Comprehensive Field Load Test and Geotechnical Investigation Program for Development of LRFD Recommendations of Driven Piles on IGM (FHWA Pooled Fund Study TPF-5-391)

12th TAC Conference Meeting (October 25th, 2021)

Lead Agency: WYDOT

Lead Agency Contact : Enid White

PIs: Kam Ng, Ph.D., P.E.; Shaun S. Wulff, Ph.D.

Duration: Five Years (2019-2023)

Participants: WYDOT, CDOT, IADOT, ITD, MDT, KDOT, and NDDOT

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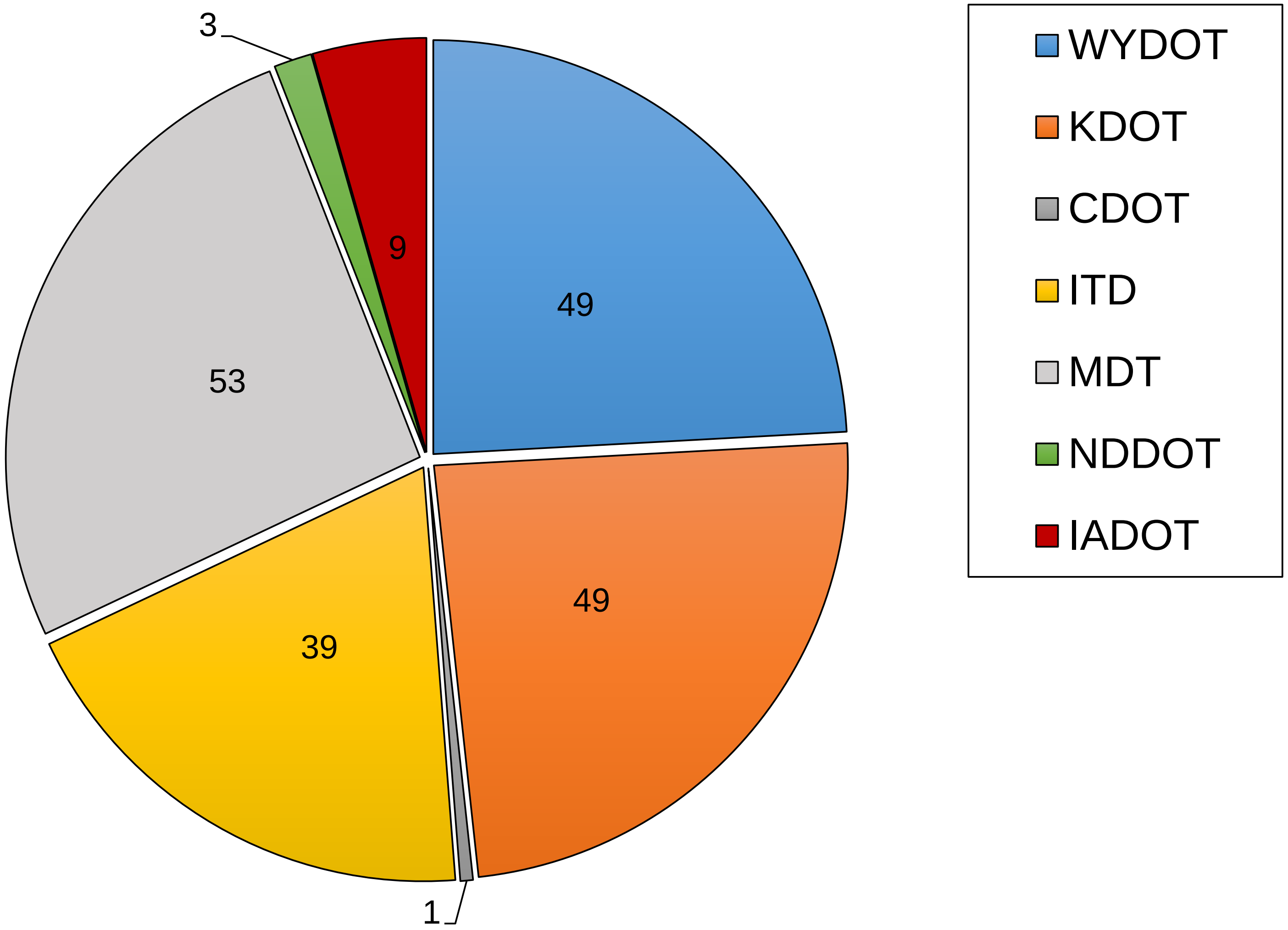
Meeting Agenda

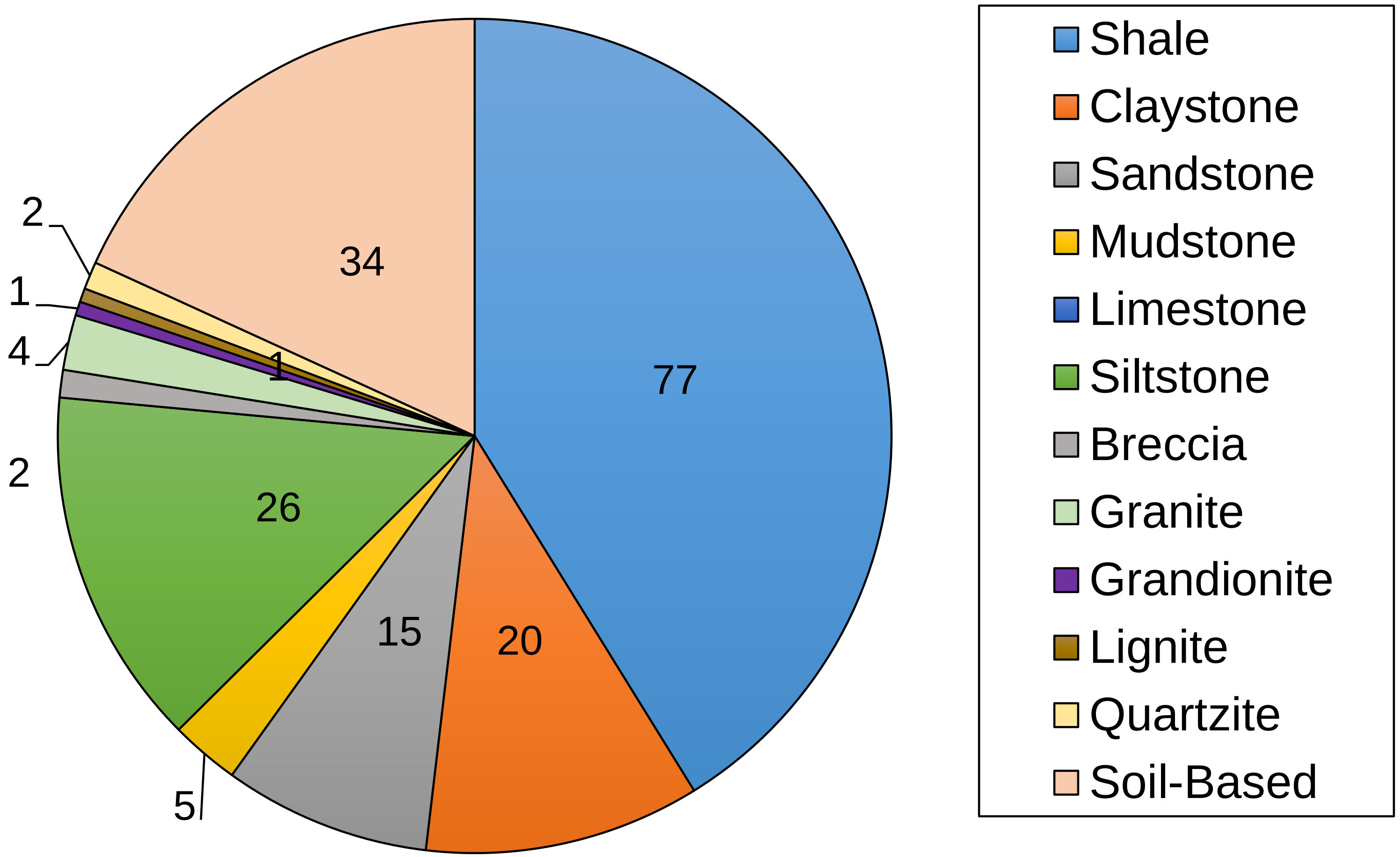
- Summary of Pile Load Test Data
- Electronic Database
- Identification of Bridge Sites
- Pile Load Test Results: NDDOT Cherry Creek Project
- Piles in Rock-Based IGMs
- Variability Analysis: LRFD Calibration
- Variability Analysis: R-Shiny
- Research Team
- Project Schedule
- Project Progress
- Technology Transfer

Task I-1: Summary of Test Pile Data



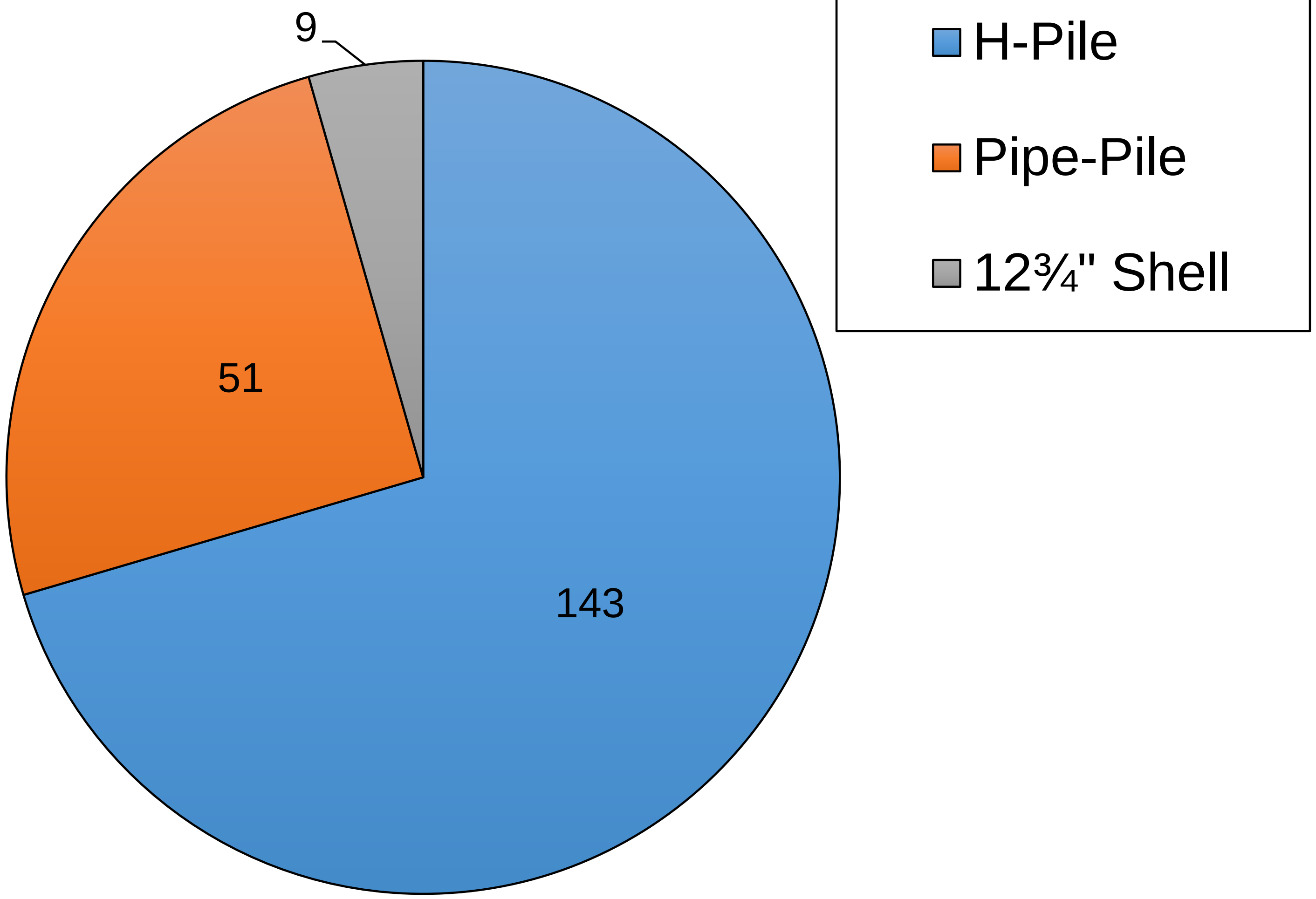
365 Test Piles Collected and 203 Test Piles are Usable

