

Case Histories – LRFD Procedures for Design of Deep Foundations

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Hastings Bridge (in construction)

- Mississippi River Crossing near St. Paul, MN
- Replace Existing Bridge in SH61

MRB (in construction)

- Mississippi River Crossing in St. Louis
- New I-70 Bridge



$$\sum \eta_i \gamma_i Q_i \leq \sum \phi_i R_i$$



Where: η_i = modifier for ductility, redundancy, and importance
 γ_i = load factor
 Q_i = force effect
 ϕ_i = resistance factor
 R_i = nominal resistance

Technical Way to Say: Factored Load \leq Factored Resistance for each Load Case

My Experience with Bridges:

1. Structural Engineer provides Factored Loads ($\sum \eta_i \gamma_i Q_i$) for each Load Case
2. Foundation Engineer provides Nominal Resistance & Resistance Factors ($\sum \phi_i R_i$)
3. Strength or Extreme Limit States controls Axial Design
4. Extreme Limit State controls Lateral Design
5. Service Limit State doesn't control (perhaps not true for buildings)

Axial Design (helpful to interact with Structural Engineer):



1. Generate Nominal Resistance Values (perhaps at EOID and Long-Term)
2. Recommend Appropriate Resistance Factors
 - Different Limit States (STR, EXT, SER)
 - Different Loading Direction (Compression vs. Uplift)
 - Different Levels of Verification (Static Load Test, High-Strain Dynamic, etc.)
 - Different Design Approaches (α , B, λ , Nordlund, Meyerhof, Schmertmann, etc.)
 - Redundancy (20% decrease if non-redundant)

Lateral Design (requires interaction with the Structural Engineer):

1. Perform GROUP Analysis using Factored Loads (also useful for axial design)
2. Evaluate Most Heavily Loaded Member for Flexural Failure using LPILE
3. Divide Resulting Horizontal Load on Most Heavily Loaded Member by ϕ (0.67 or 0.80)
4. Evaluate Push-Over of Most Heavily Loaded Member using Load from #3 & LPILE (can also use GROUP or others)




TABLE 10-2 AASHTO (2007) LIMIT STATES FOR BRIDGE DESIGN

Limit State Type	Case	Load Combination
Strength	I	Normal vehicular use of the bridge without wind
	II	Use of the bridge by Owner-specified special vehicles, evaluation permit vehicles, or both, without wind
	III	Bridge exposed to wind velocity exceeding 55 mph
	IV	Very high dead load to live load force effect ratios
	V	Normal vehicular use of the bridge with wind of 55 mph
Extreme Event	I	Load combination including earthquake
	II	Ice load, collision by vessels and vehicles, and certain hydraulic events with a reduced live load other than that which is part of the vehicular collision load, <i>CT</i>
Service	I	Normal operational use of the bridge with a 55 mph wind and all loads taken at their nominal values
	II	Intended to control yielding of steel structures and slip of slip-critical connections due to vehicular live load
	III	Longitudinal analysis relating to tension in prestressed concrete superstructures with the objective of crack control and to principal tension in the webs of segmental concrete girders
	IV	Tension in prestressed concrete columns with the objective of crack control
Fatigue		Repetitive gravitational vehicular live load and dynamic responses under the effects of a single design truck

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Drilled Shafts Manual
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10-LRFD for Drilled Shaft Design
May 2010




Table 10.5.5.2.4-1—Resistance Factors for Geotechnical Resistance of Drilled Shafts

	Method/Soil/Condition	Resistance Factor
Nominal Axial Compressive Resistance of Single-Drilled Shafts, ϕ_{cst}	Side resistance in clay α -method (O'Neill and Reese, 1999)	0.45
	Tip resistance in clay Total Stress (O'Neill and Reese, 1999)	0.40
	Side resistance in sand β -method (O'Neill and Reese, 1999)	0.55
	Tip resistance in sand O'Neill and Reese (1999)	0.50
	Side resistance in IGMs O'Neill and Reese (1999)	0.60
	Tip resistance in IGMs O'Neill and Reese (1999)	0.55
	Side resistance in rock Horvath and Kenney (1979) O'Neill and Reese (1999)	0.55
	Side resistance in rock Carter and Kulhawy (1988)	0.50
	Tip resistance in rock Canadian Geotechnical Society (1985) Pressuremeter Method (Canadian Geotechnical Society, 1985) O'Neill and Reese (1999)	0.50
	Block Failure, ϕ_{bl}	Clay
Uplift Resistance of Single-Drilled Shafts, ϕ_{up}	Clay α -method (O'Neill and Reese, 1999)	0.35
	Sand β -method (O'Neill and Reese, 1999)	0.45
	Rock Horvath and Kenney (1979) Carter and Kulhawy (1988)	0.40
Group Uplift Resistance, ϕ_{ug}	sand and clay	0.45
Horizontal Geotechnical Resistance of Single Shaft or Shaft Group	All materials	1.0
Static Load Test (compression), ϕ_{cst}	All Materials	0.70
Static Load Test (uplift), ϕ_{upload}	All Materials	0.60



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, $\phi_{\phi n}$	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.

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AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS



Table 10.5.5.2.3-1—Resistance Factors for Driven Piles (continued)

Condition/Resistance Determination Method		Resistance Factor
Nominal Bearing Resistance of Single Pile—Static Analysis Methods, ϕ_{stat}	Side Resistance and End Bearing: Clay and Mixed Soils	
	α -method (Tomlinson, 1987; Skempton, 1951)	0.35
	β -method (Esrig & Kirby, 1979; Skempton, 1951)	0.25
	λ -method (Vijayvergiya & Focht, 1972; Skempton, 1951)	0.40
Side Resistance and End Bearing: Sand	Nordlund/Thurman Method (Hannigan et al., 2005)	0.45
	SPT-method (Meyerhof)	0.30
	CPT-method (Schmertmann)	0.50
	End bearing in rock (Canadian Geotech. Society, 1985)	0.45
Block Failure, ϕ_{bl}	Clay	0.60
Uplift Resistance of Single Piles, ϕ_{up}	Nordlund Method	0.35
	α -method	0.25
	β -method	0.20
	λ -method	0.30
	SPT-method	0.25
	CPT-method	0.40
	Static load test	0.60
	Dynamic test with signal matching	0.50
Group Uplift Resistance, ϕ_{gr}	All soils	0.50
Lateral Geotechnical Resistance of Single Pile or Pile Group	All soils and rock	1.0
Structural Limit State	Steel piles	See the provisions of Article 6.5.4.2
	Concrete piles	See the provisions of Article 5.5.4.2.1
	Timber piles	See the provisions of Article 8.5.2.2 and 8.5.2.3
Pile Drivability Analysis, ϕ_{da}	Steel piles	See the provisions of Article 6.5.4.2
	Concrete piles	See the provisions of Article 5.5.4.2.1
	Timber piles	See the provisions of Article 8.5.2.2
In all three Articles identified above, use ϕ identified as "resistance during pile driving"		



