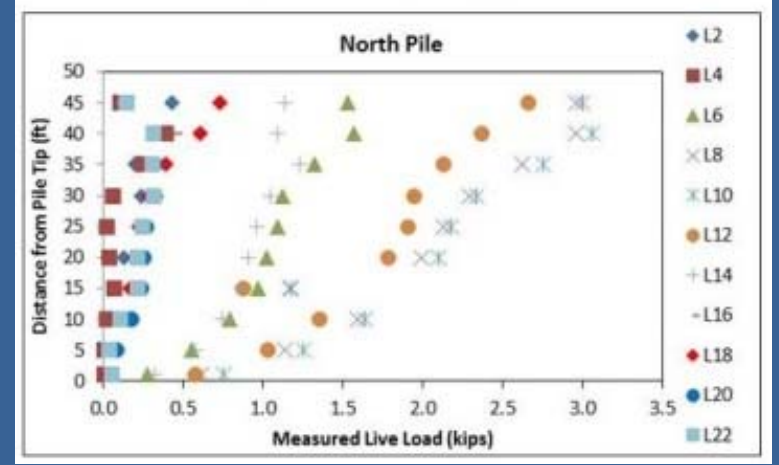
Dragload, Dead Load, Live Load











Pile Dragload/Downdrag

- New policy in development (2013)
  - Incorporates MnDOT performance monitoring
  - Strength limit
    - Pile structural capacity
  - Service limit
    - Pile head deflection
    - All cases except piles to rock
  - Performance Monitoring
- Mitigation strategies
  - Embankment preload/surcharge
  - Pile sleeves; coatings
  - Eliminate new load or design for additional load
  - Spread footings

Large Diameter Piles

Large Diameter Driven Piles

- Used for long span bridges
  - Wakota, Lafayette, Hastings
  - Dresbach, St. Croix
- Load tests (Statnamic)
- Driven open-ended
  - Filled with concrete
  - To bottom of seal or minimum 10’ below scour elevation
- If additional structural strength is required
  - Thicker wall
  - Additional reinforcing steel inside
    - Consider constructability

Spread Footings

- Now more common
  - Better prediction methods
    - SCPTu, DMT, PMT
  - Improved performance monitoring data
  - Cost effective
  - Similar deformations to adjacent embankments