Distribution of Test Piles in Known IGMs



187 Usable Test Piles into Known IGMs

Distribution of Pile Types



203 Usable Test Pile Types

Task I-2: Electronic Database

Pile Load Tests List

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MontanaPile

MONTANA MDT DEPARTMENT OF TRANSPORTATION — UNIVERSITY OF WYOMING

New Pile Load Test

ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile Toe Elevation	Pile embedment at EOD (ft)	Ha
1	Rosebud	STPB 44303(2)	16" steel pipe pile with conical point with 0.5" wall thickness	457	8/6/2015	2460.1	28.34	Del
2	Blaine	STPB 9003(50)	16" steel OEP with 0.5" wall thickness	560	6/19/2018	2305.7	82.2	
3	Blaine	STPB 9003(50)	16" steel OEP with inside fit cut shoe with 0.5" wall thickness	500	5/22/2018	2311.6	50.3	
4	Blaine	STPB 9003(50)	16" steel OEP with inside fit cut shoe with 0.5" wall thickness	560	4/17/2018	2312.6	76.2	
5	Fergus	BR 81-1(11)34	24" steel CEP with 0.75" wall thickness	1057	8/15/2007	3560.4	46.3	
6	Fergus	BR 81-1(11)34	24" steel CEP with 0.75" wall thickness	1057	8/20/2007	3569.5	35.3	
7	Prairie	BR 253-1(11)4	20" steel OEP with 0.5" wall thickness	674				
8	Prairie	BR 253-1(11)4	24" steel CEP with 0.75" wall thickness	832	3/21/2007	2251.31	57.97	
9	Musselshell	STPB 9033(27)	16" steel OEP with inside fit cut shoe with 0.5" wall thickness	455	7/11/2017	2896.5	32.7	D
10	Lewis & Clark	IM-NHPB 15-4(128)192	HP 14 X 117					
11	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness					
12	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness					
13	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness					
14	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness					
15	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness	700	6/6/2016	3927	29.47	
16	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness	670	5/3/2016	3905.2	32.16	
17	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness	650	5/11/2016	3912.4	48.47	
18	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness	700	3/27/2017	3927.5	29	
19	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness	700	3/27/2017	3928.5	27.98	
20	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness	670	5/9/2017	3909.9	27.5	
21	Lewis & Clark	IM-NHPB 15-4(128)192	16" steel pipe pile with conical point with 0.5" wall thickness	650	4/10/2017	3912.8	48.2	
22	Golden Valley	BR 9019(12)	16" steel OEP with inside fit cut shoe with 0.5" wall thickness	638	12/14/2011	3459.9	27.5	
23	Valley	BR 9053(104)	20" steel OEP with 0.5" wall thickness	610	9/13/2013	2413.8	45	

Pile Load Tests List

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WyoPile

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New Pile Load Test

ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile Toe Elevation	Pile embedment at EOD (ft)	Hammer Type	EOD Hammer Stroke (ft)
1	Laramie	1102005	HP 14 X 73	258	2/16/2012	5390.54	37.6	Delmag D16-32	7.5
2	Laramie	1102005	HP 14 X 73	322	11/17/2011	5400.55	68.3	Delmag D16-32	10.0
3	Natrona	N212084	HP 14 X 73	169	10/9/2012		24.3	MVE D-19	10.5
4	Goshen	N253081	HP 14 X 73	216	10/23/2012	3989.67	100	MVE D19	10.5
5	Hot Springs	0900013	HP 14 X 73	248	7/2/2013	5154.5	27	ICE 42-S	10.8
6	Sublette	STP-BROS 0C23039	HP 12 X 53	300	1/6/2015	7076.85	23	APE D19-42	11.2
7	Laramie	I806198	HP 12 X 53	188	5/4/2015	5029.6	87.9	Delmag D16-32	11.5
8	Laramie	I806198	HP 12 X 53	188	4/30/2015	5047.5	75.4	Delmag D16-32	11.5
9	Laramie	I806198	HP 12 X 53	202	5/7/2015	5032.73	53.6	Delmag D16-32	8.6
10	Laramie	I806198	HP 12 X 53	202	5/13/2015	5014.15	35.3	Delmag D16-32	
11	Laramie	I806198	HP 12 X 53	292	5/14/2015	5016.36	38	Delmag D16-32	
12	Laramie	I806198	HP 12 X 53	172	1/29/2015	5069.44	46.7	Delmag D16-32	
13	Laramie	I806198	HP 12 X 53	172	1/29/2015	5072.16	44.4	Delmag D16-32	
14	Laramie	I806198	HP 12 X 53	172	1/28/2015	5070.26	44.7	Delmag D16-32	
15	Laramie	I806198	HP 12 X 53	172	1/28/2015	5070.03	46.4	Delmag D16-32	9.4
16	Natrona	N212084	HP 14 X 89	372	1/28/2013	N/A	20.5	MVE D-19	8.8
17	Goshen	N253081	HP 14 X 73	216	1/16/2013	4022.3	99.2	Delmag D16-32	8.8
18	Goshen	N253081	HP 14 X 73	216	1/17/2013	3982.5	139	Delmag D16-32	8.7
19	Carbon	0804234	HP 12 X 53	207	5/5/2010	6672	41.2	MVE M-19	10.0
20	Park	0C11060	HP 12 X 53	120	5/26/2009	6178.67	19.5	MKT DE 40	8.8
21	Park	0C11060	HP 12 X 53	120	5/27/2009	6171.61	36	MKT DE 40	9.5
22	Park	0C11058	HP 14 X 73	162	4/18/2006	4070.09	45	Delmag D19-42	9.6
23	Teton	PEB-681	HP 12 X 53		5/15/1995	5961	31	IHC S-35	10.0
24	Teton	PEB-681	HP 12 X 53		5/15/1995	5956	36.5	IHC S-35	8.9
25	Teton	PEB-681	HP 12 X 53		5/15/1995	5953	39.5	IHC S-35	8.0
26	Park	031-1(61)	HP 14 X 73		10/21/1998	5921.72	69.75	ICE 42-S	8.2
27	Park	031-1(44)	HP 14 X 73		10/17/1996	6618.12	41	ICE 42-S	7.8
28	Park	031-1(44)	HP 14 X 73		10/16/1996	6622.2	32	ICE 42-S	

Pile Load Tests List

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KansasPile

Kansas Department of Transportation — UNIVERSITY OF WYOMING

New Pile Load Test

ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile Toe Elevation	Pile embedment at EOD (ft)	Hammer Type	EOD Hammer Stroke (ft)
1	Franklin	68-30 KA-2097-01	HP 12x53	190		877.15	26	Delmag D19-42	7.5
2	Barton	4-5 KA-0040-01	HP 10×42	132	3/6/2013	1698.6	79	Delmag D19-42	7.0
3	Barton	4-5 KA-0040-01	HP 12×63	232	3/6/2013	1692.86	72	Delmag D19-42	8.0
4	Finney	23-28 KA-0045-01	HP 10×42	153	2/7/2014	2520.3	58	Delmag D19-42	8.0
5	Finney	23-28 KA-0045-01	HP 12×63	252	2/7/2014	2518.1	50	Delmag D19-42	8.8
6	Finney	23-28 KA-0045-01	HP 12×63	226	2/7/2014	2520.9	50	Delmag D19-42	
7	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	130	4/2/2014	2420.11	55	Delmag D16-32	8.0
8	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	212		2435.2	33	Delmag D16-32	8.5
9	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	216		2442.2	8	Delmag D16-32	9.0
10	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	208	2/3/2014	2431.3	41	Delmag D16-32	7.5
11	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	208	4/2/2014	2435.29	33	Delmag D16-32	9.0
12	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	193		2441.2	27	Delmag D16-32	8.5
13	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	193		2435.2	27.05	Delmag D16-32	7.0
14	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	120		2438.1	42.9	Delmag D16-32	7.5
15	Sheridan	24-90 KA-0041-01	2.75" diameter shell filled v	120		2438.1	42.90	Delmag D16-32	8.0
16	Sedgwick	235-87 KA-0161-04	HP 10×42	228		1225.53	105	Delmag D19-32	6.0
17	Sedgwick	235-87 KA-0161-04	HP 10×42	228		1227	80	Delmag D19-32	7.0
18	Sedgwick	235-87 KA-0161-04	HP 10×42	228	2/10/2017	1224.08	105	Delmag D19-32	7.5
19	Sedgwick	235-87 KA-0161-04	HP 10×42	228		1225.2	84	Delmag D19-32	7.0
20	Sedgwick	235-87 KA-0161-04	HP 12×74	224		1218.1	60	Delmag D30-02	8.5
21	Sedgwick	235-87 KA-0161-04	HP 12×74	332		1218.1	70	Delmag D30-02	8.5
22	Sedgwick	235-87 KA-0161-04	HP 12×74	336		1221.4	67	Delmag D30-02	8.8
23	Sedgwick	235-87 KA-0161-04	HP 12×53	222		1227.53	73	Delmag D30-02	8.5
24	Sedgwick	235-87 KA-0161-04	HP 12×63	308		1215.06	68	Delmag D30-02	8.8
25	Sedgwick	235-87 KA-0161-04	HP 12×74	356	11/8/2016	1218.9	47	Pileco D30-32	7.8

Pile Load Tests List

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IdahoPile

IDAHO TRANSPORTATION DEPARTMENT — UNIVERSITY OF WYOMING

New Pile Load Test

ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile embedment at EOD (ft)	Hammer Type	EOD blow/ft
1	Washington	BR-3110(127)	HP 14x117	400	4/1/2008	37	Delmag D-19-42	58
2	Washington	BR-3110(127)	HP 14x117		1/15/2009		Delmag D-19-42	
3	Washington	BR-3110(127)	HP 14x117	400	6/26/2008	36	Delmag D-19-42	187
4	Washington	BR-3110(127)	HP 14x117	400	5/8/2009	37	Delmag D-19-42	118
5	Washington	BRF-3112(051)	HP 14x117		3/25/2013			
6	Washington	BRF-3112(051)	HP 14x117		3/25/2013			
7	Washington	BRF-3112(051)						
8	Washington	BRF-3112(051)		575		41.6	ICE I-30	590
9	Washington	A013(395)	HP 14x117	520	4/17/2017	68.9	ICE I-30v2	73
10	Washington	A013(395)	HP 14x117	520	4/24/2017	68.9	ICE I-30v2	52
11	Payette	A013(390)	HP 14x117	400	6/28/2018	42.9	APED36-26	31
12	Payette	A013(390)	HP 14x117		8/6/2018	54.4	APED36-27	44
13	Elmore	A013(947)	HP 14x117		6/13/2015	38	ICE I-30v2	52
14	Elmore	A013(947)	HP 14x117		5/26/2015	39.9	ICE I-30v2	64
15	Elmore	A013(947)	HP 14x117		6/4/2015	23.8		77
16	Elmore	A013(947)	HP 14x117		6/5/2015	35.9		69
17	Valley	A013(394)	HP 12x74	450	8/1/2018	56	APE D30-42	60
18	Valley	A013(394)	HP 12x74	450	8/1/2018	38	APE D30-42	60
19	Valley	A013(394)	4-in thk OEP (filled w/ 4 ks		7/18/2018	61	APE D30-42	52
20	Valley	A013(394)	4-in thk OEP (filled w/ 4 ks		9/10/2018	51.8	APE D30-42	61
21	Latah	A013(450)	5-in thk OEP (filled w/ 3 ks	430	7/27/2018	48	ICE I-30 V2	23