Limit State	Component of Resistance	Geomaterial	Equation, Method, or Chapter Reference	Resistance Factor, ϕ
Strength I through Strength V	Pushover of individual elastic shaft; head free to rotate	All geomaterials	<i>p-y</i> method pushover analysis; Ch. 12	0.67 ⁽¹⁾
	Pushover of single row, retaining wall or abutment; head free to rotate	All geomaterials	<i>p-y</i> pushover analysis	0.67 ⁽¹⁾
Geotechnical Lateral Resistance	Pushover of elastic shaft within multiple-row group, with moment connection to cap	All geomaterials	<i>p-y</i> pushover analysis	0.80 ⁽¹⁾
Extreme Event I and Extreme Event II	Axial geotechnical uplift resistance	All geomaterials	Methods cited above for Strength Limit States	0.80
	Geotechnical lateral resistance	All geomaterials	<i>p-y</i> method pushover analysis; Ch. 12	0.80 ⁽¹⁾
	All other cases	All geomaterials	Methods cited above for Strength Limit States	1.00

¹Currently not addressed in AASHTO (2007)

²Design equation differs from AASHTO (2007)

³Resistance factor different from AASHTO

⁴See AASHTO Table 10.5.5.2.3-1

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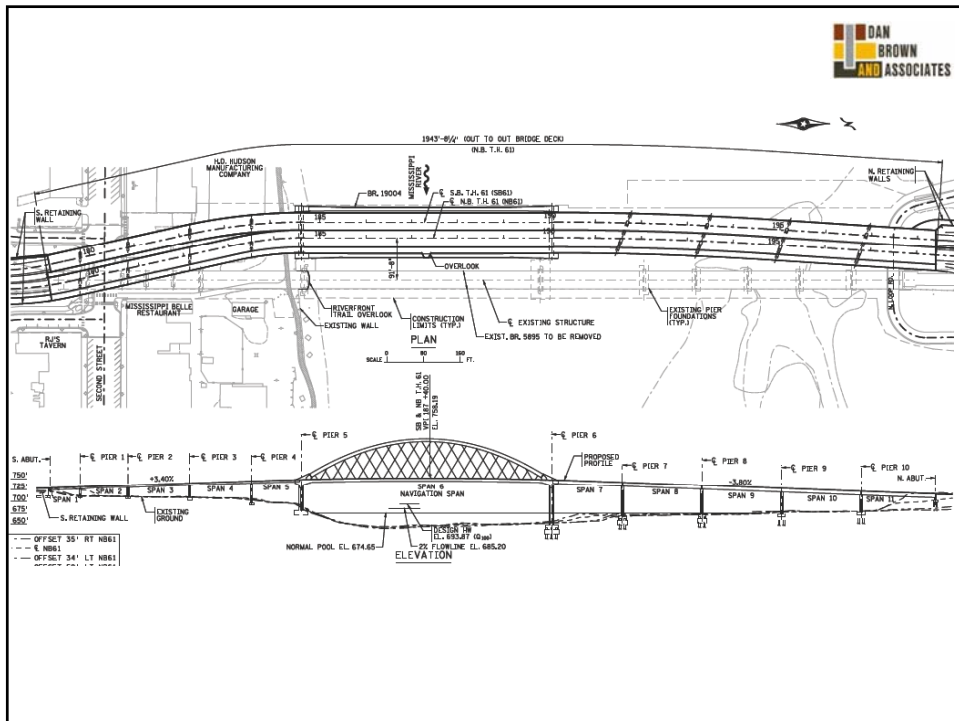
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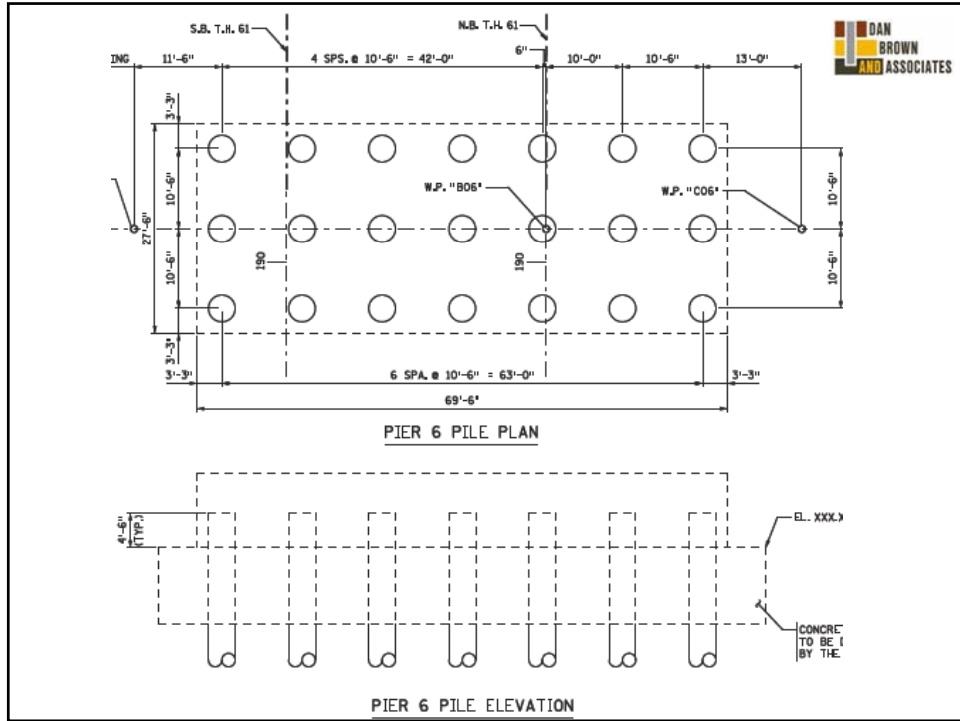
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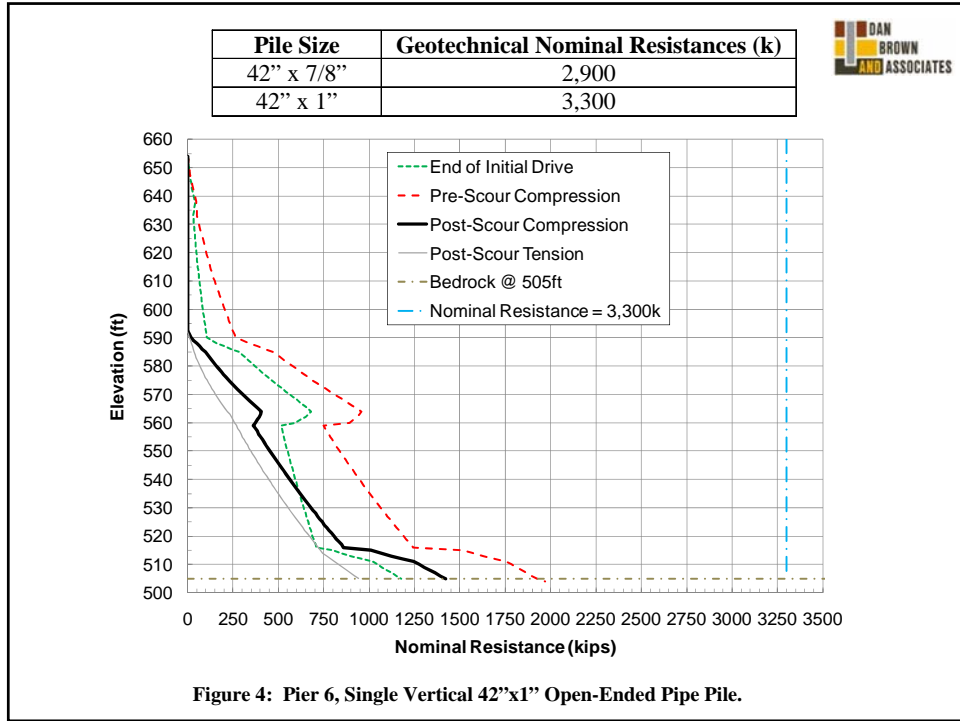