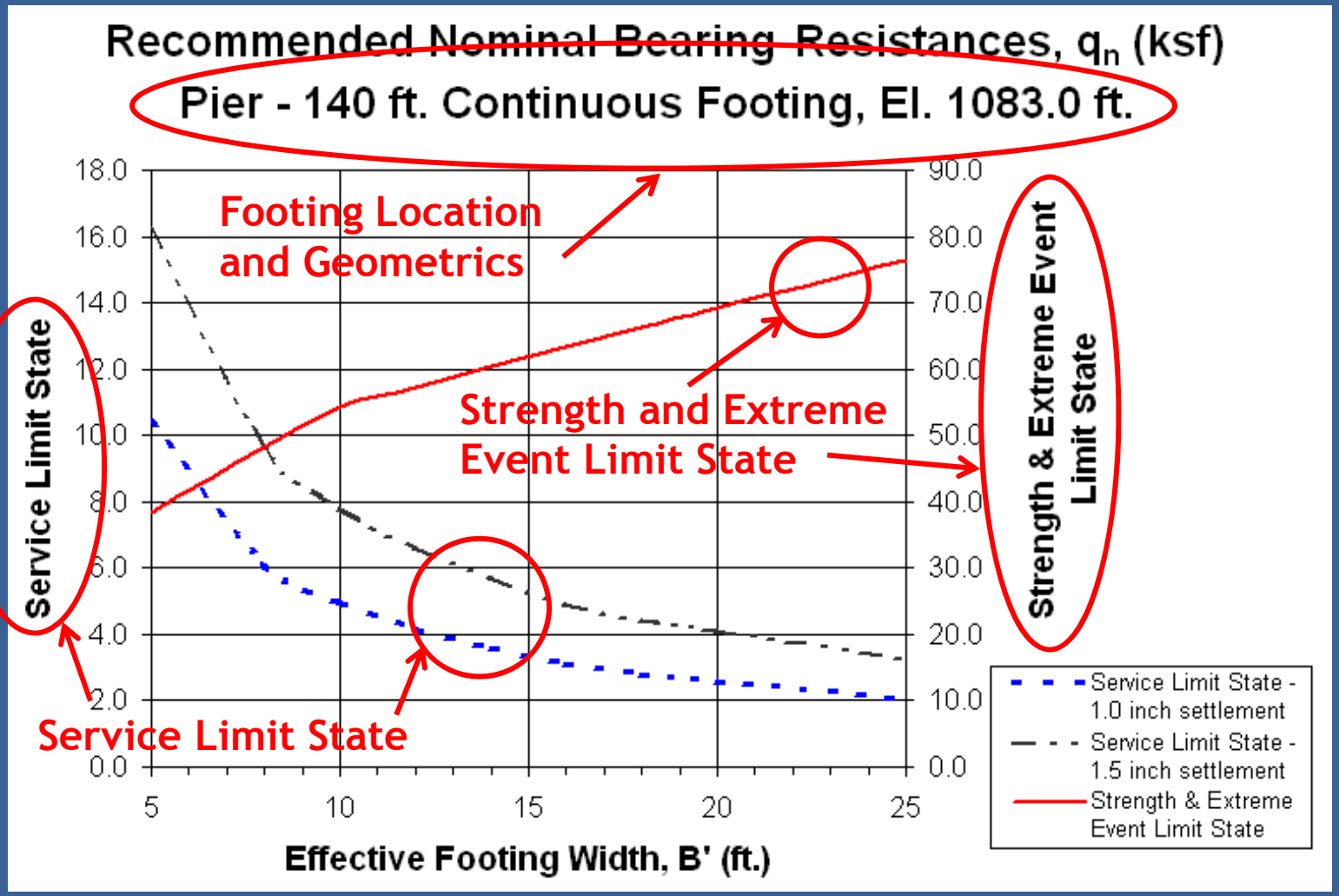
Spread Footing Monitoring

BRIDGE	Predicted Settlement			Actual Settlement*			Over - Prediction Of Settlement (Yes or No)
	N. Abut (inches)	Pier (inches)	S. Abut (inches)	N. ABUT (inches)	PIER (inches)	S. ABUT (inches)	
Pedestrian	2	1.5	2	< 0.25	< 0.25	< 0.25	YES
Hemlock Lane	1.5	1	1.5	< 0.25	< 0.25	< 0.25	YES
Zacahary Lane**	1.5	1.5	1.75	< 0.25	< 0.25	< 0.25	YES
Revere Lane	2	1.5	2	< 1	< 1	< 1	YES
Jefferson**	1.5	1.5	1.75	< 0.25	< 0.25	< 0.25	YES

**Settlement experienced by the beams and decks will be smaller than the indicated values; studies in the past have shown about 50% of settlement occurs before the beam and deck are set.*

***Construction of these brides is not complete and final settlement might be a little bit higher*

Nominal Bearing Resistance Graph



Foundation Recommendations Form

FOUNDATION AND OTHER RECOMMENDATIONS
Bridge Construction Unit

Report No. _____ Bridge No. _____

Location _____

1

Substructure Unit	Approx. Station	Estimated Bottom Elevation of Footing or Bent Cap	*Factored Spread Footing Bearing Resistance Φq_n (tsf)	Factored Pile Bearing Resistance, ΦR_n (tons)	Pile Type and Size			Estimated Pile Lengths		
					Other	Steel H	C.I.P. Concrete	Test Piles No.	Test Piles Length	Foundation Pile Length

2 3 4 5

*Based on Foundation Engineer's Recommendations dated _____ Scour Recommendations _____

- ☐ Use special pay items for piling
- ☐ Use thick wall pipe pile option
- ☐ Use the following pile tip protection
  - ☐ Pile points _____
  - ☐ Pile tip protection _____
- ☐ Use lump sum excavation item (except where rock excavation indicated)
- ☐ Excavation to be incidental (to 1A43 Concrete or other)
- ☐ Concrete seal required
- ☐ *Time delay recommended for approach embankment settlement:
  - ☐ _____ months
  - ☐ 72 Hrs.
  - ☐ None

Other Recommendations:

- ☐ Use special concrete placement procedures on deck pours (for skewed bridges, etc.)
- ☐ Paint color of exposed pile shells _____