Task I-2: Electronic Database

Pile Load Tests List

Disclaimer

IowaPile — IOWADOT — University of Wyoming

New Pile Load Test

ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile embedment at EOD (ft)	Hammer Type	EOD Hammer Str
1	Franklin	BRF-065-7(35)--38-35	HP 10 X 57	250	5/5/2020	37.6	Delmag D19-42	7.5
2	Franklin	BRF-065-7(35)--38-35	HP 10 X 57	250	5/5/2020	68.3	Delmag D19-42	10.0
3	Rockwell	BRF-065-8(57)--38-17	HP 14 X 73	250	6/19/2020	24.3	Delmag D19-42	10.5
4	Rockwell	BRF-065-8(57)--38-17	HP 10 X 42	300	6/19/2020	100	Delmag D19-42	10.5
5	Wapello	NHSX-063-2(120)--3H-9	HP 10 X 57	248	11/8/2020	27	Delmag D-22	10.8
6	Adair	BRF-092-3(36)--38-01	HP 10 X 57	300	3/8/2020	23	Delmag D-22	11.2
7	Davis	BRF-012-2(32)--38-75	HP 12 X 53	214	6/5/2021	87.9	APE D 19-42	11.5
8	Davis	BRF-012-2(32)--38-75	HP 12 X 53	214	6/5/2021	75.4	APE D 19-42	11.5
9	Davis	BRF-012-2(32)--38-75	HP 12 X 53	214	6/5/2021	53.6	APE D 19-42	8.6

Pile Load Tests List

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NorthDakotaPile — NDDOT North Dakota Department of Transportation — University of Wyoming

New Pile Load Test

ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile Toe Elevation	Pile embedment at EOD (ft)	Hammer Type
1	Morton County	HPP-TIP-TCP-1-094(078	HP 14×102	360	3/27/2007	1540.5	90	Delmag D3
2	Morton County	HPP-TIP-TCP-1-094(078	HP 14×102	360	3/27/2007	1533.5	97	Delmag D3
3	McKenzie County	SS-7-806(014)306	HP 12×53		7/13/2021	1953.5	67.5	Delmag D 30
(New)								

Pile Load Tests List

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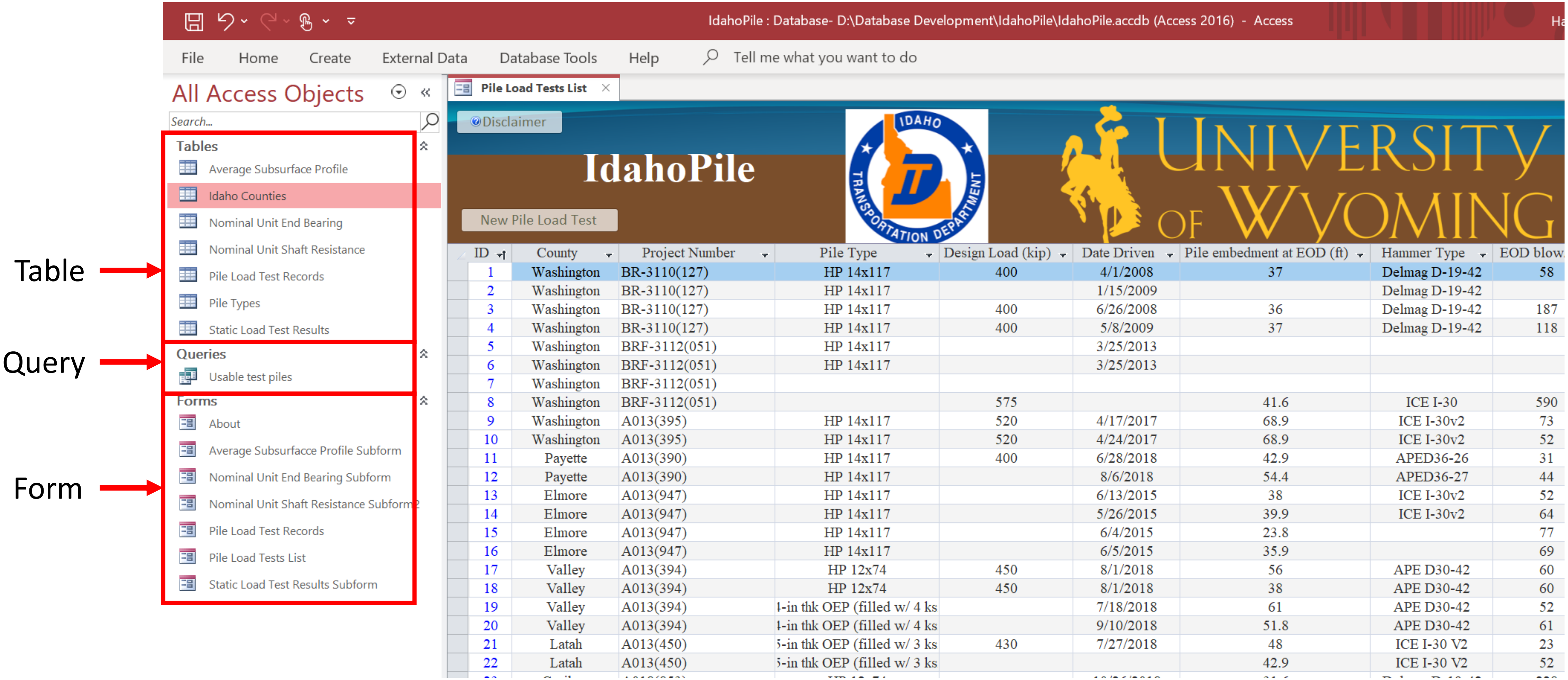
ColoradoPile — COLORADO Department of Transportation (CDOT) — University of Wyoming

New Pile Load Test

ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile Toe Elevation	Pile embedment at EOD (ft)	Hammer Type	EOD Hammer Stroke (ft)
1		37-UR-135	HP 14*89					Delmag D-25-32	
2		37-UR-135	HP 14*89					Delmag D-25-32	
3		37-UR-135	HP 14*89					Delmag D-25-32	
4		37-UR-135	HP 14*89		4/10/1998		19.5	Delmag D-25-32	
5		B-24-A0							
6		BR 0062-013	HP 12*53		7/8/2005		50	19-32 Open Ended D	6.5
7		BR 0062-013	HP 12*53		6/27/2005		64	19-32 Open Ended D	6.5
8		BR 0062-013	HP 12*53		6/30/2005		48	19-32 Open Ended D	6.5
9		BR 0062-013	HP 12*53		6/30/2005		78	19-32 Open Ended D	6.5
10		BR 0062-013	HP 12*53		7/8/2005		50	19-32 Open Ended D	6.5
11		BR 0072-015	HP 12*74		8/13/2009		39	D19-42 open Ended	7.0
12		BR 0101-024	HP 14*89		12/14/2009	4700	15.6	APE Model D30-42	12.5
13		BR 0101-024	HP 14*89		12/14/2009	4700	16.6	APE Model D30-42	12.5
14		BR 0251-162	HP 12 x 74						
15		BR 0362-027							
16		BR 0853-023	P 12*53 (2:12 Battered Pil		3/21/1997	4575.1	59	erminghammer B-35	8.0
17		BR 1151-012							
18		BR 2854-105	HP 12 x 74						
19		BR 287-3(061)	HP 12*74		10/11/2000		42.2	D19-32 open ended	8.0
20		BR 5502-031	HP 12*53		9/14/2001		18	D19-32 Open ended	7.0
21		BR 5502-053	HP 12*84(Battered)		10/6/2009	9235.5	27.5	30-32 Open ended D	7.0