Hastings Bridge

- Design/Build, Awarded on Best Value
- Free Standing Arch
- Joint Venture Contractor: Lunda/Ames
- Designer: Parsons Transportation Group (PTG)
- DBA Role: Foundation Engineers







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Compression:
 $\phi = 0.80$ for Bridge Piers (STR, redundant group, load test & PDA/CAPWAP w/ Restrikes)
 $\phi = 0.65$ for Abutment & Retain Walls (STR, redundant group, PDA/CAPWAP w/ Restrikes)
 $\phi = 1.0$ (EXT)
 $\phi = 1.0$ (SER)

Uplift:
 $\phi = 0.50$ (STR, PDA/CAPWAP w/ Restrikes)
 $\phi = 0.80$ (EXT)

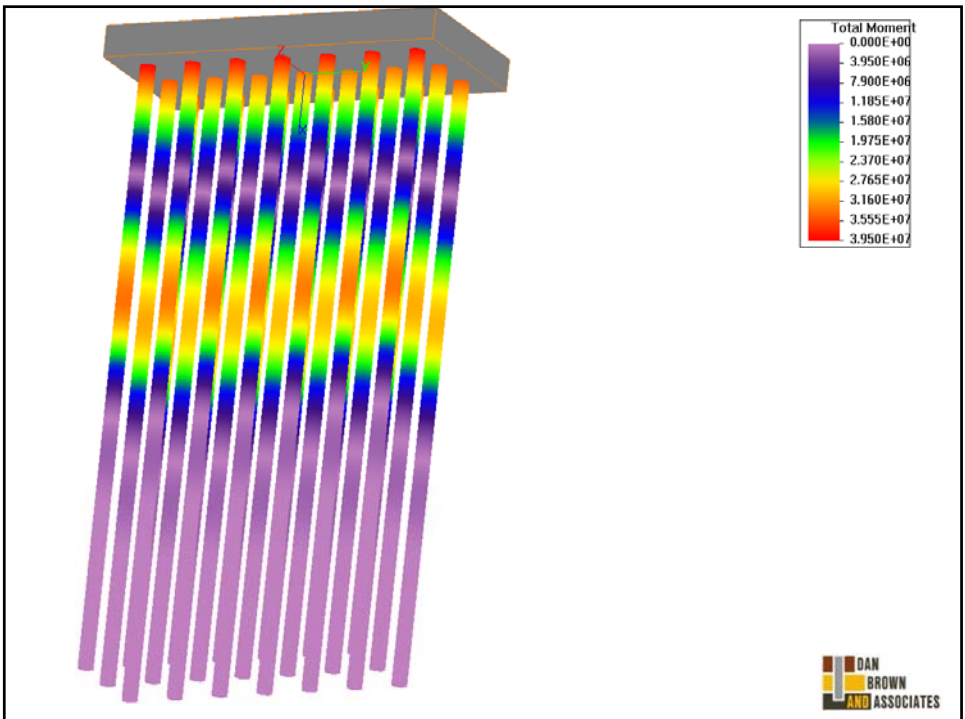
Lateral:
 $\phi = 0.80$ for push-over (STR and EXT)
 $\phi = 1.0$ for flexure (STR and EXT)