6

☐ Remarks (Basis for above determinations):

- 1. Basic project info
- 2. Substructure unit
- 3. Approximate station
- 4. Estimated Bottom footing elevation
- 5. Factored bearing resistance, ϕq_n
- 6. Additional info and remarks

Date preliminary received by reviewer _____ Reviewed by _____ Concurred by _____ Date _____

cc: Foundations Engineer, Preliminary Plans Engineer (3 copies), & Program Clerk

11/1/06
BR3983.doc

Nominal Bearing Resistance, q_n

- Foundation report will provide the nominal bearing resistance, q_n
  - On rock, q_n for all footing widths
  - On soil, q_n is plotted graphically q_n vs. $B_{(effective)}$
- Foundation report provides q_n based on
  - Bearing failure – strength limit state
  - Tolerable settlement criteria – service limit state
    - 1” max currently used in most cases by Mn/DOT for soil
    - Higher deflections may be permitted with monitoring
    - Footings on rock assumed to satisfy service limit state

GRS-IBS Abutments

- Geosynthetic Reinforced Soil Integrated Bridge System
- MnDOT/FHWA: Rock County project

GRS Approach

This GRS-IBS bridge took ten days to build, start to finish. Shown is phase 1 of construction.

Not approved for use at this time- specification, erosion potential, and approved material considerations (among others) are unresolved.

Reports and Recommendations

- State Projects
  - Foundation Investigation Report
  - Bridge Construction Foundation Recommendation

Minnesota Department of Transportation
MEMO
Office of Materials & Road Research
Geotechnical Engineering Section
Mailstop 645
1400 Gervais Avenue
Maplewood, MN 55109

Date: April 12, 2011

To: Nancy Daubenberger, State Bridge Engineer
Office of Bridges & Structures

From: Karl Johnson, Graduate Engineer
Geotechnical Engineering Section

Concur: Derrick Dasenbrock, Foundations Geomechanics Engineer
Geotechnical Engineering Section

Concur: Gary Person, Foundations Engineer
Geotechnical Engineering Section

Subject: S.P. 1002-89 Bridge 10003 (Replacing 6654)
T.H. 5 (Arboretum Blvd.) over Lake Minnetonka LRT Regional Trail
Located 4.0 miles west of junction T.H. 41 in Victoria
Foundation Investigation and Recommendations and
Recommendation for Static Load Testing at this Site

Project Description

This report provides the Foundation Investigation and Recommendations for constructing Bridge 10003, replacing in-place Bridge 6654 spanning over Lake Minnetonka LRT Regional Trail. The new structure will be approximately 139 feet long with a width of 47 feet 4 inches and will be comprised of MN45 prestressed concrete beams supported by parapet type abutments at a 42 degree skew. Please refer to the attached boring plan for more details on the proposed bridge layout. There may be some additional embankment fill placed to accommodate a raise in grade along the roadway approaches. If additional details related to slope design are necessary, these will be described in a separate report.

Field Investigation and Foundation Conditions

Five Cone Penetration Test (CPT) soundings were taken in the area of the bridge to characterize the soil. The CPT soundings were taken in August 2010 and March of 2011 by the Mn/DOT foundations unit. Four additional CPT soundings were taken below the bridge on the Lake Minnetonka LRT Regional Trail in February 2011. Lastly, Standard Penetration Test (SPT) boring was advanced below the bridge in March 2011. Copies of these soundings and boring are included with this report.

FOUNDATION AND OTHER RECOMMENDATIONS
Bridge Construction Unit

Report No. 1680 Bridge No. 73037

Location TH 23 SB over N. Fork Crow River, 0.3 mi. S. of Jct. TH 23 & TH 55

Substructure Unit	Approx. Station	Estimated Bottom Elevation of Footing or Bent Cap	*Factored Spread Footing Bearing Resistance Φq_n (tsf)	Factored Pile Bearing Resistance, ΦR_n (tons)	Pile Type and Size			Estimated Pile Lengths		
					Other	Steel H	C.I.P. Concrete	Test Piles No.	Test Piles Length	Foundation Pile Length
South Abut.	180+70	1154.0		100 t			12"	2	40'	30'
Pier 1	181+91	1162.0		135 t			16"	2	50'	40'
Pier 2	183+14	1163.0		135 t			16"	2	50'	40'
North Abut.	184+34	1154.0		100 t			12"	2	35'	25'