Electronic Database Demo

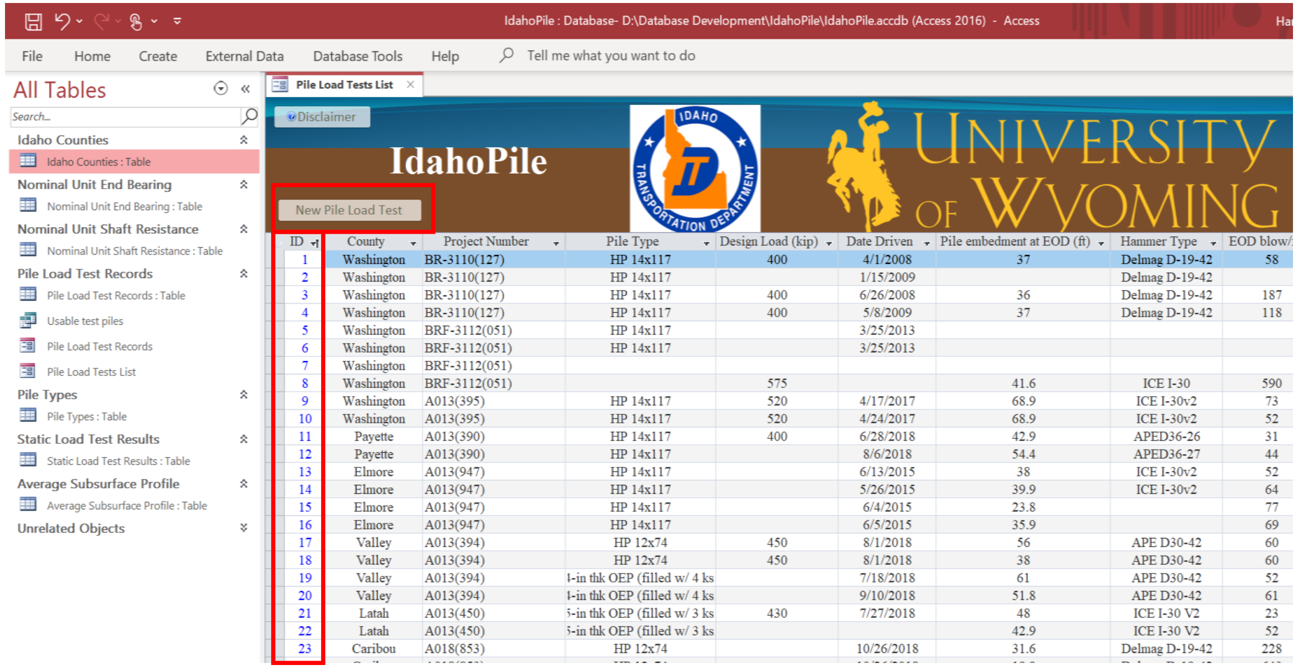
Task I-2: Electronic Database



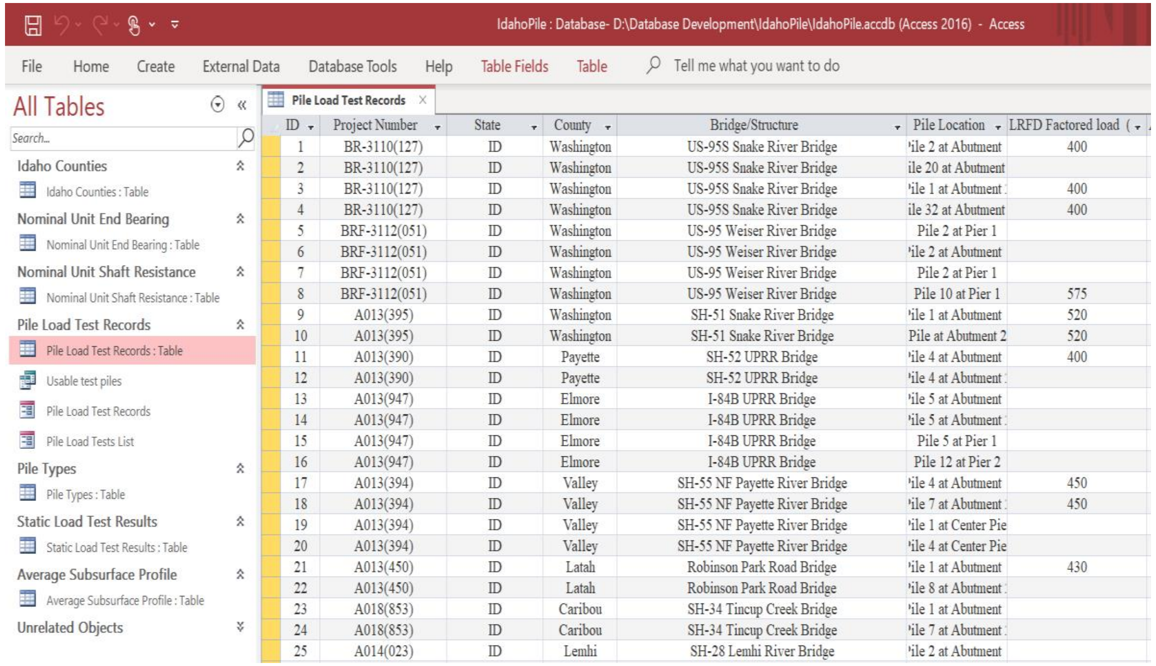
ID	County	Project Number	Pile Type	Design Load (kip)	Date Driven	Pile embedment at EOD (ft)	Hammer Type	EOD blow
1	Washington	BR-3110(127)	HP 14x117	400	4/1/2008	37	Delmag D-19-42	58
2	Washington	BR-3110(127)	HP 14x117		1/15/2009		Delmag D-19-42	
3	Washington	BR-3110(127)	HP 14x117	400	6/26/2008	36	Delmag D-19-42	187
4	Washington	BR-3110(127)	HP 14x117	400	5/8/2009	37	Delmag D-19-42	118
5	Washington	BRF-3112(051)	HP 14x117		3/25/2013			
6	Washington	BRF-3112(051)	HP 14x117		3/25/2013			
7	Washington	BRF-3112(051)						
8	Washington	BRF-3112(051)		575		41.6	ICE I-30	590
9	Washington	A013(395)	HP 14x117	520	4/17/2017	68.9	ICE I-30v2	73
10	Washington	A013(395)	HP 14x117	520	4/24/2017	68.9	ICE I-30v2	52
11	Payette	A013(390)	HP 14x117	400	6/28/2018	42.9	APED36-26	31
12	Payette	A013(390)	HP 14x117		8/6/2018	54.4	APED36-27	44
13	Elmore	A013(947)	HP 14x117		6/13/2015	38	ICE I-30v2	52
14	Elmore	A013(947)	HP 14x117		5/26/2015	39.9	ICE I-30v2	64
15	Elmore	A013(947)	HP 14x117		6/4/2015	23.8		77
16	Elmore	A013(947)	HP 14x117		6/5/2015	35.9		69
17	Valley	A013(394)	HP 12x74	450	8/1/2018	56	APE D30-42	60
18	Valley	A013(394)	HP 12x74	450	8/1/2018	38	APE D30-42	60
19	Valley	A013(394)	-in thk OEP (filled w/ 4 ks		7/18/2018	61	APE D30-42	52
20	Valley	A013(394)	-in thk OEP (filled w/ 4 ks		9/10/2018	51.8	APE D30-42	61
21	Latah	A013(450)	-in thk OEP (filled w/ 3 ks	430	7/27/2018	48	ICE I-30 V2	23
22	Latah	A013(450)	-in thk OEP (filled w/ 3 ks			42.9	ICE I-30 V2	52

Home Screen

Task I-2: Electronic Database

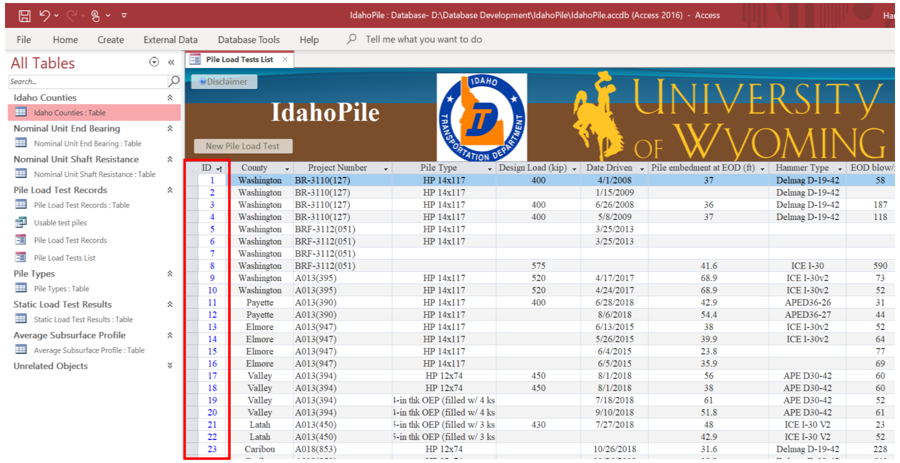


Pile Load Test List Form

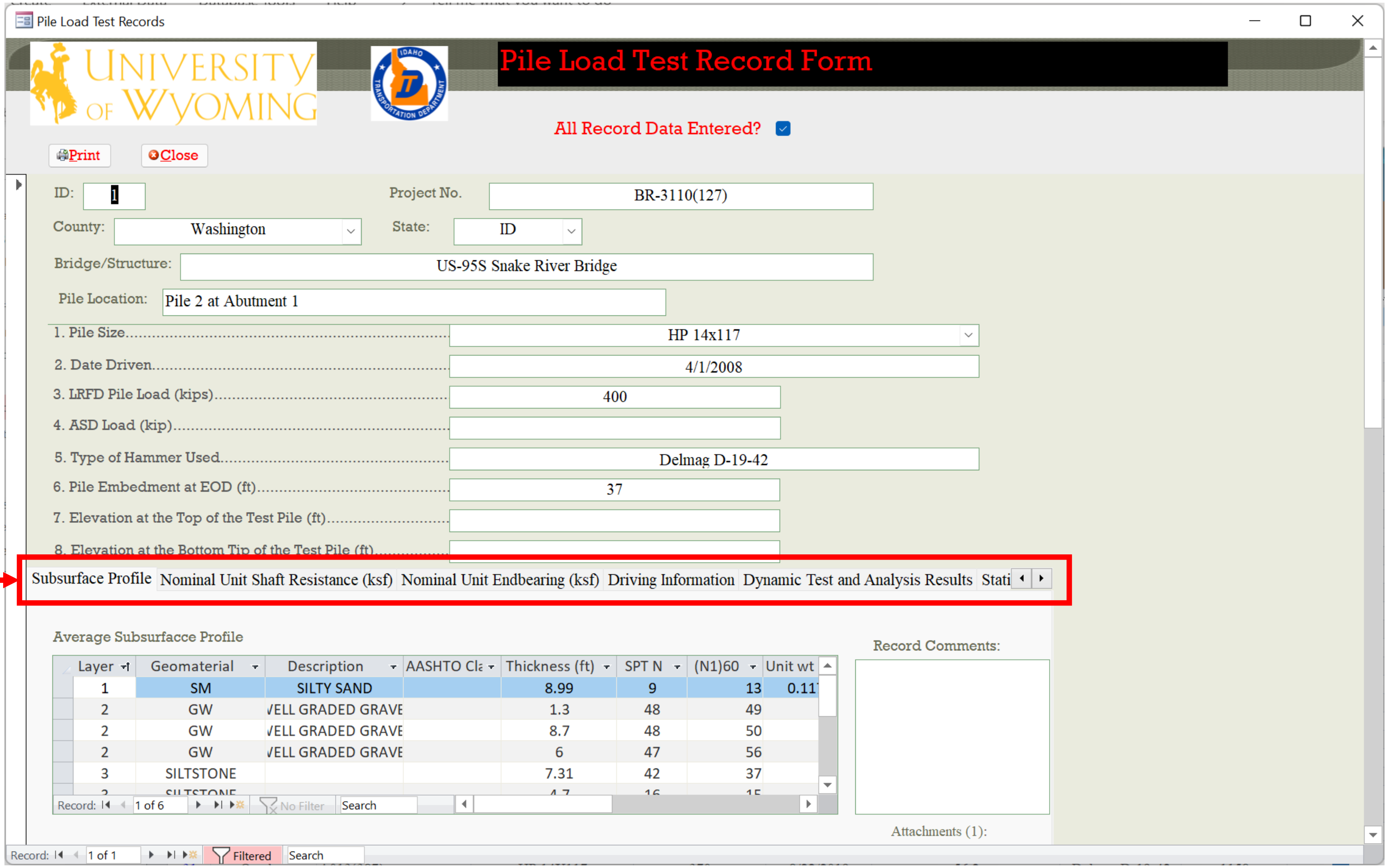


Pile Load Test Record

Task I-2: Electronic Database

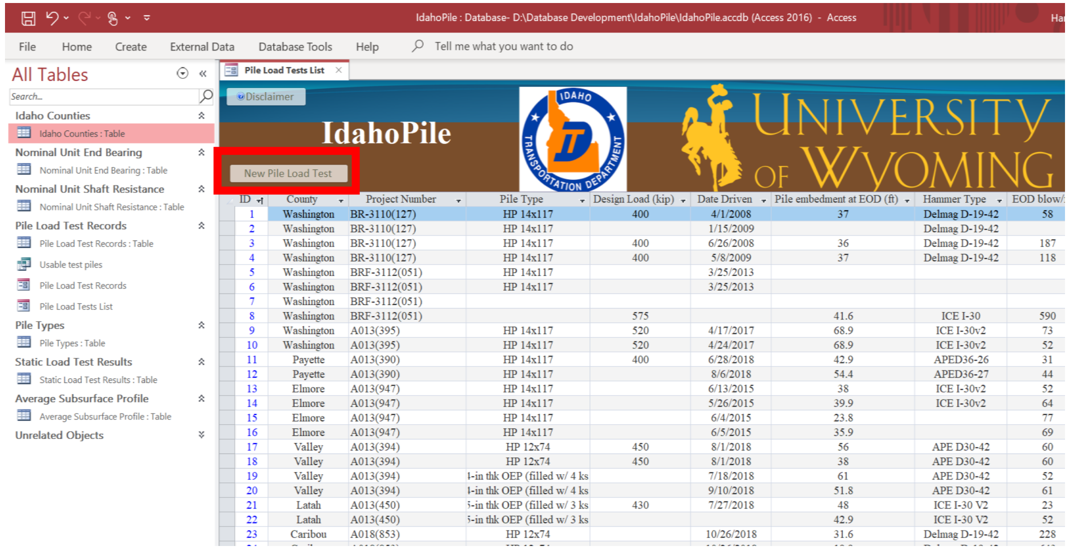


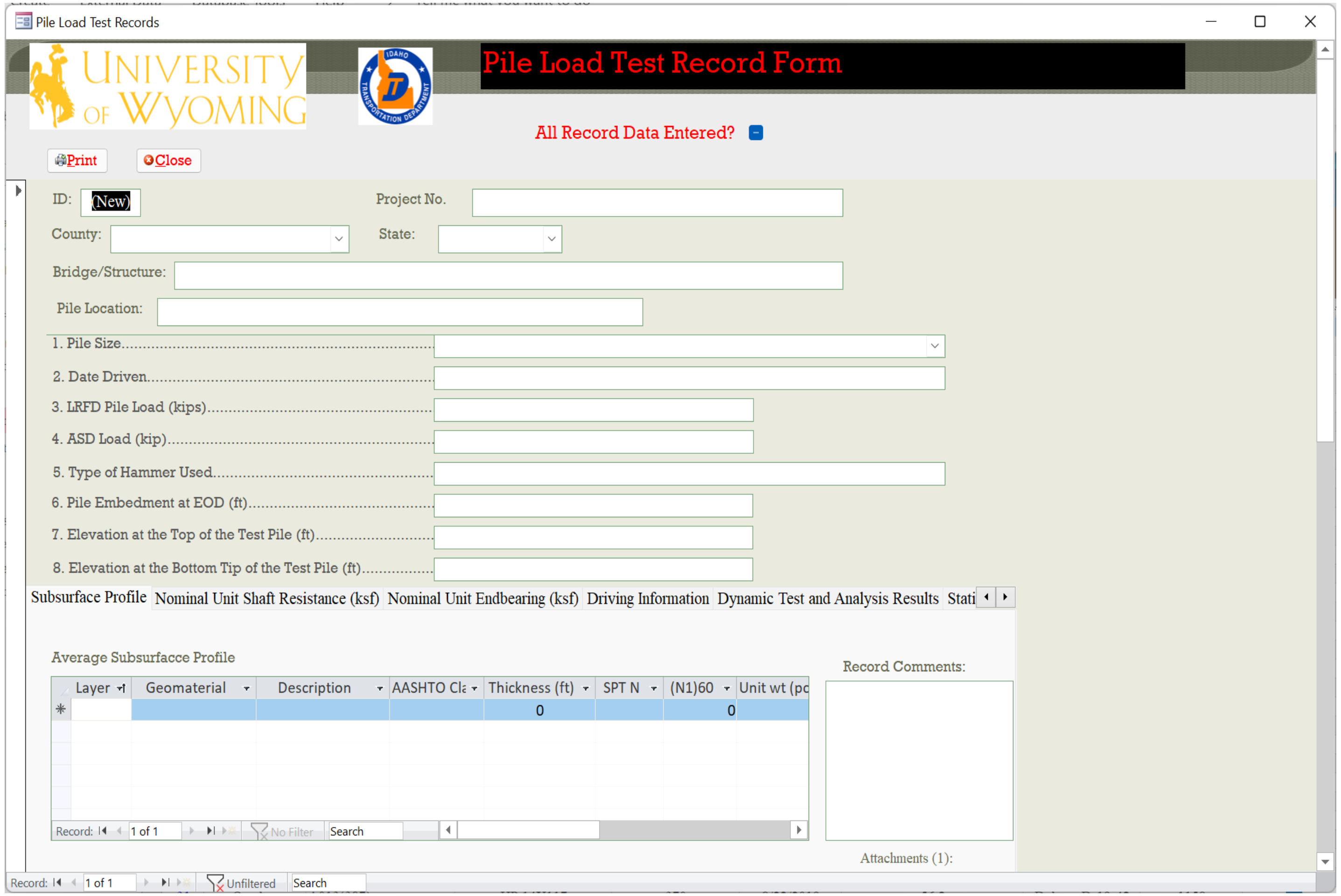
Additional Information for Test Piles



Pile Load Test Record Form (Data View)