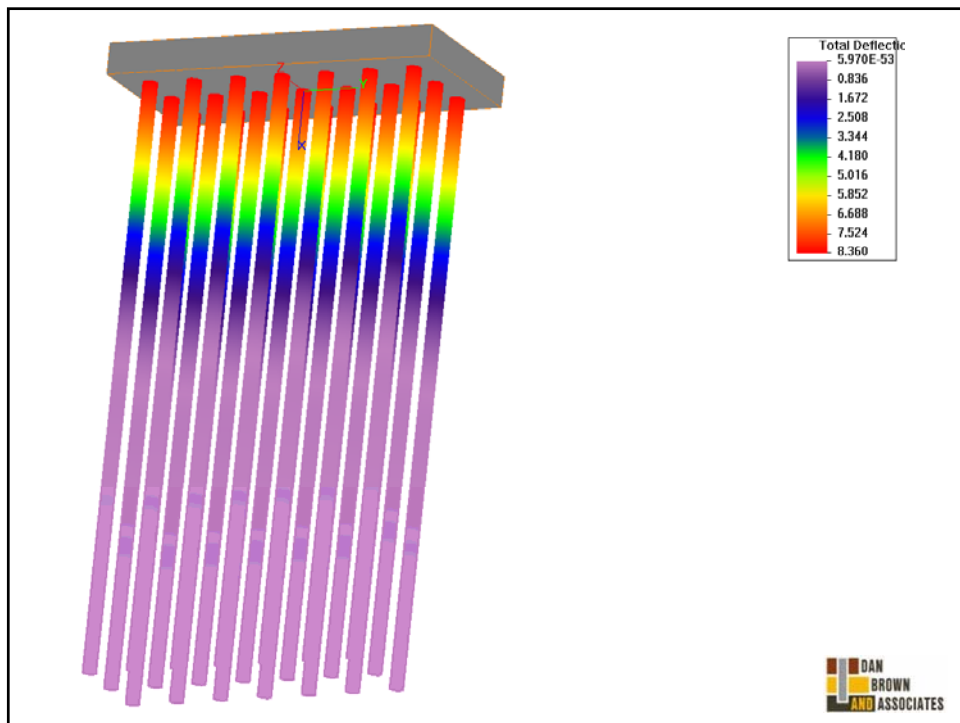
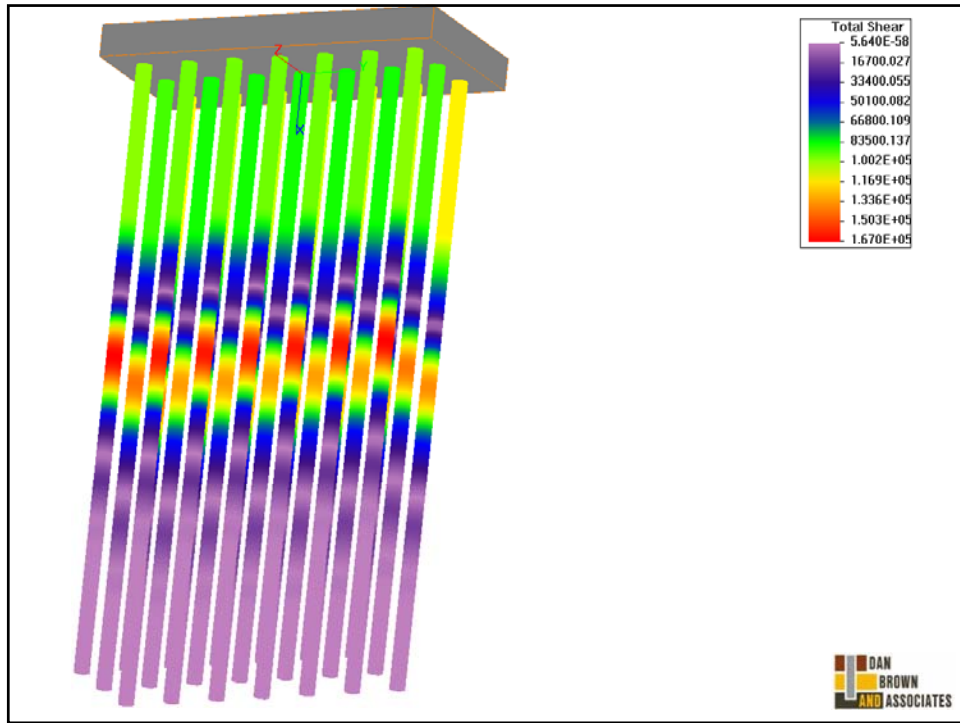
Tied Arch Foundation Loads

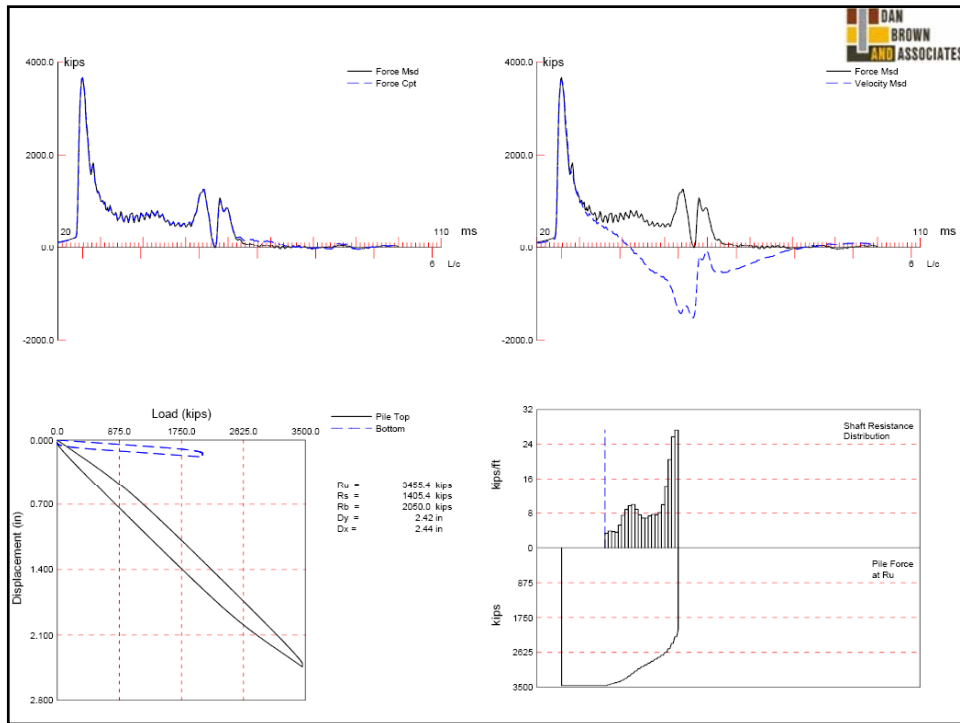
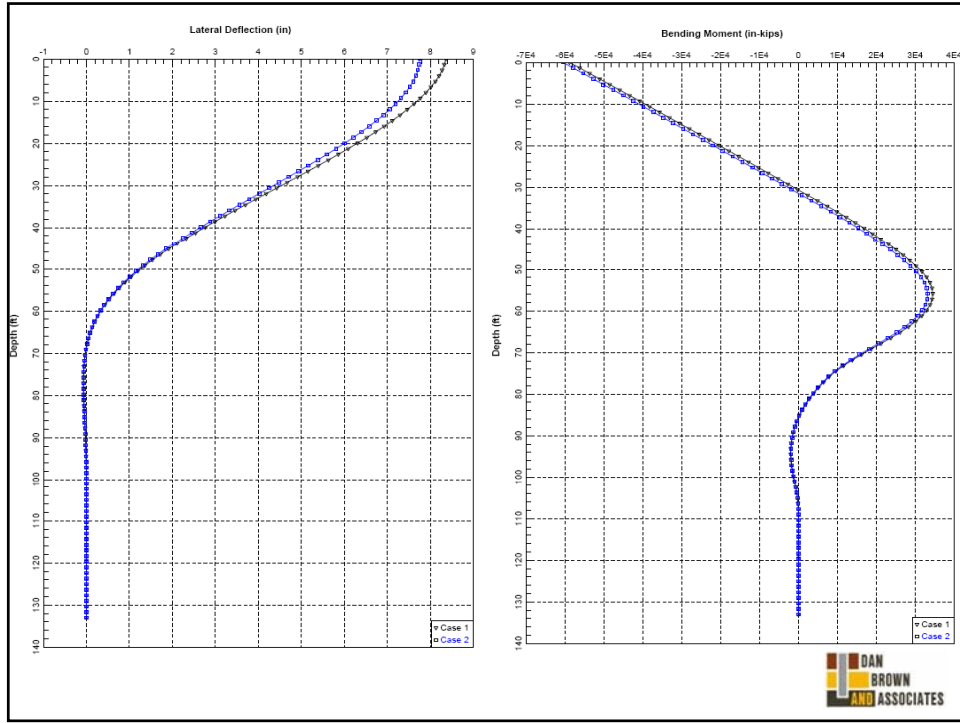
Strength I					
	V	Fx	Fy	Mx	My
Pier 6	28,130	715	-	58,160	51,484
Pier 5	31,970	710	-	59,538	68,915
Pier 4	14,900	264	97	36,166	18,949
Pier 3	14,519	393	97	20,439	22,068
Pier 2	14,355	393	97	19,814	22,345
Pier 1	13,672	264	97	33,908	12,745