*Based on Foundation Engineer's Recommendations dated 7-14-08 Scour Recommendations 6-13-07

___ Use special pay items for piling
___ Use thick wall pipe pile option
___ Use the following pile tip protection
  ___ Pile points ____
  ___ Pile tip protection ____
X Use lump sum excavation item (except where rock excavation indicated)
___ Excavation to be incidental (to 1A43 Concrete or other)
___ Concrete seal required
X *Time delay recommended for approach embankment settlement:
  ___ ____ months
  X 72 Hrs.- North Abutment
  X None - South Abutment

Other Recommendations:
X Use special concrete placement procedures on deck pours (for skewed bridges, etc.)
X Paint color of exposed pile shells Aluminum

X Remarks (Basis for above determinations):

Specify that the pier piling be driven to a minimum penetration of tip elevation 1130. (Preliminary estimated scour elevation is 1145.4. If a final analysis for scour is significantly deeper, the minimum pile tip elevation may be revised).

Do not required PDA (Pile Analysis) in the special provisions.

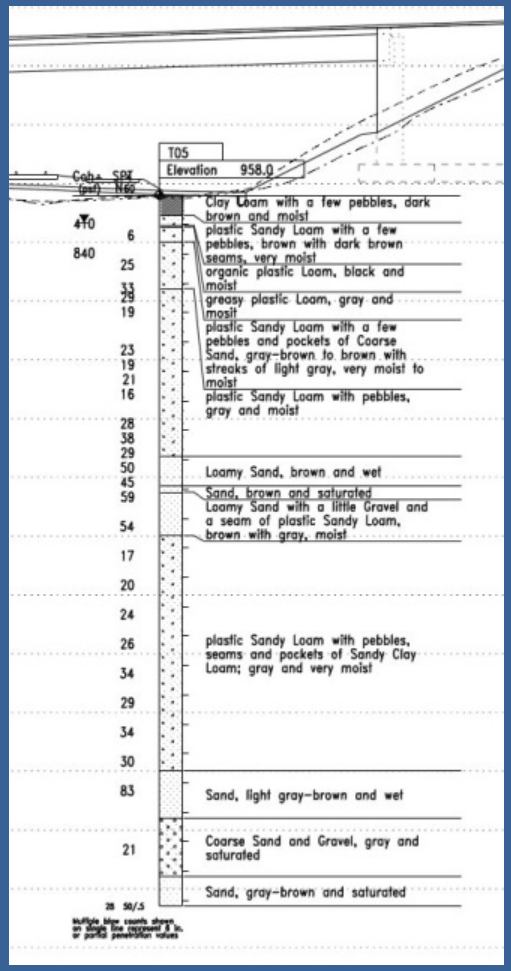
72 hour time delay for settlement of embankment is only at North Abutment.

Date preliminary received by reviewer 1-29-09 Reviewed by B.A. Iwen Concurred by [signature] Date 2/5/09

cc: Foundations Engineer, Preliminary Plans Engineer (3 copies), & Program Clerk

Reports and Recommendations

- CSAH Projects
  - Geotechnical Consultant Report
  - Bridge Design Consultant
- Report should address:
  - Foundation type (Strength)
    - shallow, piles, shafts, etc.
  - Construction control choice
    - Dynamic formula, PDA/CAPWAP, SLT
    - Project value (strata, damage, cost)
  - Settlement (Service)
    - Waiting periods/settlement plates/instrumentation
  - Scour, downdrag/dragload
  - Stability (where appropriate)
  - Other considerations- utility conflicts, erosion



Performance Monitoring

- Instrumentation: (during construction/service)
  - Piezometers
  - Inclinometers/ShapeAccelArrays (SAA)
    - (horizontal/vertical/angle)
  - Settlement plates, settlement cells
  - Strain gages/earth pressure cells/tiltmeters
  - Survey targets/prisms

Questions?

- Construction Control
  - Driven Piles
- SLT LRFD Calibration- MnPile
- Dragload/Downdrag
- Large Diameter Piles
- Shallow and GRS Foundations
- Reports/Recommendations
- Performance Monitoring
  - Instrumentation

Thanks for your participation.