Task I-2: Electronic Database





Pile Load Test Record Form (New Input)

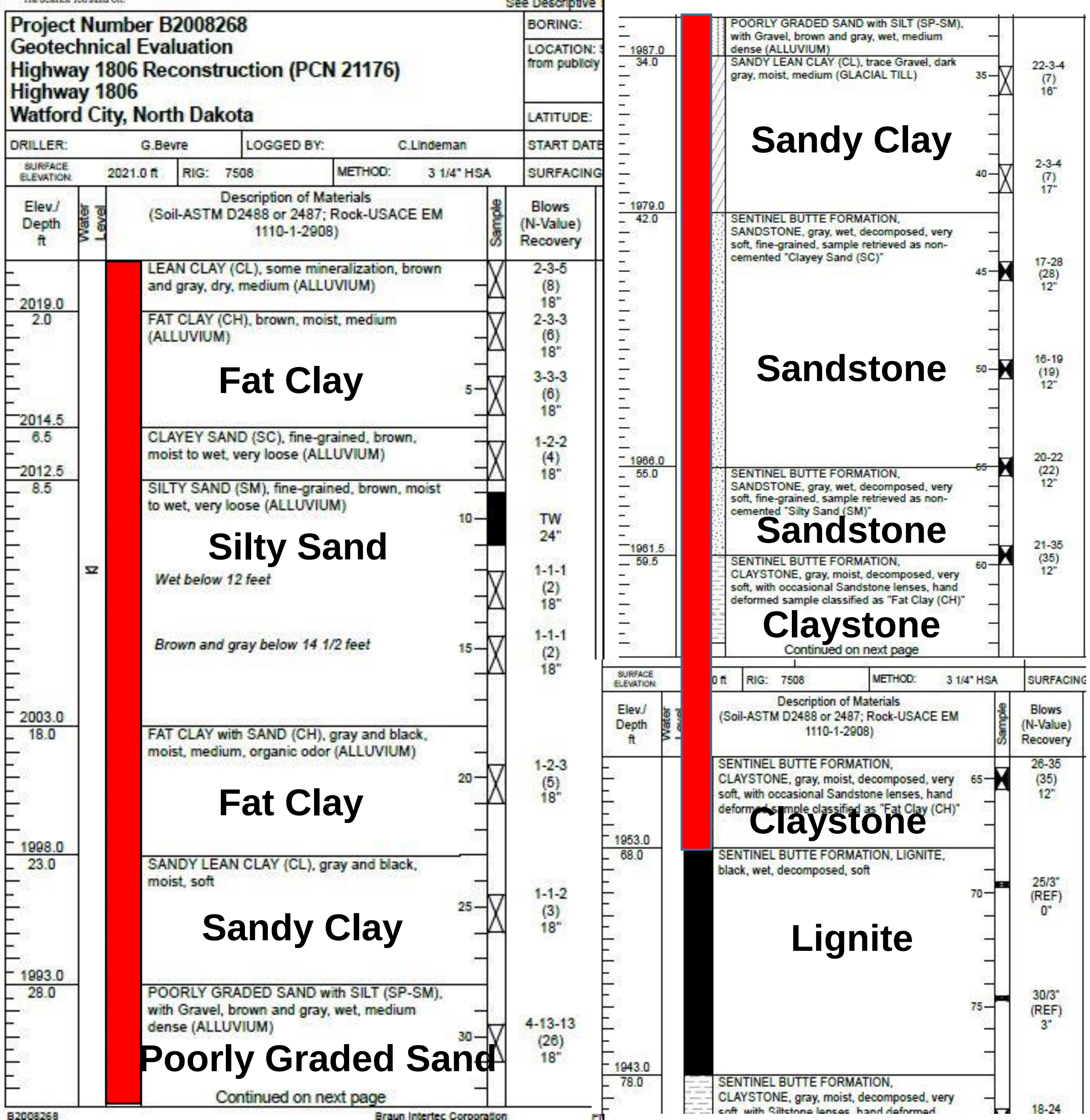
Task I-3: Summary of Bridge Projects for Field Tests

DOT	Test	Bridge Sites	IGM Type
WYDOT	2 SLTs + PDAs	1) Lodgepole Creek Bridge in 2019	Siltstone
		2) I-80 Interchange Bridge in 2021	Siltstone
IADOT	2 SLTs + PDAs	1) Wapello Bridge in 2020	Shale
		2) Adair Bridge in 2020	Shale
	14 PDAs	3) Bridge Projects for Dynamic Testing	Mainly Shale
KDOT	2 SLTs+PDA	North Junction, Wichita in 2022	Shale
CDOT	3 SLTs+PDAs	1) Bridge I-05-V over Gunnison River in 2022 2) Bridge E-17-GX, York St under I-76 in 2022 3) Bridge J-17-XA, CO115 over Rock Creek Pass in 2023	Shale Siltstone/Claystone Claystone
NDDOT	1 SLT+PDA	1) Cherry Creek Bridge in 2021	Claystone/Lignite

Task I-5:NDDOT Highway 1806 at Cherry Creek Bridge

Task I-5:NDDOT Highway 1806 at Cherry Creek Bridge

Day	Date	Description
Monday	07/12	Sensor Installation & Protection; Steel Angle Welding
Tuesday	07/13	Pile Installation; 1-hr Restrike
Wednesday	07/14	24-hour Restrike; Load Frame Installation; Static Load Test Setup and Testing



NDDOT Highway 1806 at Cherry Creek Bridge

Overburden: Fat Lean Clay, Silty Sand, Poorly Graded Sand and Sandy Clay (Glacial Till).

Pile: HP12x53

IGM: Sandstone, Claystone, Lignite

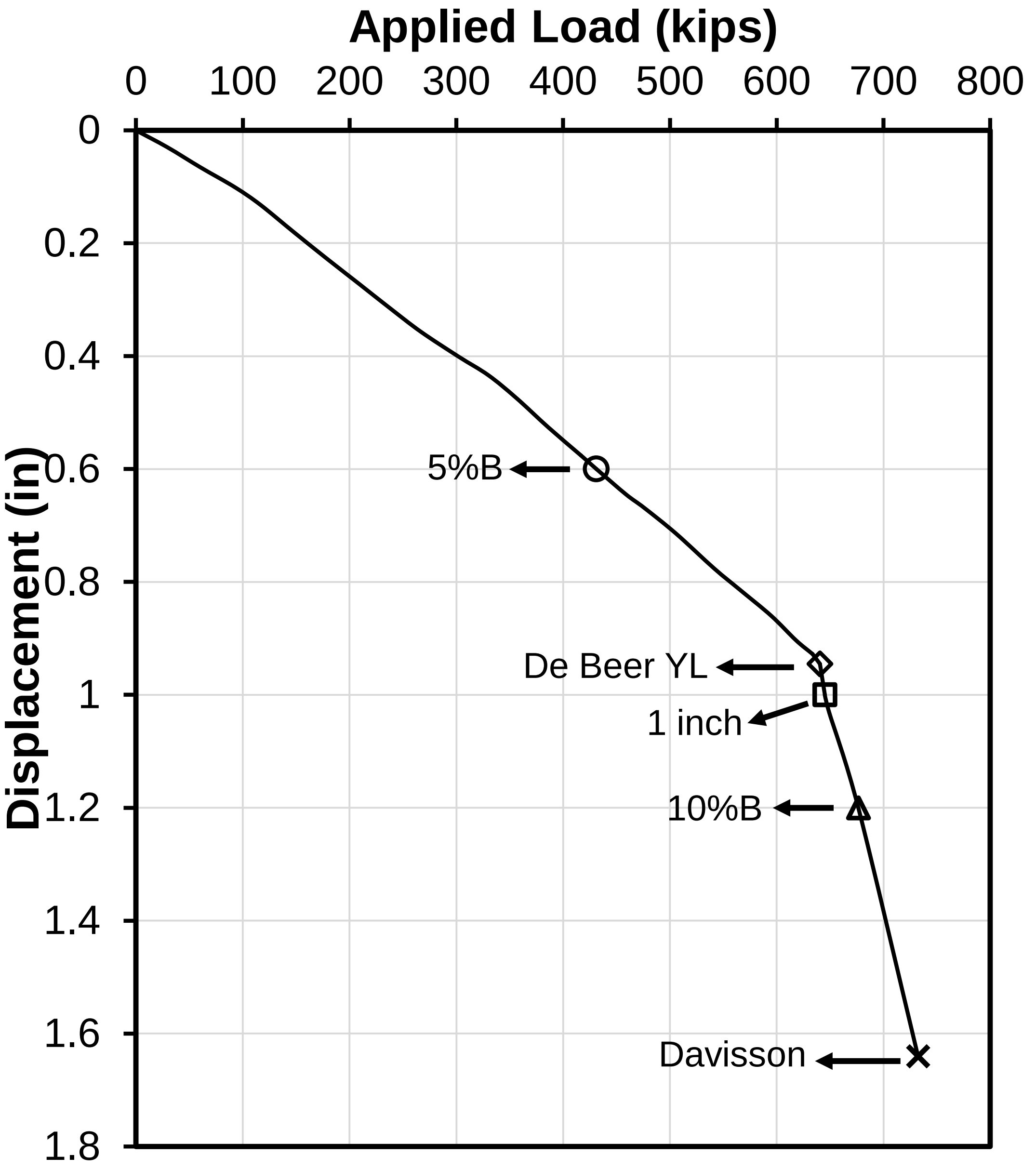
Hammer: Delmag D 30-32

Task I-5:NDDOT Highway 1806 at Cherry Creek Bridge

CAPWAP Analysis at Event	Embedded Pile Length (ft)	Bearing Layer	Total Resistance (kip)	Shaft Resistance (kip)	End Bearing (kip); %	Hammer Blow Count (b/ft)
Pile initial driving BN: 130 (E-1)	50	Sandstone	165	134	31; 19.1	10
Pile initial driving BN: 275 (E-2)	60	Sandstone	288	246	42; 14.7	19
Pile initial driving BN: 409 (E-3)	66	Claystone	367	339	28; 7.6	25
Pile initial driving BN: 442 EOD	67	Lignite	429	403	26; 6.2	28
1-hr restrike	67.52	Lignite	791	756	35; 4.5	192
24-hr restrike	67.54	Lignite	820	785	35; 4.3	192+

Note: E=Event

Task I-5:NDDOT Highway 1806 at Cherry Creek Bridge



Failure Criterion		R (kips)	R/P_u	S/B(%)
Gradual Failure Methods	Davisson	732.5	0.95	13.67
	De Beer YL	640.6	0.83	7.88
	Fuller & Hoy	640	0.83	7.88
Plunging Failure Methods	Chin-Kondner	1666.7	2.15	-
	De Court	1996.5	2.58	-
	Van Der Veen	860	1.2	-
Settlement Based Methods	10%B	676.5	0.87	10
	5%B	431.1	0.56	5
	1 inch	645.2	0.83	8.33
Others	Mazurkiwicz	1000	1.29	-

NOTE: R= Total Resistance; P_u= Structural Capacity; S = Settlement; B = Pile Dimension

Task I-5:NDDOT Highway 1806 at Cherry Creek Bridge

IGM	Depth (ft)	Unit Shaft resistance (ksf)						
		E-1	E-2	E-3	EOD	1-hr Restrike	24-hr Restrike	SLT (D)
Sandstone	42-50	0.6	1.95	3.15	3.35	7.3	7.72	3.68
Sandstone	50-60	--	1.9	2.92	4.45	8.1	7.66	7.97
Claystone	60-66	--	--	0.9	0.57	2.32	2.33	5.47
Lignite	66-67.54	--	--	--	0.52	1.7	1.74	3.83

Note: E-1=Pile initial driving BN130; E-2=Pile initial driving BN275; E-3=Pile initial driving BN409; SLT(D)= Static load test based on Davisson criterion.