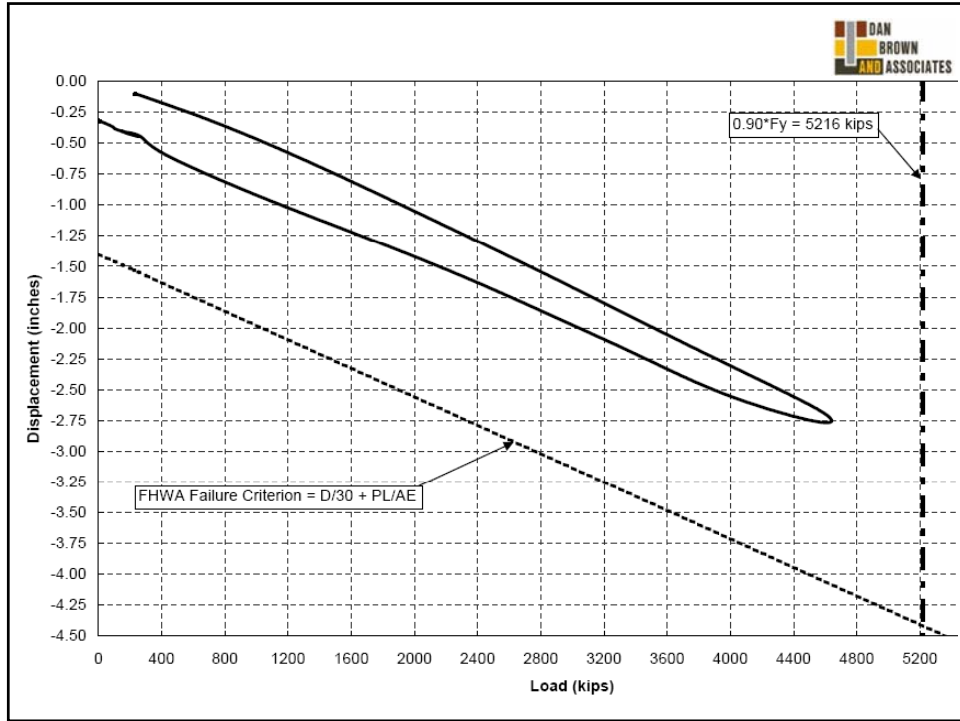
Extreme II (Longitudinal)					
	V	Fx	Fy	Mx	My
Pier 6	25,198	851	-	15,826	52,049
Pier 5	28,736	2,041	-	16,201	125,776
Pier 4	13,484	1,251	92	6,568	44,247
Pier 3	12,748	1,286	92	5,791	41,570
Pier 2	12,592	1,286	92	5,196	40,477
Pier 1	12,315	1,251	92	4,418	34,338

Extreme II (Transverse)					
	V	Fx	Fy	Mx	My
Pier 6	25,198	601	500	33,326	43,299
Pier 5	28,736	591	2,900	153,081	57,336
Pier 4	13,484	251	2,092	66,933	18,047
Pier 3	12,748	286	2,092	58,098	18,141
Pier 2	12,592	286	2,092	57,503	16,277
Pier 1	12,315	251	2,092	56,783	12,138