Task I-5:NDDOT Highway 1806 at Cherry Creek Bridge

IGM	Depth (ft)	Unit End Bearing (ksf)						
		E-1	E-2	E-3	EOD	1-hr Restrike	24-hr Restrike	SLT (D)
Sandstone	50	32.04	--	--	--	--	--	--
Sandstone	60	--	43.13	--	--	--	--	--
Claystone	66	--	--	28.48	--	--	--	--
Lignite	67.5 to 67.54	--	--	--	26.96	36.11	35.91	19.54

Note: E-1=Pile initial driving BN130; E-2=Pile initial driving BN275; E-3=Pile initial driving BN409; SLT(D)= Static load test based on Davisson criterion.

Phase II

Task II-2: Pile Resistance Estimation:

Rock-Based IGM Validation

Proposed Pile Resistance Estimation Methods For Piles in Rock-IGMs

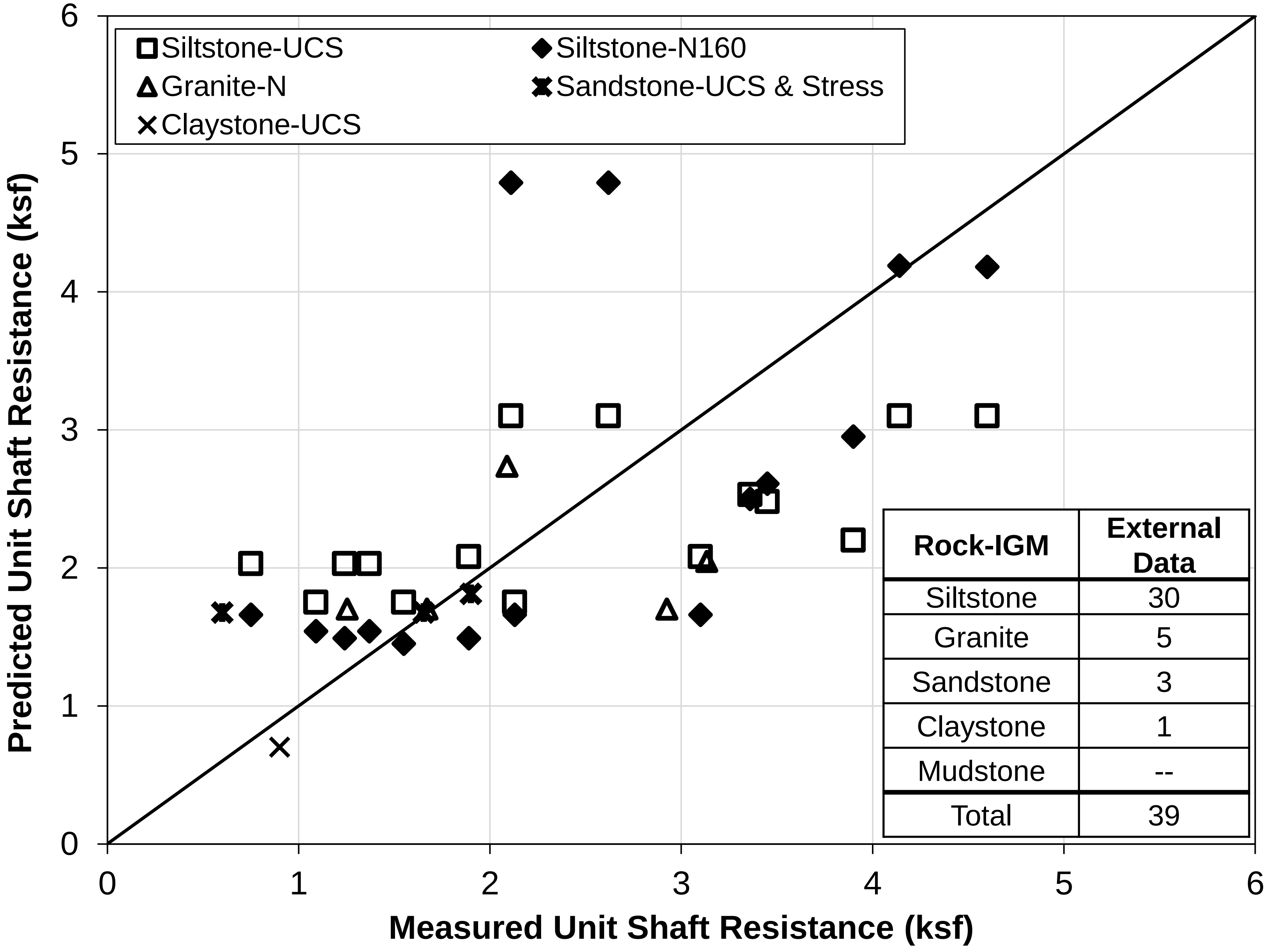
Steel Pile Type	Rock-IGM	Proposed Static Equation for Unit Shaft Resistance ($\bar{q}_s$)
H-Pile	Granite	$\hat{q}_s = \left[0.7\frac{N}{43} - 0.5\right] P_a$
H & Pipe Pile	Siltstone	$\hat{q}_s = 0.45{q_u}^{0.44}$ or $\hat{q}_s = 0.42P_a\left[\frac{(N_1)_{60}}{16}\right]^{0.63}$
H & Pipe Pile	Claystone	$\hat{q}_s = 0.74(q_u)^{0.305}$
H & Pipe Pile	Mudstone	$\hat{q}_s = 6.19\left[1 - e^{\left(-0.052\frac{N\times\sigma_v'}{19}\right)}\right]$
H-Pile	Sandstone	$\hat{q}_s = \frac{2.8(q_u \times \sigma_v{}')}{19.58 + (q_u \times \sigma_v')}$

Proposed Pile Resistance Estimation Methods For Piles in Rock-IGM

Steel Pile Type	Rock-IGM	Proposed Static Equation for Unit End Bearing ($\overline{q}_p$)
H & Pipe Pile	Siltstone	$\hat{q}_p = 12.9P_a\left[2.43^{\left(\frac{32.4N}{30D_B}\right)}\right]$
H & Pipe Pile	Claystone	$\widehat{q_p} = \frac{313.27q_u}{20.96 + q_u}$
Pipe Pile	Mudstone (Limited Sample Size)	$\widehat{q_p} = 35.71{q_u}^{0.93}$

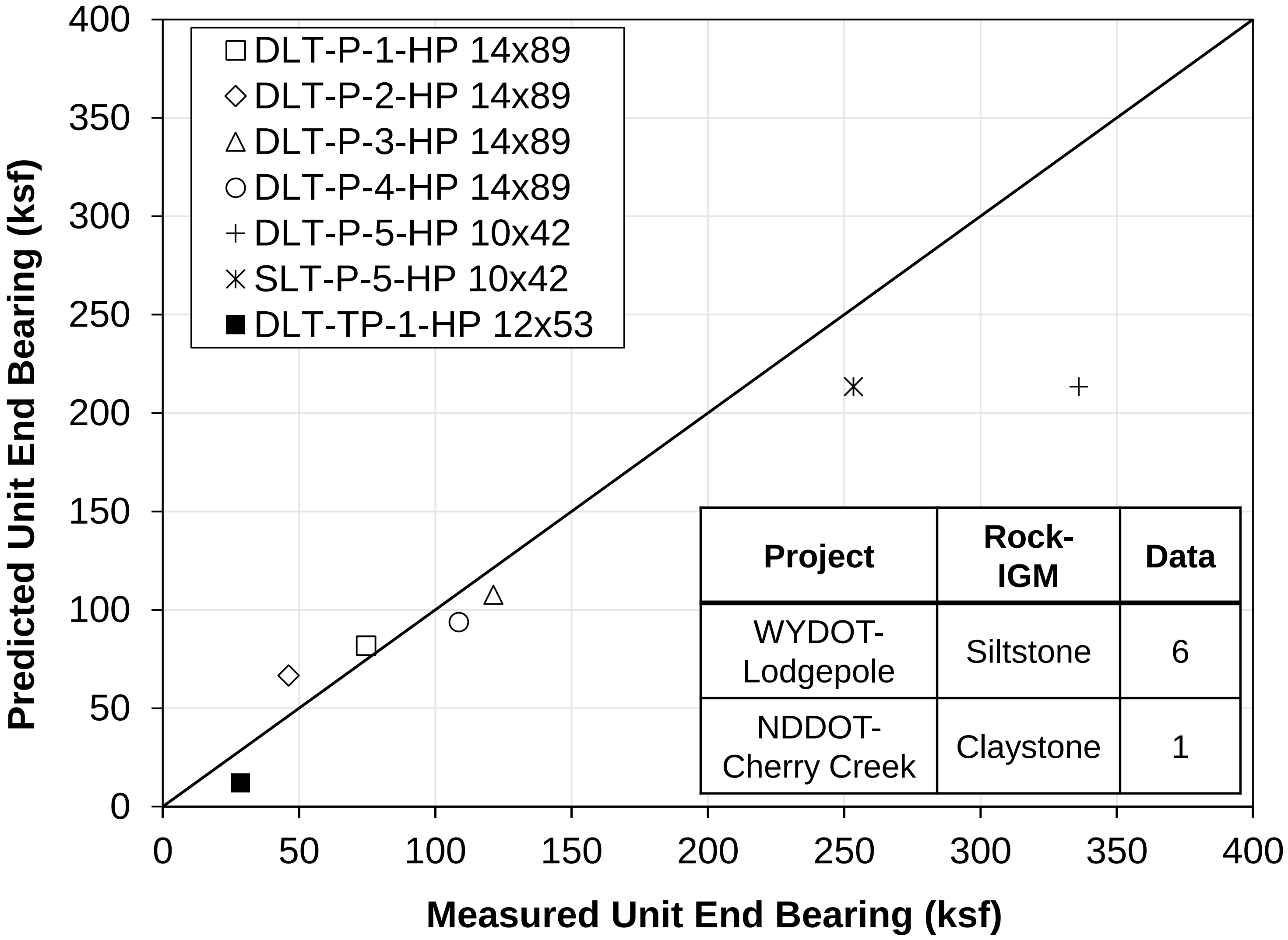
D_B–Total pile penetration; P_a–Atmospheric pressure; q_u–Unconfined compressive strength

Rock-Based IGM Validation-Unit Shaft Resistance



Rock-IGM	External Data
Siltstone	30
Granite	5
Sandstone	3
Claystone	1
Mudstone	--
Total	39

Rock-Based IGM Validation-Unit End Bearing



Project	Rock-IGM	Data
WYDOT-Lodgepole	Siltstone	6
NDDOT-Cherry Creek	Claystone	1

New Pile Data?

Task II-4: Variability Analysis (Spatial Uncertainty Consideration in The Development of LRFD Static Analysis Methods)

Introduction

- The need for spatial (parameter and geological) uncertainty:
  - The estimation of pile resistance during the design process depends on the geomaterial parameter and its associated uncertainty (inherent variability).
  - The characterization of geomaterial layer boundary positions is critical to the design of an adequate deep foundation (geological uncertainty).

- Objectives:
  - Formalize a procedure for characterizing and analyzing uncertainties in a design in which geomaterial and pile specific prediction equations have been obtained.
  - Consider cross-site uncertainties in estimation of LRFD resistance factor.

Method

Geological uncertainty

Assign categorical data from boreholes to the corresponding discretized elements

↓

Estimate transition rates with the Maximum Entropy method

↓

Perform Multinomial Categorical Simulation (MCS)

↓

Parameter uncertainty

Assign parameter data from boreholes to the corresponding discretized elements

↓

Estimate variogram

↓

Simulate parameter values conditionally (krige) and unconditionally (gstat) according to the geomaterial categories (layers) given by that MCS

↓

Transformation uncertainty

Transform parameter values in the pile domain area using proposed prediction equations based on the geomaterial and pile type

↓

Obtain the equivalent measured resistance for the domain area and perform nonlinear regression analysis to estimate mean resistance bias λ_R and resistance coefficient of variation, CV_R

↓

Estimate LRFD resistance factor φ using modified FOSM

LRFD Calibration

- Modified FOSM LRFD Calibration is given by:

$$\varphi = \frac{\lambda_r \left(\gamma_D \times \frac{Q_D}{Q_L} + \gamma_L\right) \times \sqrt{\frac{1 + CV_Q^2}{1 + CV_R^2}}}{\left(\lambda_{QD} \times \frac{Q_D}{Q_L} + \lambda_{QL}\right) \times exp\left(\beta \times \sqrt{\ln\left((1 + CV_R^2) + \left(1 + CV_Q^2\right)\right)}\right)}$$

where; γ_D = 1.25, γ_L = 1.75, $\frac{Q_D}{Q_L}$ = 2, λ_{QD} = 1.08, λ_{QL} = 1.15, CV_{QD} = 0.128, CV_{Ql} = 0.18, and

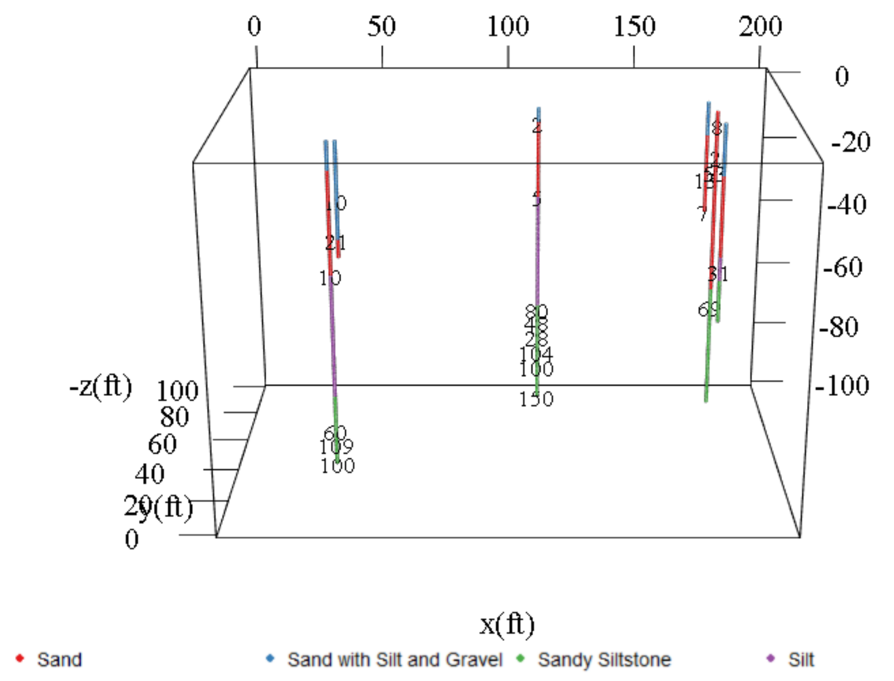
$$CV_Q^2 = \frac{\left(\lambda_{QD}\frac{Q_D}{Q_L}CV_{QD}\right)^2 + \left(\lambda_{QL}CV_{Ql}\right)^2}{\left(\lambda_{QD}\frac{Q_D}{Q_L}\right)^2 + 2\frac{Q_D}{Q_L}\lambda_{QD}\lambda_{QL} + \lambda_{QL}^2}$$

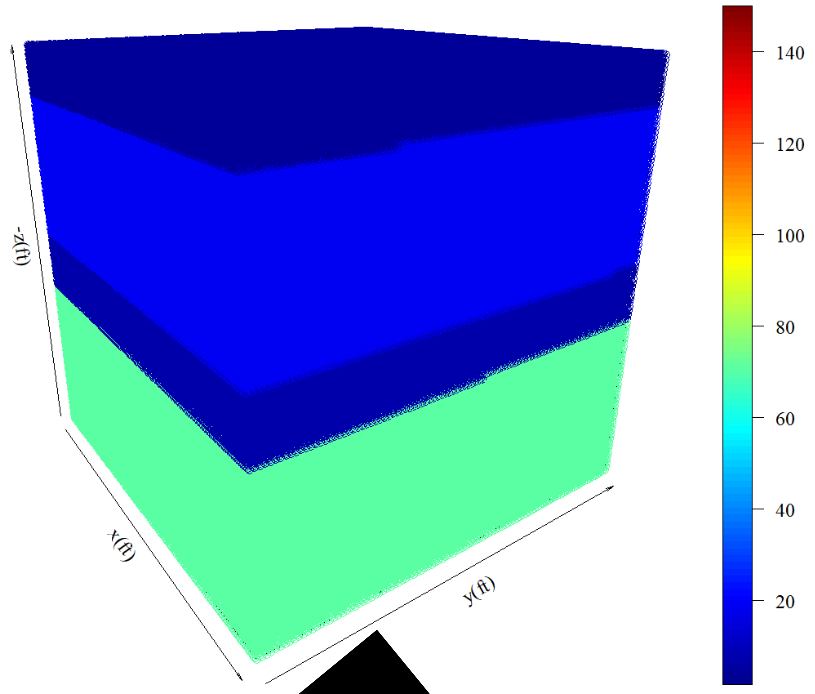
NHI (1998) assumed the coefficient of variation of the load CV_Q in the initial FOSM LRFD calibration as the equation below:

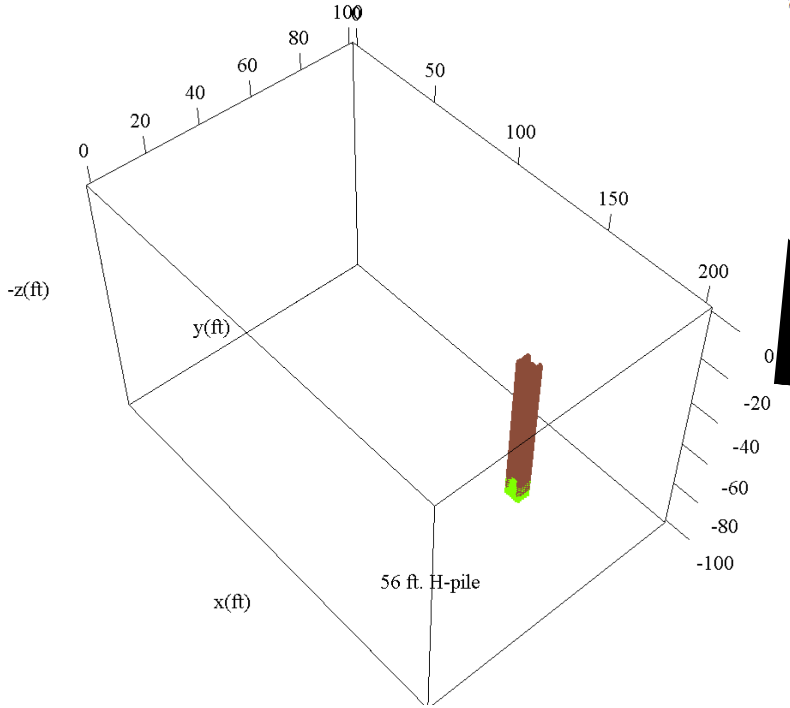
$$CV_Q^2 = CV_{QD}^2 + CV_{QL}^2$$

These equations resulted in lower than actual resistance factors. The FOSM resistance factor equation can be made closer to those of the FORM and Monte Carlo.

Example: Lodgepole Creek Site







- Prediction equation for unit toe resistance of H and pipe Piles driven in Siltstone is given by

$$\hat{q}_p = 12.9 P_a \left[2.43^{\left(\frac{32.4N}{30D_B}\right)}\right]$$

Where P_a is the atmospheric pressure
N is the SPT N value
D_B is the pile penetration depth

LRFD Resistance Factors
(End Bearing on Siltstone)

LRFD resistance factor considering spatial and transformation uncertainties

Pile Types	Rock-Based IGM	Sample Size	Mean Bias	Simulation Type	CV_R	MFOSM	
						β_T=2.33	β_T=3.00
						ϕ	ϕ
H & Pipe Pile	Siltstone	20	1.00	Conditional	0.52	0.36	0.26
H & Pipe Pile	Siltstone	20	1.04	Unconditional	0.53	0.36	0.26

LRFD resistance factor considering transformation uncertainty alone

Pile Types	Rock-Based IGM	Sample Size	Mean Bias	CV_R	MFOSM	
					β_T=2.33	β_T=3.00
					ϕ	ϕ
H & Pipe Pile	Siltstone	20	1.03	0.47	0.42	0.31

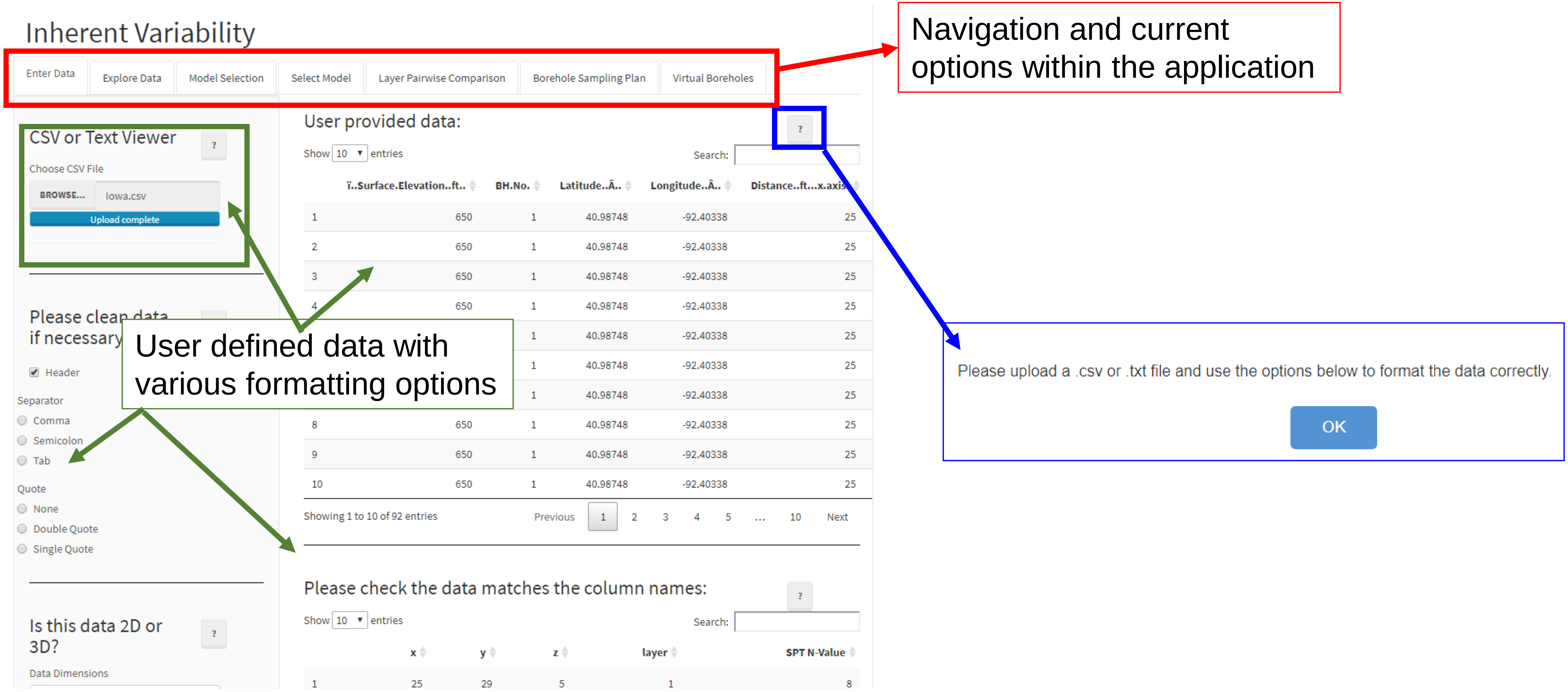
Concluding Remarks

- A prediction equation is usually obtained using regression analysis based on a regional data set but may be used in different locations with the same geomaterial conditions. However, only the prediction error (transformation uncertainty) is considered.
- This study considers the spatial uncertainty involved in applying the prediction equation for the estimation of pile resistance and the LRFD resistance factor. Spatial uncertainty is incorporated by inputting the simulated parameter value into the prediction equation, and this results in a predicted resistance that adjusts for the spatial location.
- The study provides a background to study the effect of site investigation on pile design.