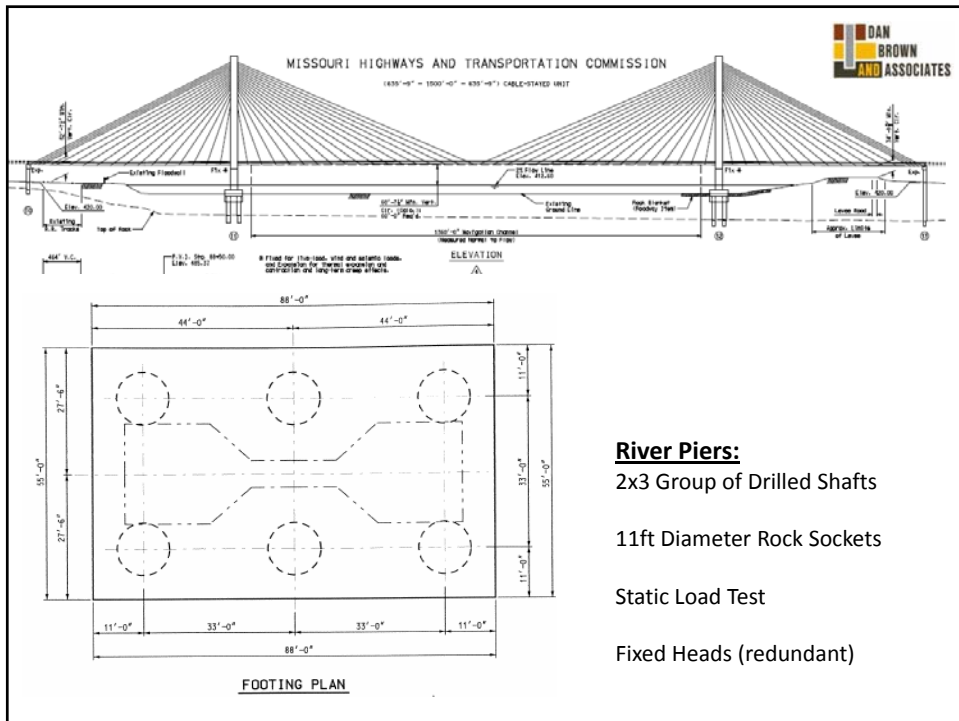


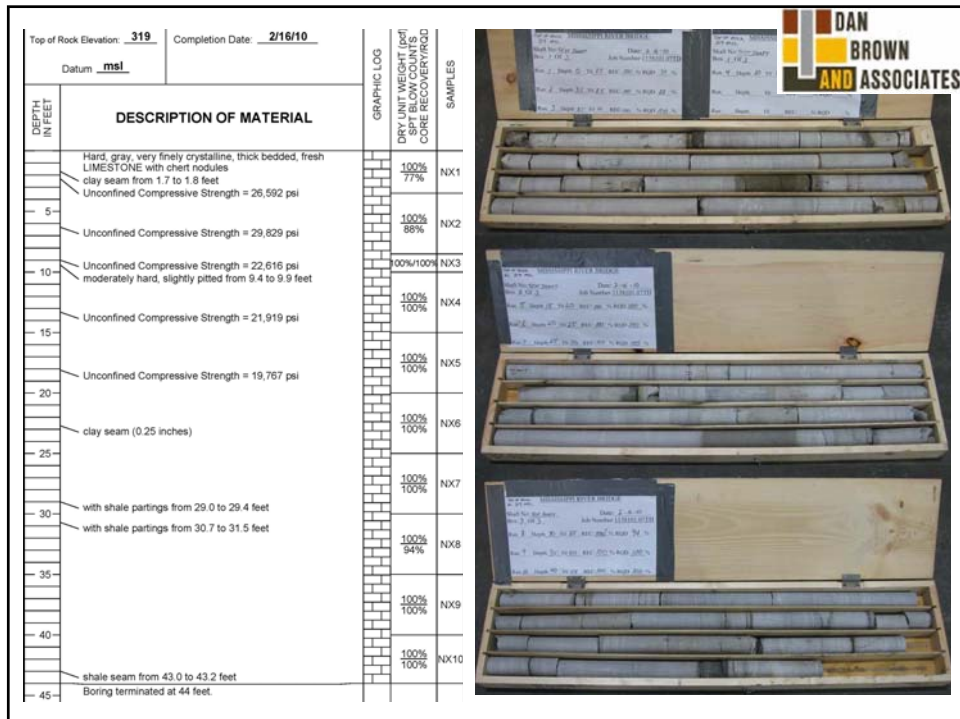
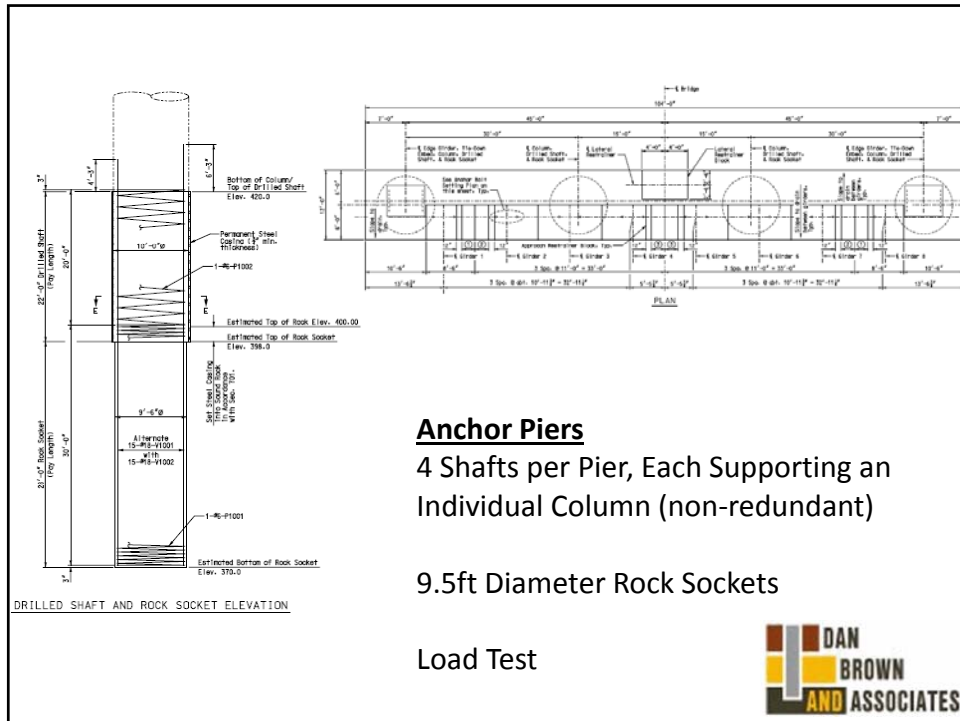




MRB

- Design-Bid-Build with ATC's
- Cable-Stay Main Span with 2 River Piers
- Joint Venture Contractor: Massman/Traylor/Alberici
- Designer: HNTB
- DBA Role: ATC Foundation Development











Compression:

- φ = 0.70 for River Piers (STR, redundant group, load test)
- φ = 0.56 for Anchor Piers (STR, non-redundant group, load test)
- φ = 1.0 (EXT)
- φ = 1.0 (SER)

Uplift:

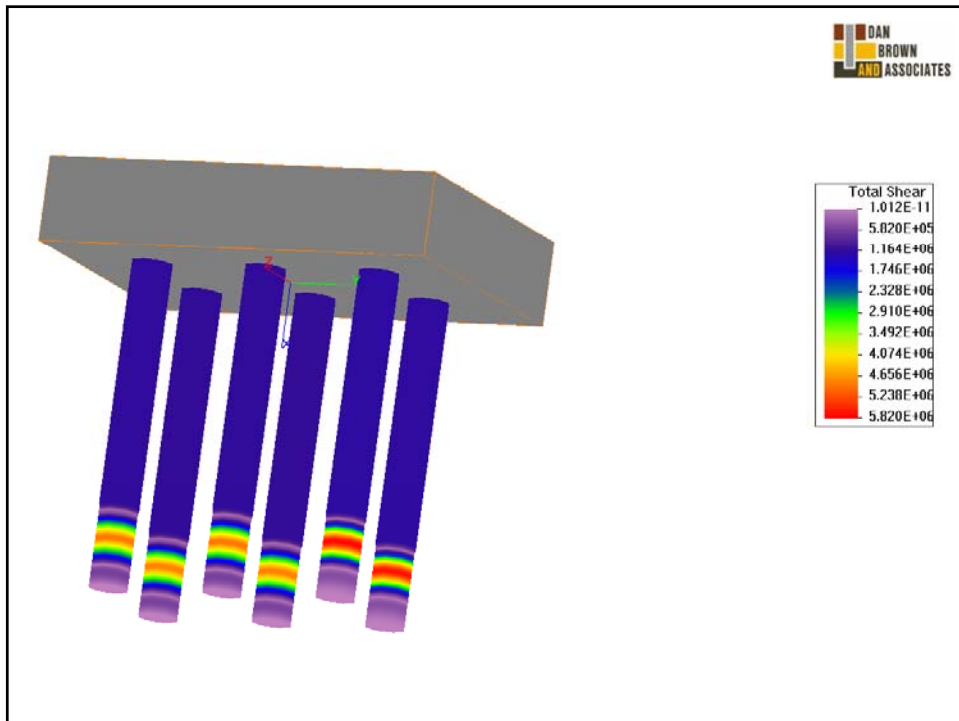
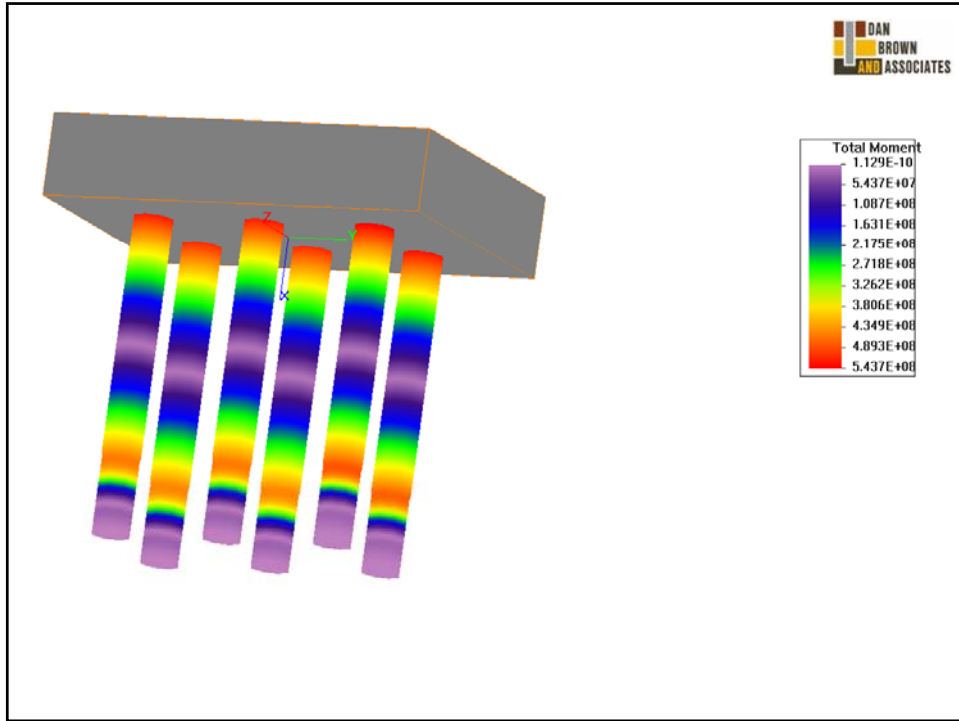
No foundation elements in uplift in any load case

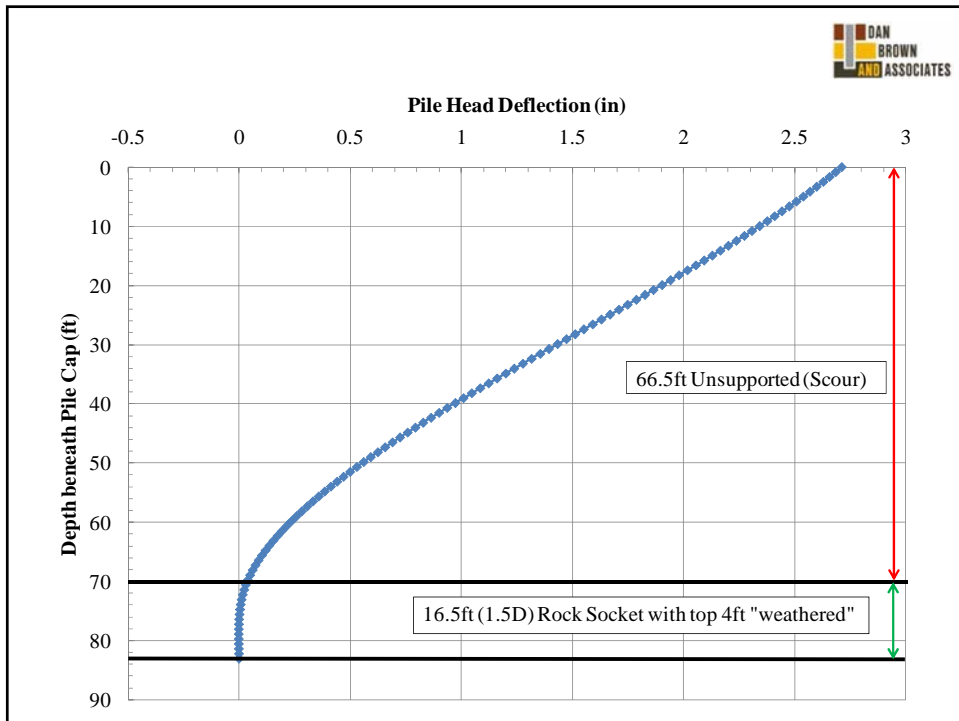
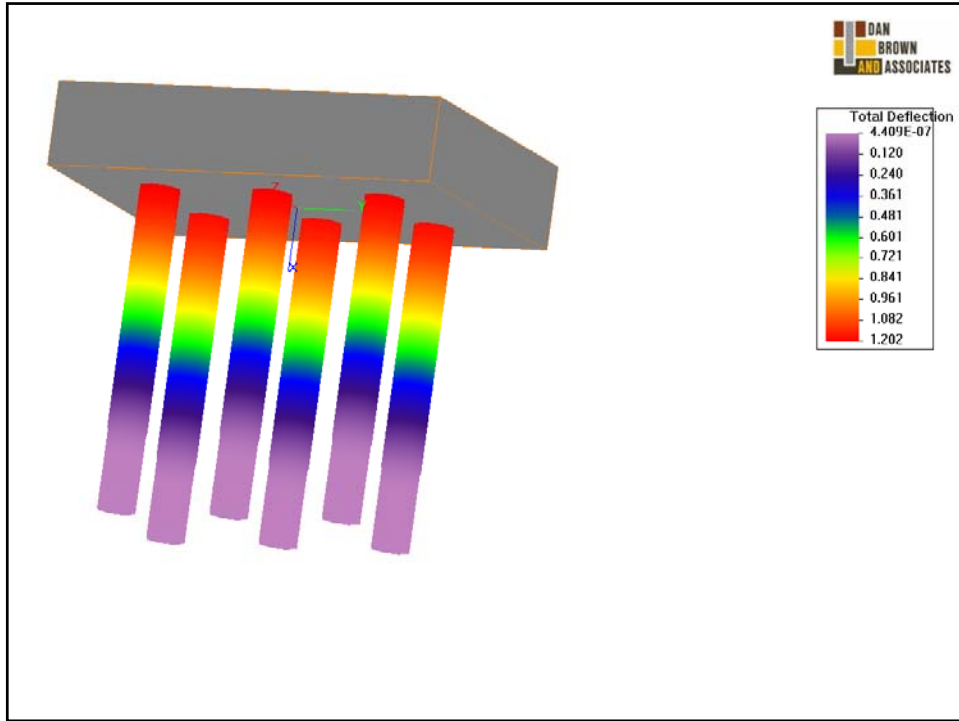
Lateral:

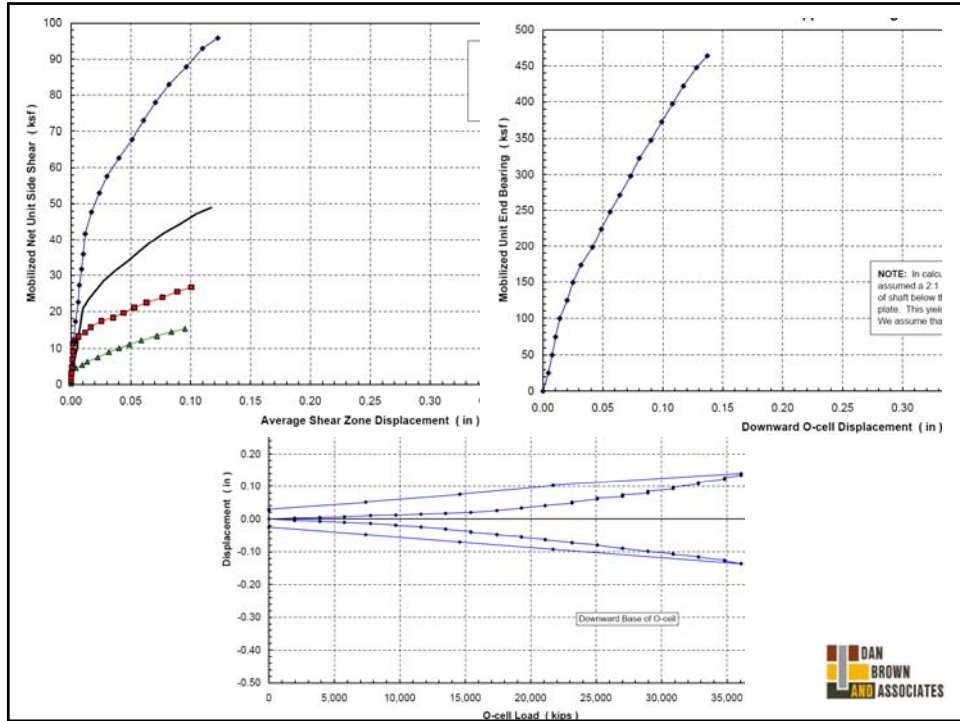
- φ = 0.80 for push-over (STR and EXT) at River Piers because fixed-head
- φ = 0.67 & 0.80 for push-over (STR & EXT) at Anchor Piers because free-head
- φ = 1.0 for flexure (STR and EXT)

Load Combination	Load Case	F _x (k)	F _y (k)	F _z (k)	M _x (k-ft)	M _y (k-ft)	M _z (k-ft)
EXT_I_	MaxMz	119,100	2,990	-1,086	-425	50,385	468,283
EXT_I_	MaxFy	138,391	7,145	-870	-11,230	77,914	401,334
EXT_I_	MinMx	133,928	3,952	374	-20,224	114,171	342,586
EXT_II_	MaxFx	129,334	883	-316	503	8,461	208,016
EXT_II_	MinFz	128,055	756	-7,238	969	336,237	142,241
EXT_II_	MaxMy	128,055	754	-7,233	2,521	346,276	141,310
SER_I_	MinMy	103,256	-389	642	-11,772	-239,734	30,590
SER_I_	MinMx	104,136	663	571	-53,553	-133,185	26,111
SER_I_	MinMz	103,242	421	186	-3,868	-84,601	-166,733
SER_II_	MinFy	104,919	-1,644	-158	2,169	-11,510	60,010
SER_II_	MinMy	104,035	-8	-73	1,868	-127,328	-788
SER_II_	MinMz	103,385	201	-154	671	4,409	-131,884
SER_III_	MinFz	103,012	-3	-247	-1,450	64,155	21,267
SER_III_	MinMx	103,338	693	-125	-32,409	4,374	10,624
SER_III_	MinMz	102,839	571	-189	628	8,605	-115,438
STR_I_	MaxFz	89,586	-199	-26	8,607	-144,899	90,857
STR_I_	MinMy	89,855	-451	-48	2,607	-181,828	13,989
STR_I_	MinMz	89,707	664	-161	912	4,633	-217,712
STR_III_	MinMx	135,214	492	2,640	-49,432	-600,485	89,513
STR_III_	MinMy	87,431	-353	2,640	-49,429	-600,487	83,555
STR_III_	MinMz	86,882	316	1,463	-17,443	-427,131	-107,186
STR_IV_	MinFy	86,271	322	-161	112	4,619	29,453
STR_IV_	MinMy	86,271	322	-161	112	4,619	29,453
STR_IV_	MinMz	86,271	322	-161	112	4,619	29,453
STR_V_	MaxMz	137,855	1,114	-903	7,615	164,208	502,449
STR_V_	MaxFy	134,579	3,210	-872	4,203	162,357	273,899
STR_V_	MinMz	89,079	500	348	-5,337	-124,077	-204,704









Conclusions:

1. LRFD is not difficult, so don't fear the change from ASD or the Greek terminology
2. LRFD provides a more logical framework that incorporates probability & reliability. The approach is also consistent with modern structural design.
3. Just as with ASD, *accurately* estimating the nominal resistance (ultimate capacity) is the difficult part.
4. The Structural Engineer provides the Factored Loads (generally) for several load cases
5. Factored Resistance must equal or exceed Factored Load
6. The resistance factors change with:
 - Limit state (STR, SER, EXT)
 - Load direction (compression, uplift)
 - Resistance verification (load test, PDA) or Design Approach (α , B, λ , etc.)
 - Redundant & Non-Redundant Groups