Task II-4: Variability Analysis (Additional Task: R-Shiny)

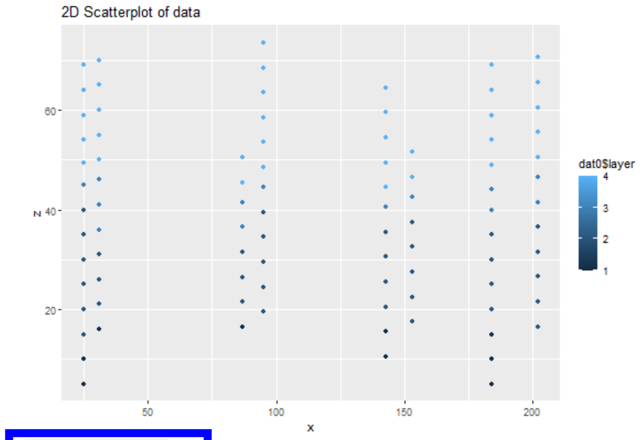
R-Shiny Demo

Application of R Shiny for Inherent Variability



Application of R Shiny for Inherent Variability

Plot of each layer per borehole at it's (x, z) location:



DOWNLOAD PLOT

Download results for lab reports

Which layer should we focus on?

Layer Input

Layer 4

SPT N-value at all depths per layer or 1 depth per layer

Depth Input

All depths

Please enter the x & y coordinate of user defined boreholes below:

x location of boreholes

70,130,180,60

y location of boreholes

80,180,160,75

The x coordinates you entered are:

```
[1]  70 130 180  60
```

The y coordinates you entered are:

```
[1]  80 180 160  75
```

User defined sampling plan options

Unconditional Simulation

x & y location of virtual boreholes:

```
[using universal kriging]
[using universal kriging]
[using unconditional Gaussian simulation]
[using unconditional Gaussian simulation]
     vb.x vb.y
[1,]  120   25
[2,]  160   60
[3,]  150   40
[4,]  195   60
[5,]  145   45
[6,]  115   55
[7,]   30   95
[8,]   75   10
```

Based on data & user inputs, simulation is used to select the next best locations for boreholes to reduce inherent variability

Next Steps

- Incorporate geological uncertainty through the layer boundaries
- Incorporate additional analyses for inherent variability
  - Conditional simulation
  - 1 depth per layer
- Test the production with additional datasets and users
- Develop user manual
- Implement a code maintenance plan

Research Team

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PhD: Opeyemi Oluwatuyi

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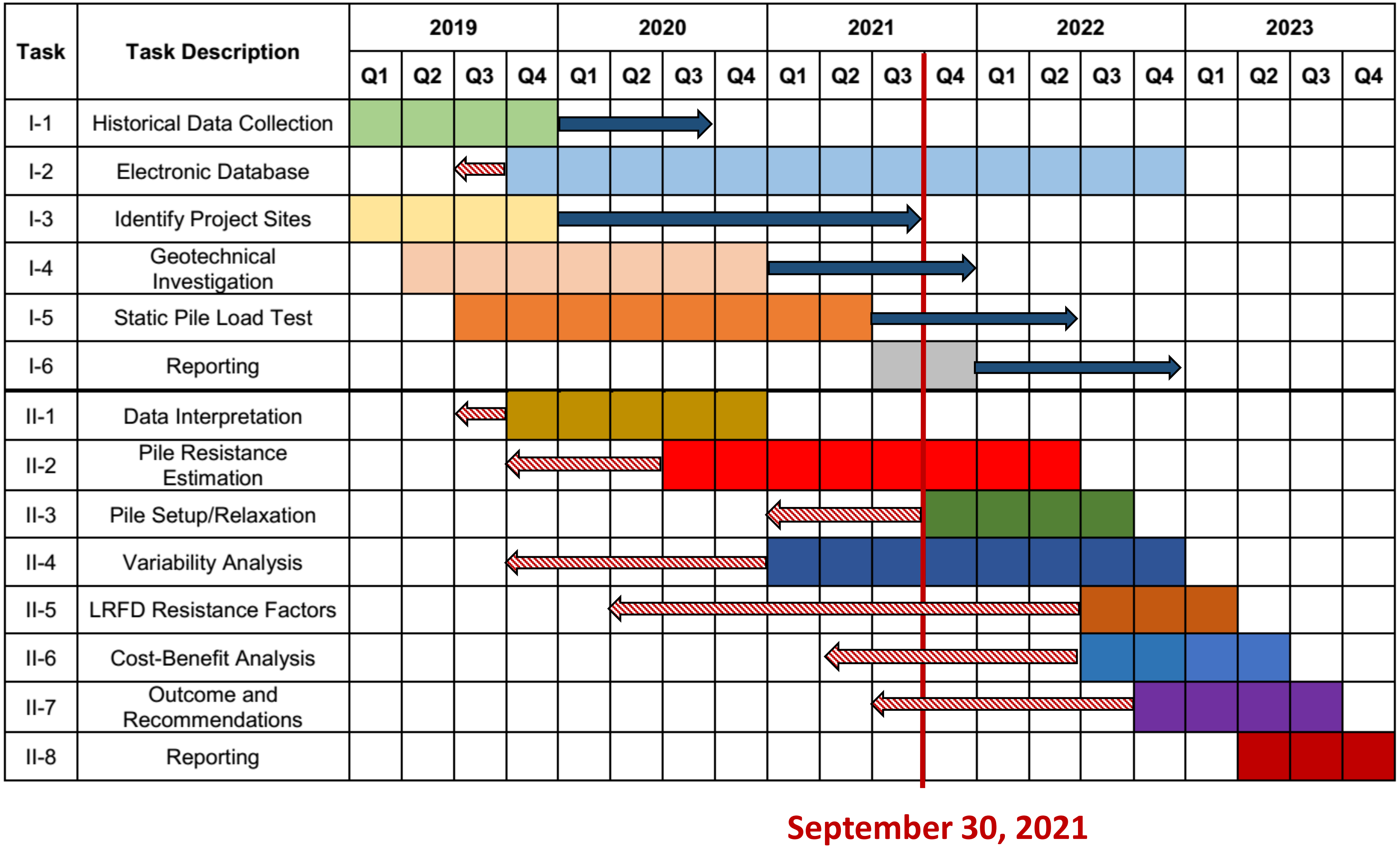
MS: Carmen Elliott

MS: Shafiqul Islam
(Graduated in 2021)

Project Schedule



Project Progress

Task	Description	Expected Percent Completion (Time)	Actual Percent Completion	Difference
I-1	Historical Pile Data Collection	100.00%	100.00%	0.00%
I-2	Expand Electronic Database	61.50%	85.71%	24.21%
I-3	Identify Bridge Projects for Field Test	100.00%	83.33%	-16.67%
I-4	Detailed Geotechnical Investigation	100.00%	58.33%	-41.67%
I-5	Innovative Static Load Tests	100.00%	41.67%	-58.33%
I-6	Reporting for Phase I	49.73%	0.00%	-49.73%
II-1	Geotechnical and Pile Data Interpretation	100.00%	100.00%	0.00%
II-2	Pile Resistance Estimation	62.55%	92.86%	30.31%
II-3	Pile Setup/Relaxation Investigation	0.00%	30.00%	30.00%
II-4	Variability Analysis	37.31%	40.00%	2.69%
II-5	Development of LRFD Resistance Factors	0.00%	70.00%	70.00%
II-6	Cost-Benefit Analysis	0.00%	10.00%	10.00%
II-7	Outcomes and Recommendations	0.00%	0.00%	0.00%
II-8	Reporting for Phase II	0.00%	0.00%	0.00%
Average Percent Completion		**50.79%**	**50.85%**	**0.06%**

Technology Transfer

Journal Manuscripts Submitted:

1) Oluwatuyi, O., Holt, B., Rajapakshage, R., Wulff, S.S., and Ng, K.W. "Inherent Variability Assessment from Sparse Property Data of Overburden Soils and Intermediate Geomaterials Using Random Field Approaches." ***Georisk Journal***. (Review Submission)
2) Oluwatuyi, O., Rajapakshage, R., Wulff, S.S., and Ng, K.W. "Simulation of Geologic Uncertainty and Geomaterial Boundaries Using Spatial Markov Chains." ***Acta Geotechnica***.
3) Islam, M.S., Ng, K.W., and Wulff, S.S. "Prediction of driven piles in shales considering weathering and time effects." ***Canadian Geotechnical Journal***.
4) Masud, N., Ng, K.W., Wulff, S.S., and Johnson, T. "Driven Piles in Fine Grained Soil-based Intermediate GeoMaterials." ***Journal of Bridge Engineering***. (Revised Submission)
5) Islam, M.S., Ng, K.W., and Wulff, S.S. "Improved Wave Equation Analysis of Steel H-Piles in Shales Considering LRFD and Economic Impact Studies." ***Journal of Bridge Engineering***.
6) Kalauni, H.K., Ng, K.W., Masud, N., and Wulff, S.S. "Improved Prediction Of Pile Resistances In Soil-based IGMs Using WEAP With LRFD Recommendations." ***Deep Foundation Institute Journal***.

Technology Transfer

Journal Manuscripts In Preparation:

1) Oluwatuyi, O., Rajapakshage, R., Wulff, S.S., Ng, K.W. “An optimal site investigation plan through unified treatment of inherent variability and geological uncertainty.”
2) Islam, M.S., Ng, K.W., Wulff, S.S. “Finite Element Analysis of Driven Piles in Intermediate GeoMaterials.”
3) Masud, N., Ng, K.W., Wulff, S.S., and Johnson, T. “Driven piles in coarse-grained soil-based Intermediate GeoMaterials.”
4) Kalauni, H.K., Ng, K.W., and Wulff, S.S. “Improved prediction of pile resistances in rock-based IGMs using WEAP.”

Technology Transfer

Conference Manuscripts:

1) Kalauni, H., and Masud, N. (2021). “Improved Estimation of Pile Resistances in Soil-based IGMs Using WEAP with LRFD Recommendations.” ***46th Annual Conference on Deep Foundation,*** Las Vegas, NV. (Awarded Runner-up for the Deep Foundation Institute Student Paper Competition)

2) Masud, N., Ng, K.W., Islam, S. and Wulff, S.S. “Static and dynamic pile load tests on steel H-piles in intermediate geomaterials.” ***ASCE GeoCongress 2022***, ASCE, March 20 to 23, Charlotte, NC. (Accepted)

3) Masud, N., Ng, K.W., and Wulff, S.S. “New static analysis method for the estimation of driven piles resistances in siltstone.” ***ASCE GeoCongress 2022***, ASCE, March 20 to 23, Charlotte, NC. (Accepted)

4) Oluwatuyi, E.O., Rajapakshage, R., Wulff, S.S., and Ng, K.W. “Quantifying geological uncertainty using conditioned spatial Markov Chains.” ***ASCE GeoCongress 2022***, ASCE, March 20 to 23, Charlotte, NC. (Accepted)

Technology Transfer

Conference Presentation:

1) Kam Ng will Present in the ASCE Geo-Institute 6th Annual Web Conference (December 6th-10th, 2021).
2) Kam Ng was Selected as the ASCE 2022 Geo-Institute GeoCongress State of the Practice Speaker. (March 20-23, 2022).
3) Kalauni, H.K., Ng, K.W., and Wulff, S.S. “Improved prediction of pile resistances in rock-based IGMs using WEAP with LRFD recommendations.” *TRB 2022 Annual Meeting.* (January 9-13, 2022).

Thank You for Your Participation